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Mapping the Preferential Flow Paths within a Fractured Reservoir

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ABSTRACT

In a fractured reservoir, three dimensional (3-D) preferential flow paths are likely to be formed (i.e. 3-D channeling flow) due to the heterogeneous aperture distributions of individual fractures. However, to date there is no practical modeling method that precisely maps the 3-D channeling flow. In this study, we developed a novel method to analyze and predict channeling flow in an actual fractured reservoir, where a novel discrete fracture network (DFN) model simulator, GeoFlow, is used. In GeoFlow, heterogeneous aperture distributions are given for individual rock fractures depending on their scale and shear displacement under confining stress. By using GeoFlow, fluid flow is simulated for a fractured reservoir of the Yufutsu oil/gas fields, where one can observe an interesting phenomenon wherein the difference in productivity between two neighboring wells is three-orders-of-magnitude. This phenomenon can be reproduced only with the GeoFlow model, which strongly supports the idea that the three-orders-of-magnitude difference in productivity is mainly caused by the occurrence of 3-D channeling flow within the reservoir. Specifically, the impact of 3-D channeling flow on well production is expected to be significant in the domain where the degree of fracture connectivity is relatively limited. The contacting asperities within such a domain play a significant role as a resistance for 3-D preferential flow paths and, as a result, it is difficult for flow paths to be maintained consistently and there is some possibility that the flow paths vanish due to the occurrence of 3-D channeling flow. Through a series of these simulations, it is revealed that the wrong conclusions might be obtained for the development or utilization of a fractured reservoir if the occurrence of 3-D channeling flow within the reservoir is not considered.

1. INTRODUCTION

The Yufutsu oil/gas field in Hokkaido (Japan) is known as fractured basement reservoir, and the permeability development of the reservoir is inferred to be controlled by the shear dilation mechanism for the mega-fractures, which have apertures of more than 5 cm [*Kumano et al.*, 2012]. For this field, it is reported that approximately three orders of magnitude difference in productivity was observed between two neighboring wells which were drilled in this field [*Tamagawa et al.*, 2010; *Tamagawa et al.*, 2012]. This phenomenon is considered to be scientifically interesting, though such a phenomenon is a serious problem for oil development companies.

For the Yufutsu oil/gas field, comprehensive quality data sets (well productivity data, 3-D seismic data, core and wellbore imaging data, and microseimic data) have been compiled [*Tezuka et al.*, 2004]. Owing to these data sets, highly reliable distribution of fractures can be revealed and the active fractures under a strike-slip faulting stress regime (i.e. critically-stressed fractures), which have very high permeability, can also be delineated for the Yufutsu field. In other words, highly reliable discrete fracture network (DFN) models for the fracture distributions, where permeabilities of critically-stressed fractures are much higher than those of noncritically-stressed fractures due to shear dilation mechanism, can be created for the prescribed regime of 2.4 km (East-West) × 2.6 km (North-South) × 1.5 km (Depth) of this field (see Figure 1). However, although the fluid flow is analyzed for the DFN models, the huge difference in well productivity, observed from the field, has never been reproduced and the cause of the huge difference is still unexplained [*Tamagawa et al.*, 2010; *Tamagawa et al.*, 2012]. Thus, mapping the actual fluid flow within a fractured reservoir remains significantly difficult today.

In this study, the causes of the discrepancy between the observation and the model will be considered. For the natural rock fractures, since the apertures are formed by pairs of rough surfaces that are in partial contact with each other, the rock fractures have heterogeneous aperture distributions. Consequently, fluid flow through rock fractures are characterized by the formation of preferential flow paths (i.e., channeling flow) [*Brown*, 1987; *Matsuki et al.*, 2006; *Watanabe et al.*, 2008]. However, regardless of this fact, rock fractures are simply represented by pairs of parallel smooth plates with unique apertures for the DFN model utilized in the previous study [*Tamagawa et al.*, 2010]. Due to this simplification, the occurrence of channeling flow within the individual rock fractures is ignored in the past modeling, though the three dimensional preferential flow paths are expected to be formed (i.e., 3-D channeling flow) in an actual fractured reservoir. Thus, one of the most considerable causes for the discrepancy is whether the 3-D channeling flow within a fractured reservoir is adequately modeled or not. In other words, if the occurrence of 3-D channeling flow is considered adequately, the huge difference in well productivity for the Yufutsu oil/gas field is expected to be reproduced.

