Integration of Borehole Image and Sonic to Evaluate Critically-Stressed Fractures to Optimize Production at FORGE Geothermal Field

E Sulistyowati\textsuperscript{1, a} and A Haris\textsuperscript{2, b}
\textsuperscript{1}Reservoir Geophysics Graduate Program, Physics Dept, Universitas Indonesia
Jl. Salemba Raya no. 4, Jakarta 10430, Indonesia
\textsuperscript{2}Physics Department, FMIPA, Universitas Indonesia
Kampus UI Depok, Depok 16424, Indonesia
Email: \textsuperscript{a}emiliana.sulistyowati@outlook.com; \textsuperscript{b}aharis@sci.ui.ac.id

Abstract. Geothermal integration solutions as unconventional environment have workflows or methods that must be able to optimize existing data and be adapted to overcome existing challenges. The integration method consists of geology, Petrophysics and Geomechanics domains. Geological analysis to identify fractures, fracture classification, knowing the dip azimuth and the magnitude of the fracture, quantitative analysis (intensity, aperture and porosity) by using the wellbore image log. Petrophysics analysis is to distinguish open / healed fractures that analysed from sonic data. Fracture orientation analysed further for the stress calculation on fracture planes and to determine the effective fractures (most likely to flow) that has a high ratio of shear to normal stress. Geomechanical analysis in geothermal fields, among others, is to determine the dynamic permeability behaviour of fractures during the production / injection phase, determine the orientation and productive fracture interval. The integration is using FORGE well 21-31 in 8.5in section with depth interval 6,226 – 7,920 ft-MD and well 58-32 in 8.5in section with depth interval 7,390-7,527 ft-MD. Well 21-31 shows dominant fracture strike orientation to NNE-SSW, while Well 58-32 shows slightly different set strike orientation to N-S with minor striking to NE-SW and NW-SE. Evaluation of critically stressed fracture intended to have knowledge on production mechanism and based on analysis, fracture/fault that has high potential of shearing is striking to NNE-SSW and dipping to Westerly.

1. Introduction
This paper presents a case study of borehole image and sonic data to understand fracture characterization of geothermal field that needed to evaluate the critically stressed fracture within the study interval. These fractures in many cases are showing enhanced permeability due to shear dilation and lie above the failure line in normal and shear stress spaces. Evaluation of such fractures require an understanding of the stress state, fracture geometry, mineralogy of infill material, and fracture slip properties like coefficient of friction (Anzar et al., 2011 [1]). Fracture characterization is obtained from the analysis of log data, borehole images and Stoneley sonic data. Stress state to obtain three principal stresses (vertical stress, maximum horizontal stress and minimum horizontal stress) and the direction of maximum horizontal stress. Integration of the density log provides the vertical stress in most cases. The minimum and maximum horizontal stress is determined using drilling-induced fracture and breakout information from
borehole image as no drilling data, LOT test and mini-freak test are available. The US Department of Energy's (U.S. DOE) Frontier Observatory for Research in Geothermal Energy (FORGE) is a field laboratory built as an ESG (Enhanced Geothermal System) laboratory. This EGS area has natural fractures and very small porosity values that make it possible to regulate water circulation for heat extraction. Utah FORGE is situated in a gently sloping alluvial area, between the peaks of the Mineral Mountains to the east and the central north to west of the Milford valley. The site is located on the southeastern edge of the Great Basin in a broad zone characterized by increased heat flow (Blankenship, D et al., 2018 [2]). The Fallon FORGE, Nevada area located in the Carson Sink is a large half-Graben basin, similar to many locations throughout the Great Basin Region.

Figure 1. FORGE Location Area: well 58-32 (Left) and well 21-31 (right).

2. Geologic Information about FORGE Field
The regional stratigraphy consists of Paleozoic-Mesozoic folds and carbonate imbrications which are the result of Tertiary-current mafic-felsic magmatic eruptions, including in the Mineral Mountains, and are widespread with extension patterns in basins and mountains. The local lithology is divided into two broadly defined units, consisting of a crystalline bedrock and an overlying basin filled with sedimentary deposits (Moore, J. et al., 2018 [3]).