To test this concept, realistic DFN models, where heterogeneous aperture distributions are given for individual fractures depending on their scale and shear displacement under confining stress, are created for the Yufutsu oil/gas field. Subsequently, the fluid flow paths within the DFN models are analyzed by GeoFlow, which was recently developed to investigate 3-D channeling flow in a fracture network [*Ishibashi et al.*, 2012a]. In the present study, through GeoFlow simulations for the Yufutsu oil/gas field, three dimensional preferential flow paths within a fractured reservoir are first mapped. Then, the characteristics and impact of 3-D channeling flow in a fractured reservoir are discussed.

2. METHOD

2.1 Modeling of a Fractured Reservoir

An area of 1,080 m (East-West) × 1,080 m (North-South) × 1,080 m (Depth) in the Yufutsu field, which is shown in Figure 1 with bold lines, is the focus in the present study. This area includes well A (high productivity) and well B (low productivity), and the difference in productivity of these two wells is approximately three orders of magnitude. Therefore, the characteristics and impact of 3-D channeling flow in a fractured reservoir can be discussed through the GeoFlow simulations of this area.

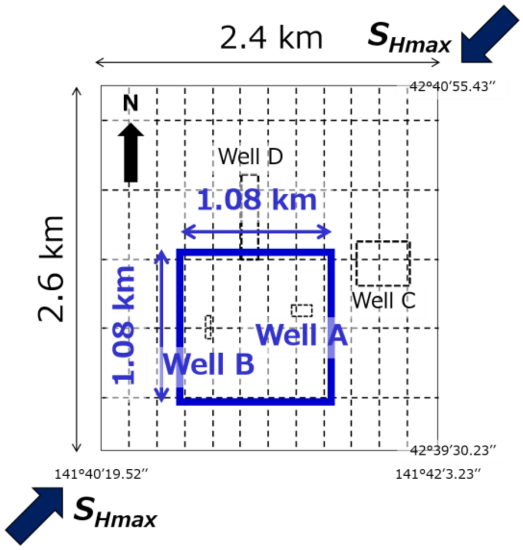

Figure 1: Locations of production wells, which are enclosed with thin dashed lines, within the Yufutusu oil/gas field. Study area of GeoFlow simulation in the present study is enclosed with bold line. The overall trend of the maximum principal stress direction is northeast-southwest as shown with arrows.

In modeling the DFN for the Yufutsu field, the present study assumes that the fracture system is simply developed as follows. First, a number of fractures are generated within the rock mass by various reasons such as cooling of the rock mass, change in the stress field, and so on. Then, the fractured rock mass is placed in the current stress state of a strike-slip-faulting. According to the stress state, rock fractures with the specific directions, which satisfy the Mohr-Coulomb failure criterion, are sheared.

Discrete fracture networks are created on the specified area, where the permeability of rock matrix is set to 10^{-19} m^2, which is equivalent to the matrix permeability of granite. Rock fractures are represented by squares of 18 different scales (44, 62, 80, 98, 115, 133, 151, 168, 186, 204, 222, 239, 257, 275, 293, 310, 328, and 346 m on a side), and approximately 15,000 fractures are distributed in the analytical domain. Center coordinates and orientations of the individual fractures are given so that they coincide with those determined in *Tamagawa et al.* [2010]. Then, 15 kinds of stochastic equivalent discrete fracture networks, where the center coordinates and orientations of the individual fractures are different, are prepared. This is because DFN models are recognized to be best treated in a stochastic framework by considering Monte Carlo analyses based on multiple realizations. One example of the created DFN for the Yufutsu field is shown in Figure 2, where x-, y-, z-axes are mounted in east-west, north-south, deep-shallow directions, respectively. Such correspondences for the axes are common in the following figures.

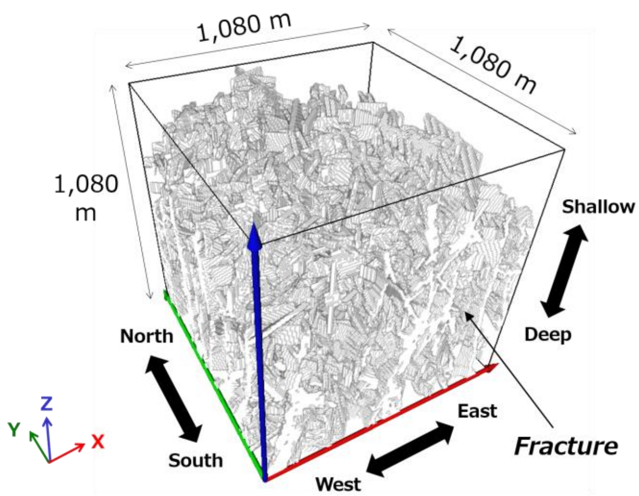

Figure 2: An example of the created DFN for the Yufutsu oil/gas field.

In the present study, two different models, "GeoFlow model" and "Conventional DFN model", are used for analyzing fluid flow in the fractured reservoir. Heterogeneous aperture distributions are considered in response to the fracture scale and shear displacement in GeoFlow model, whereas fractures are represented by pairs of parallel smooth plates with scale-dependent unique apertures in Conventional DFN model. Between these two models, fracture distributions (fracture scales, center coordinates, and orientations of the individual fractures) are the same. Moreover, permeabilities (or hydraulic apertures) of the corresponding fractures are also the same. Consequently, by comparing the result of GeoFlow model with the result of Conventional DFN model, the characteristics and impact of 3-D channeling flow can be discussed.

In creating GeoFlow models of the Yufutsu field, heterogeneous aperture distributions for rock fractures in various scales are determined with the method reported in *Ishibashi et al.* [2012b]. In this method, a pair of fractal fracture surfaces is placed in contact so that the fracture has the scale-independent contact area. When this method is applied, the surface geometries of the fractures are numerically created by using the parameters, such as fractal dimension and standard deviation for the surface height, calculated for the tensile fracture of granite of laboratory scale. As the grid spacing in the *X*- and *Y*-directions is set to one m for the surfaces, the dimension of fracture element, which is defined in *Ishibashi et al.* [2012a], is 1 m × 1 m.

In the GeoFlow model of the Yufutsu field, critically-stressed fractures, which are expected to experience multiple slips, can be distinguished from noncritically-stressed fractures by considering the current stress state. Thus, heterogeneous aperture distributions are given separately for these fractures. In other words, the GeoFlow model consists of 36 kinds of fractures with various combinations of fracture scale and shear displacement. A ratio of shear displacement to fracture length ("shear displacement" hereafter) is set equal to 5×10^{-5} (0.005%) for the noncritically-stressed fractures, whereas a ratio of shear displacement to fracture length is set to 2×10^{-2} (2%) for the critically-stressed fractures. These values of the ratio of shear displacement to fracture length are determined by a trial-and-error method.

In order to analyze fluid flow within a fracture reservoir, the discrete fracture networks are converted into the equivalent permeability continua, which is common for both GeoFlow model and Conventinal DFN model. The analytical domain of 1,080 m × 1,080 m × 1,080 m is first divided into a total of 5,832,000 matrix elements, which is also defined in Ishibashi et al. (2012a), with the dimension of 6 m × 6 m × 6 m. Then, equivalent permeabilities are calculated at all matrix element interfaces. One example of a permeability map for the equivalent permeability continua of the Yufutsu field is shown in Figure 3, where the highly permeable zone is shown with colors. Parameter values used for the fluid flow simulations of the Yufutsu oil/gas field is summarized in Table 1.