2.1. Geological Setting of Well 58-32
In 2018, well 58-32 was drilled vertically to a total depth of 2290 m (7515 ft) GL where at 961 m (3154 ft) GL contact with a low permeability crystalline rock and a bottom hole temperature of 199°C (390°F). The well penetrates layered alluvium deposits to 3176 feet (968 m), where it crosses contact with crystalline basement rock to the bottom of the wellbore. The upper interval of layered alluvium (0–3176 ft; 0–968 m) consists of poorly sorted and poorly lithified sediments made of quartz and feldspar eroded from plutonic rocks in the Mineral Mountains. The lower interval (3176–7536 ft; 968–2298 m) consists of granitoids (i.e. Igneous rocks), petrographically identical to those exposed in the Mineral Mountains (Figure 2). These crystalline rocks form strong low porosity reservoir rocks, ranging from granite to monzodiorite to monzodiorite quartz in composition, plus minor dirt. Eltie and chlorine are the main clay minerals, but make up <5% of the rock. Other secondary minerals include carbonates and anhydrides, and fractures at intervals that are casted are filled with chlorite or epidote (Moore et al., 2020 [4]).
2.2. Geological Setting of Well 21-32

The Fallon FORGE site located in the Carson Sink is a large half-graben basin, similar to many locations throughout the Great Basin Region. The general stratigraphy of the area is Late Miocene to Quaternary sedimentary basin (<1.5 km thick), overlying Miocene volcanic rocks (0.7-1.3 km thick), and Mesozoic basement consisting of meta-volcanic and meta-volcanic rocks. Sediments breached by a full-size Pluton. This area is located in the western part of the half-graben fold which is widely intersected by normal faults trending north with a displacement of about 200 m (Siler et al., 2018, Figure 3 [5]). The primary rock units that fill the basin found at the Fallon location are: a) Quaternary sediments, b) Quaternary-Tertiary sediments, c) Miocene mafic volcanic rocks, mainly basaltic andesite, but also lithic Tuff, andesite, rhyodite, and volcanic breccias. The infill rock of the basin is located unconformably at the top of the Mesozoic basement, which consists of: a) Mesozoic quartz monzonite, b) Mesozoic meta-basalt and meta-basaltic-andesite, c) Mesozoic quartzite with little pilot, meta-basalt, and marble, d) Mesozoic meta-Rhyolite with lower meta-basalt. The deepest well in the area ending in the Mesozoic basement at depths of 2112-2886 m recorded a maximum downhole temperature of 194 to 214 °C (Blankenship, 2016, Siler et al., 2016 [6]).
3. Method
The flow of research to be carried out is explained as follows: Geological analysis is obtained from borehole image (FMI) data and core data. Petrophysical analysis was obtained from log data (gamma ray, resistivity, neutron porosity, and density) and Stoneley sonic wave. Geomechanical and critically-stressed analysis is the integration of all existing analysis results.

3.1. Borehole Image Interpretation
FMI (Fullbore Formation Microimager) is image data that provide microresistivity formation images for geological, geomechanical and 3D reservoir modeling analysis. FMI imaging is an approach to determine subsurface image data and the direction of layer slope, fracture, fracture. FMI images are generated with two types of resistivity scales, whereas static and dynamic images. Natural fractures that classified and picked in this study only conductive fracture are which is considered to be open / filled with conductive minerals. A fracture is a planar feature without displacement along the fracture plane. Shear fractures and/or drilling induced fractures are also found throughout the interval and occur in clusters. These fractures are not natural and are related to drilling activities. The orientation of the current geological horizontal stress can be determined by measuring the orientation of the induced fracture as well as the breakout hole in the vertical or near-vertical wall. These features tend to be localized and run vertically down the sides of the borehole and against each other. The orientation of the breakout hole can indicate the orientation of the minimum horizontal stress (\(\sigma_{Hmin}\)) on the borehole wall, and the orientation of the induced fracture can indicate the direction of the maximum horizontal stress (\(\sigma_{Hmax}\)). Further quantitative analysis was performed to determine fracture properties: fracture density (corrected), fracture aperture (FVAH) and fracture porosity (P33).