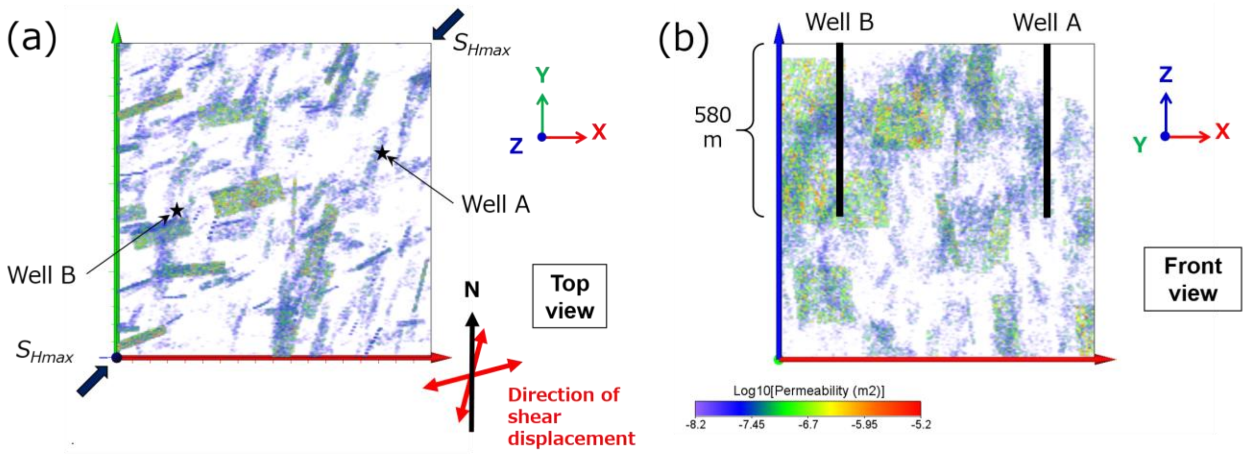

Figure 3: An example of permeability map for the equivalent permeability continuum of the Yufutsu oil/gas field evaluated in GeoFlow model ((a) Top view and (b) Front view).

Table 1: Parameter set for the fluid flow simulations of the Yufutsu oil/gas field.

Analytical domain	1,080 m × 1,080 m × 1,080 m
Minimum fracture	44 m × 44 m
Maximum fracture	346 m × 346 m
Number of fracture	Approximately 15,000
Fracture element	1 m × 1 m
Matrix element	6 m × 6 m × 6 m
Number of matrix element	180 × 180 × 180 (=5,832,000)
Shear displacement of noncritically-stressed fractures	0.005% of fracture length
Shear displacement of critically-stressed fractures	2.0% of fracture length

2.2 Analysis of Fluid Flow in a Fractured Reservoir with GeoFlow

For the equivalent permeability continuum, steady-state laminar flow of a viscous, incompressible fluid can be simulated under radial flow geometry (Figure 4a) and unidirectional flow geometry (Figure 4b). For both simulations, the upper and lower sides, which are not shown in Figure 5, are no-flow boundaries where the pressure gradient is zero. Results of radial flow simulations will reveal the distribution of flow paths in a state of oil and gas production, and fluid macroscopically flows from sidewall boundaries to well A and well B in Figure 4a. In contrast, fluid macroscopically flows in the direction of the x-axis in Figure 4b, and it is also possible to simulate macroscopic fluid flows in the directions of the y-axis and the z-axis by setting the similar boundary conditions. Results of unidirectional flow simulations will reveal the distributions of flow paths in a state of nature (i.e. no production wells). In this study, differential pressure, ΔP, is set to constant value of 0.1 MPa for the both flow geometries. For both well A and well B, the depth of well is 580 m (see Figure 4b), which is also determined so that the actual settings of the Yufutsu oil and gas field can be imitated.

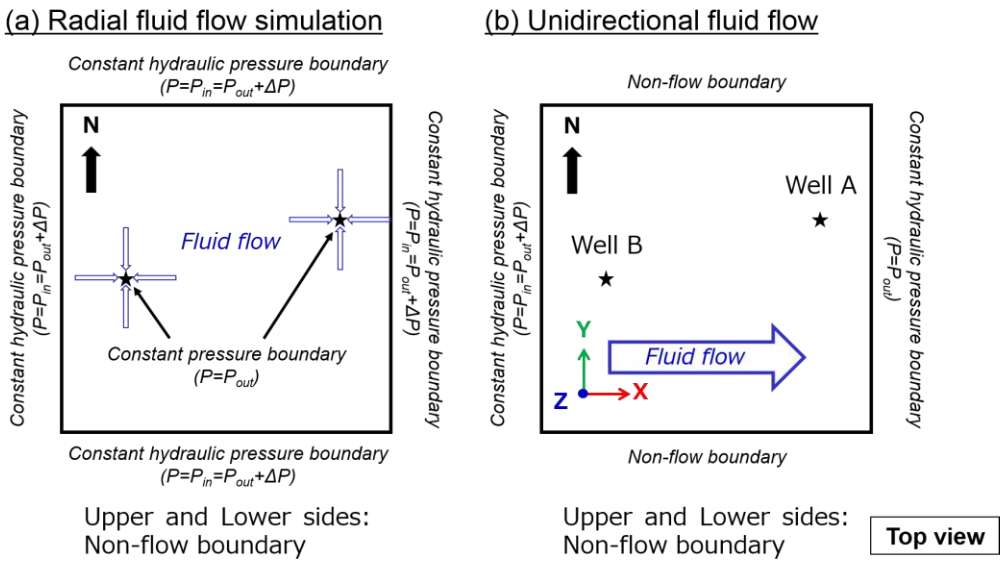

Figure 4: Boundary condition for (a) radial fluid flow simulation and (b) unidirectional fluid flow simulation.

In the present study, radial fluid flow simulation are initially conducted for both GeoFlow model and Conventional DFN model, and these results are compared. In the radial fluid flow simulations, the flow path distributions are evaluated. In addition, the productivities of well A and well B, and the fluid existing volume, which is defined as the ratio of the volume where 95% of total flow exists to the volume where fractures exist within the analytical domain, are also calculated. Subsequently, unidirectional fluid flow simulations in the direction of the x-, y-, and z-axes are conducted for the GeoFlow model and the flow path distributions of the unidirectional fluid flow in the respective direction are evaluated. On the basis of these simulation results, the characteristics and impact of 3-D channeling flow in a fracture reservoir are examined and discussed.

3. RESULTS AND DISCUSSION

3.1 Reproduction of Three orders of Magnitude Difference in Well Productivity Observed in the Yufutsu Oil/Gas Field by GeoFlow Simulations

The results of the fluid flow simulations reveal that three orders of magnitude difference in well productivity observed in the Yufutsu oil and gas field can be reproduced only with the GeoFlow model. Since the principal difference between the GeoFlow model and the Conventional DFN model is whether the occurrence of 3-D channeling flow is considered or not, it can be concluded that one of the most likely causes for the significant difference in well productivity is 3-D channeling flow. The details of the simulation results are as follows. In evaluating the fluid flow characteristics of a fractured reservoir by using DFN modeling techniques, it is desirable that the parameters for fluid flow characteristics, which are calculated for multiple realizations, are ensemble averaged [*Tamagawa et al.*, 2010]. This is because the parameters for fluid flow characteristics vary significantly in response to the distribution of rock fractures, even though the fracture distributions are stochastically equivalent. Additionally, to visualize flow path distributions, local flow rates, which are calculated for the respective elements of the equivalent permeability continuum of DFN, should be ensemble averaged as well.

With respect to the permeability map of the fractured reservoir, highly permeable zones, which are almost corresponding to the critically stressed fractures, are distributed as dots in the GeoFlow model, since the individual fractures have heterogeneous aperture distributions in response to fracture scales and shear displacement (see Figure 3). On the other hand, highly permeable zones correspond to the entire fracture plane of critically-stressed fractures in the Conventional DFN model, since the individual fractures are modeled by pairs of parallel smooth plates with scale-dependent unique apertures. It is preliminary confirmed that the both well A and well B intersect more than one critically-stressed fracture. These results show that 3-D channeling flow in the fractured reservoir can only be simulated in the GeoFlow model.

When the flow path distributions are visualized, the ensemble averaged local flow rates are furthermore normalized by their maximum value. The flow path distributions are shown with different colors in response to the normalized values. Particularly, when the results of the radial fluid flow simulations are shown in the following, the summation of the normalized values for the elements corresponding to the visualized flow path is 95% of the summation for the entire analytical domain. The results of the radial fluid flow simulations for the fractured reservoir are shown in Figure 5 as flow path distributions. Figure 5a is the flow path distributions evaluated with GeoFlow model, whereas Figure 5b is the flow path distributions evaluated with Conventional DFN model. Between these two models, the appearances of flow path distributions are completely different, which is due to the fact that the impact of 3-D channeling flow in a fractured reservoir is introduced only in the GeoFlow models. With respect to the GeoFlow model, flow paths are formed just towards well A, and no flow paths are formed towards well B. On the other hands, with respect to the Conventional DFN models, flow paths are formed both towards well A and towards well B. The presence or absence of the flow paths towards well B within the reservoir, which located within the area enclosed by the bold break line in Figure 5, is critically important for reproducing the three orders of magnitude difference in well productivity observed at the Yufutsu field.