3.2. Sonic Stoneley Wave Analysis
To determine the “openness” of the fracture, two approaches have been used by integrating FMI image and Sonic Scanner data. A reflective analysis of Stoneley was carried out and compared with selected fractures in FMI. When the exposed fracture cuts through the borehole, Stoneley causes well fluid to be pumped in and out of the fracture, dissipating energy. This results in attenuation of the Stoneley wave. The dipole emitter is so strong and directional that it has a strong sensitivity to “open” and “wide” fractures. The fracture zone interval at which significant energy loss was observed was used to identify open and wide fracture intervals. At the same time, a change in acoustic impedance causes a partial reflection of the signal. The greater the energy loss (high attenuation), the wider the propagation of the fracture. Meanwhile, the smaller the energy (low attenuation) lost, the lower the fracture propagation. Fractures with very high magnitude slopes may not be detected by sonic scanners. Thus, the effect of the fracture opening in Stoneley is the reduction of the Stoneley Amplitude (attenuation) and the Stoneley Reflection. A Stoneley reflection is a wave that starts at the transmitter that is received directly by the receiver, but propagates further and can be reflected by the fracture and detected a second time later. Besides being sensitive to fractures (discontinuities), the Stoneley Reflection is also sensitive to changes in borehole size and layer boundaries (lithological changes) in the formation. A similar chevron pattern can be seen in VDL due to the presence of washout and layer boundaries. Due to these limitations, compression and shear lag were used to model the Stoneley reflection response due to non-fracturing effects (borehole enlargement and layer boundary effects).

3.3. 1D Mechanical Earth Model
The development of the Mechanical Earth Model (MEM) (Plumb et al., 2000 [7]) is very important in the formation of field Geomechanics information. MEM is a description of forces, stresses and stresses as a function of depth, referred to a stratigraphic column. MEM consists of a description of the rock material (ie, the mechanical stratigraphy of the formation is considered), rock elastic parameters, including Young's Modulus and Poisson's Ratio; rock strength parameters: Unconfined Compressive Strength (UCS), tensile strength and internal friction angle; Stressor model: vertical stress, minimum and minimum horizontal stress and orientation, and pore pressure.
3.4. Critically stressed Fracture Analysis

Tectonic stress conditions can cause fractures/faults with a directional orientation to slip caused by high shear stresses, potentially resulting in increased permeability due to shear dilatation [Barton et al., 1995 [8]]. These fractures are "critically-stressed" and are located above the failure line in the normal and shear stress zones. With increased permeability, these fractures can act as fluid conduits between wells or between different reservoir intervals. Given the stress field and the orientation of the fracture and fault sets, it is possible to determine which fracture and fault sets are susceptible to shear slip, and therefore the likely paths for fluid flow or increased permeability. This is done by determining how stable the fracture or fault is under a current stress field, using the Mohr Coulomb criteria.

4. Results and Discussion
4.1. Fracture Characterization and Critically stressed Fracture of Well 58-32

Well 58-32 in 8.5in section with depth interval 7,390-7,527 ft-MD is comprised entirely by granitoids. The violations were observed in this well, but not picked and analyzed as not contribute in producing (tend to not flow). Three (3) types of dip that was manually picked consists of conductive fracture, drilling induced fracture and breakout. Conductive fracture shows dominant strike direction to N-S with minor striking to NE-SW and NW-SE where dip magnitude range of 20 - 74 deg (Figure 4). No further classification for low and high angle conductive fractures was performed due to all natural conductive fracture dips are needed for further critically-stressed analyses.

Drilling induced fractures mainly observed in the upper interval of study and consistently show NE-SW orientation. The breakout was observed and show perpendicular orientation from drilling induced fractured, show direction to NW-SE. Well 58-32 is vertical well and very small inclination (max 3deg), the strikes of drilling induced fractures and borehole breakouts may align with the trends of maximum and minimum horizontal stress (respectively). As no Stoneley wave sonic is available in this well, thus no sonic fracture analysis was performed. Thus, further classification of probable open fractures cannot be analyzed.