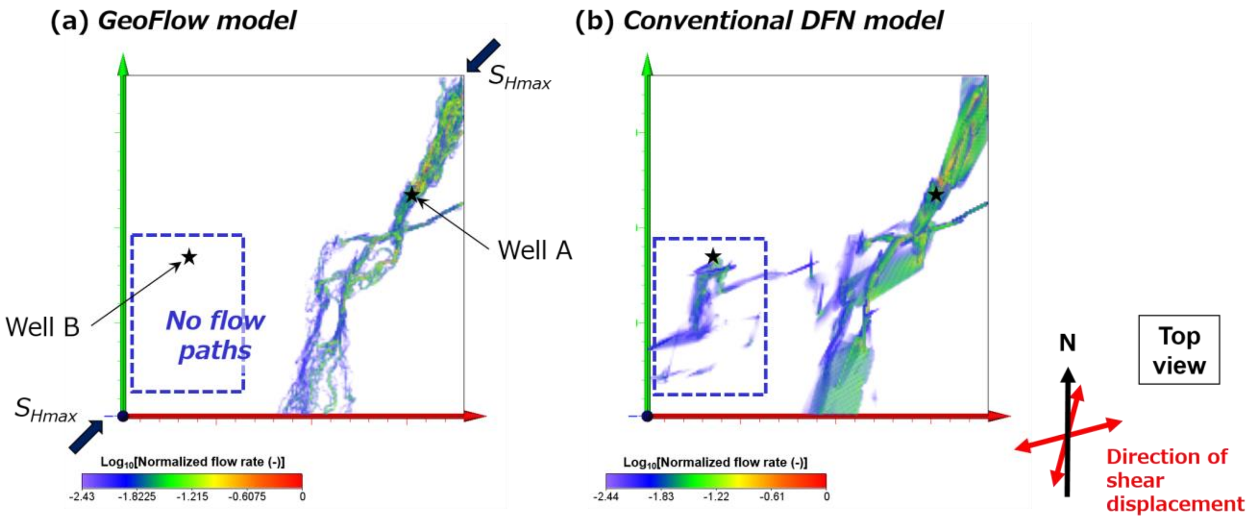

Figure 5: Flow path distributions for the Yufutsu field evaluated with (a) GeoFlow model and (b) Conventional DFN model. The shear displacement for critically-stressed fractures is 2×10^{-2} (2.0%).

In the GeoFlow model, the productivities of well A and well B are 2.30×10^{2} m^3/sec and 1.47×10^{-1} m^3/sec, respectively. The productivity of well A is 1.56×10^{3} times higher than that of well B. In contrast, in the Conventional DFN model, the productivities of well A and well B are 17.4 m^3/sec and 4.96×10^{-1} m^3/sec, respectively. Moreover, the productivity of well A is 35.1 times higher than that of well B. Certainly, both models can reproduce the observation of the Yufutsu oil and gas field in that the productivity of well A is higher than that of well B. However, the three orders of magnitude difference in productivity between well A and well B is successfully reproduced only in the GeoFlow model. As described above, the difference between the GeoFlow model and the Conventional DFN model is whether the occurrence of 3-D channeling flow within the reservoir is considered or not. Considering this fact, it can be concluded that the cause of the significant difference in well productivities is the occurrence of 3-D channeling flow, which specifically corresponds to the presence or absence of the flow paths towards well B within the reservoir. The 3-D channeling flow within a fractured reservoir can be considered only by analyzing with GeoFlow or the similar concept of DFN model simulators. It should be noted that there are some concerns that one will come to the wrong conclusions for the development and utilization of a fractured reservoir if the occurrence of 3-D channeling flow within the reservoir is ignored.

3.2 Clarification of the Mechanism Causing the Huge Difference in Well Productivity

In order to clarify the mechanism causing the significant difference in well productivity, the flow paths distributions of unidirectional fluid flow in the directions of the x-, y-, and z-axes are evaluated. Since it is considered that the distribution of flow paths within fractured reservoir in a state of oil and gas production (i.e. radial fluid flow simulation) is closely related to the distribution of flow path in a state of nature (i.e. unidirectional fluid flow simulation), the comparison between these flow paths are meaningful. The flow paths distributions for the x-, y-, and z-axes are respectively shown in Figure 6a, 6b, and 6c.

Through the comparisons, it is revealed that well A is set for the area where natural flow paths in x- and y-directions exist originally. Due to this fact, it is also found that both degrees of fracture connectivity in x- and y-directions are good. Additionally, since the natural flow path in z-direction overlaps substantially with the natural flow path in y-direction for the area, fluid flow in z-direction can contribute on the oil and gas production at well A. In this manner, since all of fluid flow paths for x-, y-, and z-directions can contribute to the oil and gas production at well A, the productivity of well A is significantly higher. In contrast, it is revealed that well B is set for the area where only the natural flow paths in x-direction exists originally, although well B deviates from the flow paths. Considering this fact, it can be concluded that both degrees of fracture connectivity in x- and y-directions are not so good for the area. Moreover, it is difficult for fluid flow in the z-direction to contribute on the oil and gas production at well B, because the natural flow path in z-direction deviates from well B and is isolated from the natural flow path in x-direction. Thus, only the fluid flow for x-direction can contribute to the on the oil and gas production at well B and, as a result, the productivity of well B is low.

Moreover, with respect to the flow paths towards well A, the appearances of flow paths are alike between Figure 5a and Figure 6a and 6b. With respect to the flow paths towards well B, due to the fact that well B deviates from the natural flow path in x- and z-directions (Figure 6a, 6c), no such flow path is formed in a state of oil and gas production (Figure 5a). These correspondences implicated that the optimum locations of wells can be predicted for a fractured reservoir if 3-D channeling flows in a state of nature are evaluated precisely within the reservoir, which are realized only by using GeoFlow or similar concept of DFN model simulators.

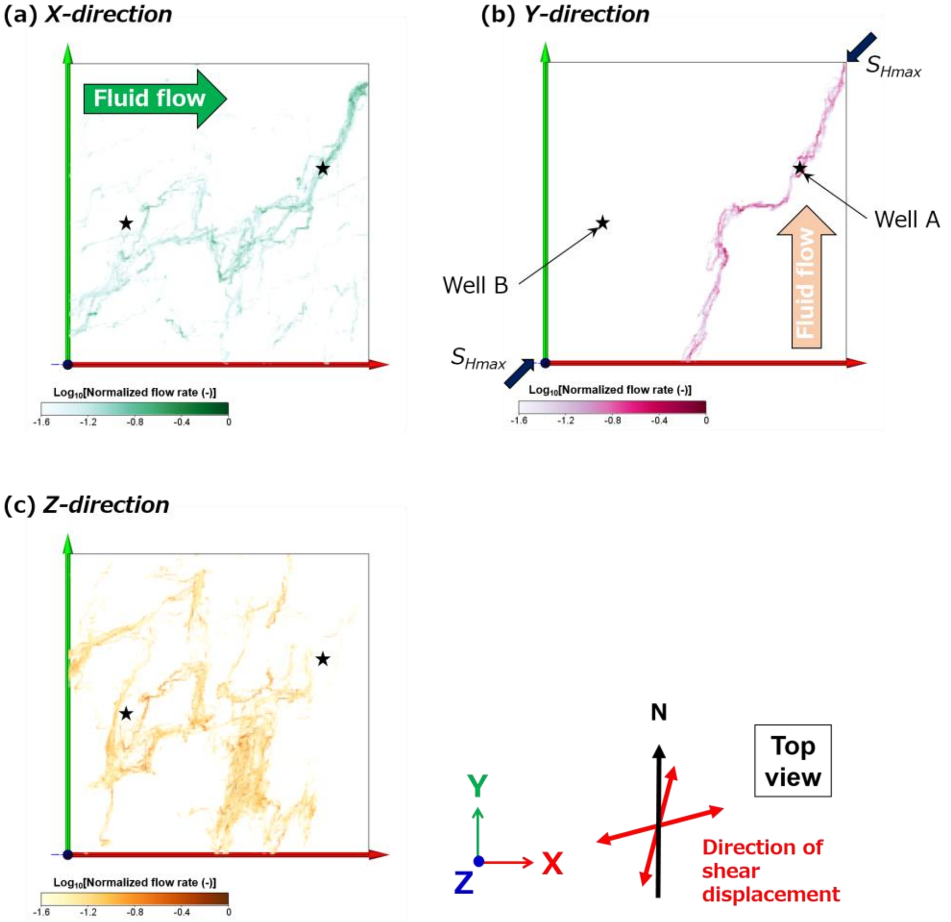

Figure 6: Flow path distributions of the Yufutsu field in a state of nature for (a) x-direction, (b) y-direction, and (c) z-direction. The shear displacement of critically-stressed fractures is 2×10^{-2} (2.0%).

The reason why the productivity of well A is higher than that of well B is clarified above. However, the reason of the three orders of magnitude difference in well productivity is still not explained fully. To discuss the mechanism causing the significant difference, the result of radial flow simulation with GeoFlow model (Figure 5a) is compared with the result evaluated with Conventional DFN model (Figure 5b) in detail. As previously mentioned, the significant difference between Figure 5a and Figure 5b is whether the flow paths towards Well B are formed or not, which reflects the impact of 3-D channeling flow in the fractured reservoir. Considering the fact that the degree of fracture connectivity in all of x-, y-, and z-direction is limited around well B, it is expected that the impact of 3-D channeling flow is enormous specifically within the area of low fracture connectivity.