Isotropic was applied to the rock types within the reservoir during 1D construction. Integrating density log was used for Overburden construction where pressure is taken to be hydrostatic pressure at a given depth z from the top of the water table. Key parameters requiring correlation are Unconfined Compressive Strength (UCS) and Tensile Strength also correlated from Young Modulus (static) and Poisson’s ratio. The result of MEM parameters was calibrated with rock mechanics test from the lab and caliper data from FMI (breakout / borehole failure indicator). Stress regime in this well is normal regime \( (\sigma_v > \sigma_h > \sigma_x) \) and using the input (pore pressure, vertical stress, minimum and maximum horizontal), maximum horizontal stress direction 40deg and friction angle 20deg, the result of fracture stability shows that fracture that has high potential of shearing is striking to N-S, dipping to Westerly with dip magnitude range 45-70 deg align with maximum horizontal stress direction (Figure 5).

4.2. Fracture Characterization and Critically stressed Fracture of Well 21-31

Well 21-31 in 8.5in section with depth interval 6226 – 7920 ft-MD is comprised of Rhyolite-Tuff, basalt, quartzite, metabolite, and felsic intrusion rock formations. Foliation in this well is abundant along the study interval. Three (3) types of dip also manually picked consists of conductive fracture, drilling induced fracture and breakout. Conductive fracture shows dominant strike direction to NNE-SSW where dip magnitude range of 25 - 85 deg (Figure 6).

Drilling induced fractures mainly observed in the upper interval of study and consistently show NNE-SSW orientation. The breakout was observed and show perpendicular orientation from drilling induced fractured, show direction to WNW-ESE. Well 21-31 is vertical well and very small inclination (max 4.5 \(^\circ\)), the strikes of drilling induced fractures may align with the trends of the maximum horizontal stress while breakouts align with minimum horizontal stress.

Same workflow as Well 58-32 for 1D MEM construction, parameter and fracture stability were applied in Well 21-31. Fortunately, in Well 21-31 Stoneley wave sonic is available and sonic fracture analysis was performed. All natural conductive fractures picked from FMI that has potential critically stressed
fracture was filtered based on potential zone that shows an energy loss (after washout and bed boundary zone reduced). Using the input (pore pressure, vertical stress, minimum and maximum horizontal), maximum horizontal stress direction 30deg and friction angle 20deg, the result of fracture stability shows that fracture that has high potential of shearing is striking to NNE-SSW with dip magnitude range 40-70 deg (Figure 7).

Figure 4. Fracture characterization of Well 58-32 for entire study interval.

Figure 5. Critically stressed fracture (red points) using FANG 20 dog show dominant azimuth orientation to Westerly, striking to N-S and dip magnitude 45-70 deg.
Figure 6. Fracture characterization of Well 21-31 for the entire study interval.

Figure 7. Critically stressed fracture of Well 21-31.

It is also important to analyze the effect of depletion or reduction in pore pressure on critically stressed fractures. With depletion, pore pressure will decrease, and horizontal stress will decrease as well without any change in overburden stress. From analysis in both wells, no change in 10% depletion and an increase in critically stressed fractures at 30% and 50% depleted.
5. Conclusions & Recommendation
To increase production nearby Well 58-32, fractures that have potential to increase production are natural fractures that have a dip azimuth towards Westerly and a dip magnitude > 45deg. While for nearby well 21-31, fractures that have potential to increase production are natural fractures that have dipped azimuth towards the NW and SE and dip magnitude > 32deg. Evaluation of critically stressed fracture intended to have knowledge on production mechanism and based on analysis, fracture that has high potential of shearing is striking to NNE-SSW.
It is important to improve the stress model by improving the understanding of critically stressed fracture. The recommendations are:

- conduct rock mechanical core tests to obtain mechanical properties of the critical formations
- Acquire more stress related data, like Sonic Scanner, extended leak-off tests (XLOT) or Mini-FRAC. Those data very useful to provide stress calibration data
- conduct a 3D Geomechanics analysis over the whole field to identify a sweet spot area based on connection within critically stressed fractures

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