The conceptual diagram of the network of critically-stressed fractures around well B is shown in Figure 7, where the directions of shear displacement are constrained as shown by arrows. When a rock fracture has undergone shear displacement, there is an anisotropy in the fluid flow characteristics of the fracture. In other word, the permeability for the parallel flow to the shear displacement ($k_{//}$) is different from the permeability for the perpendicular flow to the shear displacement ($k_{\perp}$). The grouped contacting asperities are generally arrayed in the perpendicular direction to the shear displacement. Since these contacting asperities become a barrier for the parallel flow to the shear displacement, $k_{//}$ is from one to three orders of magnitude less than $k_{\perp}$ [*Nemoto et al.*, 2009]. It is also noted that the parallels flow to the shear displacement is more tortuous than the perpendicular flow to the shear displacement herein. With these in mind, the reality of the fluid flow towards well B is considered as the following. Although the fracture permeability for the fluid flow in the depth direction is high, this fluid flow does not contribute on the production of well B. This is because the degree of connectivity of critically-stressed fractures is originally low in the depth direction. In contrast, 3-D preferential flow paths are less likely to be formed in the x-direction (i.e. from west side boundary), since the contacting asperities arrayed in the depth direction block the fluid flow in the x-direction. In this manner, as the 3-D preferential flow paths are not maintained around well B, the productivity of well B is significantly low, which results in the three orders of magnitude difference in well productivity. In the case of the Conventional DFN model, the flow paths towards well B are, on the other hand, consistently maintained since there is no resistance such as contacting asperities. As a result, the productivity of Well B is overestimated and the three orders of magnitude difference in well productivity is never reproduced.

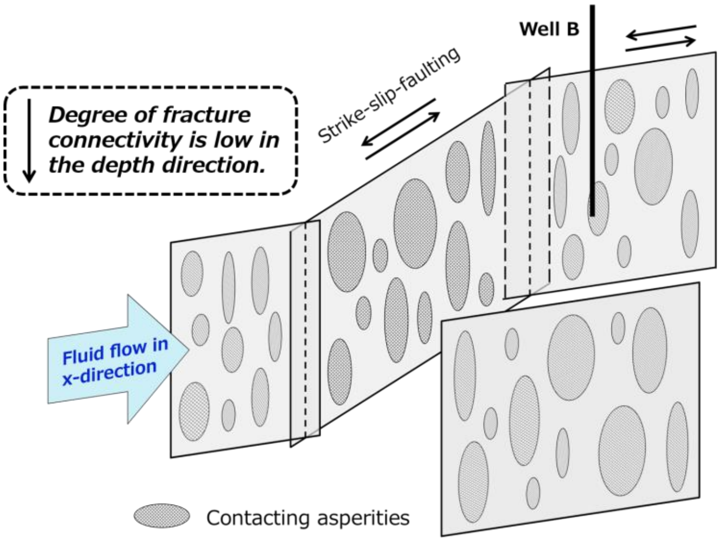

Figure 7: Conceptual diagram of the network of critically-stressed fractures around Well B in the Yufutsu oil/gas field.

4. CONCLUSION

Fluid flow in a fractured reservoir (i.e. the Yufutsu oil/gas field) is simulated with GeoFlow model, where heterogeneous aperture distributions are considered for each fractures depending on their scale and shear displacement under confining stress. Through a series of the fluid flow simulations, it is revealed that the reality of fluid flow within a fractured reservoir is 3-D channeling flow, which should be considered for predicting the optimum well locations for a fractured reservoir. Specifically, the impact of 3-D channeling flow is expected to be significant in the domain where the degree of fracture connectivity is relatively limited. Moreover, there are some concerns that one will come to the wrong conclusions for utilization of a fractured reservoir, if the occurrence of 3-D channeling flow within the reservoir is ignored.

As shown in this study, as long as highly-reliable discrete fracture networks are created for a fracture reservoir on the basis of 3-D seismic data, crustal stress data, and so on, one can now map the realistic flow path distribution (i.e. 3-D channeling flow) with GeoFlow. If such a method is applied to fractured reservoirs of various fields and their results are accumulated, the 3-D channeling flow in fractured reservoirs will be modeled more accurately.

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