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Permeability inhomogeneity accounting in terms of efficient development strategy

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Abstract. The main questions concerning flow and permeability anisotropy are: presence of anisotropy (is a reservoir anisotropic or not), orientation and degree of anisotropy. Answers were obtained through the analysis of grain fabric, spatial permeability spread and tracer injection data. The magnitude of permeability was determined to be within a range from 0.5 to 1 and with the azimuth of 48 from the North. Thereafter, the incorporation of new information about field K into the simulation model matched and the comparison of isotropic (the existing model) and anisotropic (the model upgraded with novel information) were performed. This process showed that the simple introduction of obtained anisotropy properties improved the history match, which was interpreted as the proof of anisotropy being present on both the macroscopic and microscopic scale. At the end, general recommendations for the optimal production practice in the anisotropic reservoir were proposed and the potential strategy for further development was suggested. This optimal strategy was created by changing several producing wells into injectors and it resulted in an overall oil production increase and individual well production increase amounting to as much as 20%.

1. Introduction

Permeability and its anisotropy influence a fluid flow direction and velocities in the subsurface, which in turn causes problems with an uneven and unwanted water front, high early water production, losses of production and many other problems [1]. Kuchuk and Brigham [2] showed that in the presence of anisotropic horizontal permeability production rate decreases with the increase in anisotropy. Unfortunately, anisotropy becomes evident only when those unwanted symptoms occur. The knowledge of the magnitude and direction of anisotropy can be very important in production planning and management. Well pattern orientation, spacing, perforation program can all be optimized at the very early stages of development.

The goal of this paper was to analyze gathered data and draw conclusions about anisotropy features. The main questions concerning flow and permeability anisotropy are: presence of anisotropy (is the reservoir anisotropic or not), orientation and degree of anisotropy. Thereafter, the incorporation of new information about field K into the simulation model matched and the comparison of isotropic (the existing model) and anisotropic (the model upgraded with novel information) were performed.

2. Theoretical justification

The following methods are performed on wells upon the start of production. The most widely used methods are well tests and inter well tracer tests.

There are several variations of well tests that can be used for this purpose, but all of them have the same principle of triggering the impulse and measuring the response. Ramey et al. [6] derived an interference method that can be used to determine anisotropy direction and magnitude. It can be performed for two observation wells, but if ϕμct - factor is unknown, at least three wells are needed. This formal method is very sensitive if permeability anisotropy is high and if well-anisotropy configuration is unfavorable. If this is the case (but cannot be known a priori), a new quick method was developed and can be used [7, 8, 10]. This technique uses the log-log plot of pressure change versus time/(distance)^2 responses and the direction of anisotropy can be obtained by comparing them for different observation wells. Even without the knowledge of reservoir properties (ϕμct), a unique solution, if at all, can be obtained in the 90 ° range for two wells and in the 45 ° range for three observation wells.

On the other hand, the tracer injection technique is more favorable. It uses specially engineered substances, tracers, and after analysis can show the degree of inter-well pathways, orientation of anisotropy and velocity at which tracers are traveling and evaluate areal water breakthrough between injectors and producers. This method gives more precise information about the fluid flow in the subsurface compared to others, which only give assumptions about responses and permeability, but in combination with them the whole picture is formed.

3. Permeability analysis

For the purpose of anisotropy investigation, quantification and orientation determination, several sets of data were available:

- Interpreted logs for 29 wells
- Tracer injection test results for injection wells 156, 190P and surrounding production wells

3.1 Absolute permeability isoline distribution

Another data set considered in this case study was interpreted logs. They were used to construct absolute permeability maps. The resulting maps showed the spatial distribution of a formation with better reservoir qualities. As it has already been mentioned, J_1^{3-4} can be divided into three layers with different composition and properties. It was used in order to plot the maps of the absolute permeability spatial spread. Three layers that can be separated by log response interpretation where they are very noticeable (especially in the GR and SP logs) (figure 1) are as follows:

- YU 1-3-A – The upper part of the section is characterized by well sorted medium-fine sand with permeability ranging from 10 to few hundreds of mD. It lies between the top of the reservoir and the depth of 6 m (about 30% of the reservoir thickness).
- YU 1-3-B – The middle section of the reservoir of all subtypes is characterized by massive sandstone ranging from fine to medium and being poorly sorted. The permeability of this layer ranges from one to few tens of mD. This layer begins at the depth of 6 m and ends at about 11 m from the top (covering about 25% of the J13 thickness).
- YU 1-3-C – Poorly sorted fine sand and siltstone characterize the lowest section of the reservoir in all subtypes. The permeability of this layer does not exceed one mD and this last section covers the thickness from 11 to about 20 m (≈ 45% of the reservoir thickness).

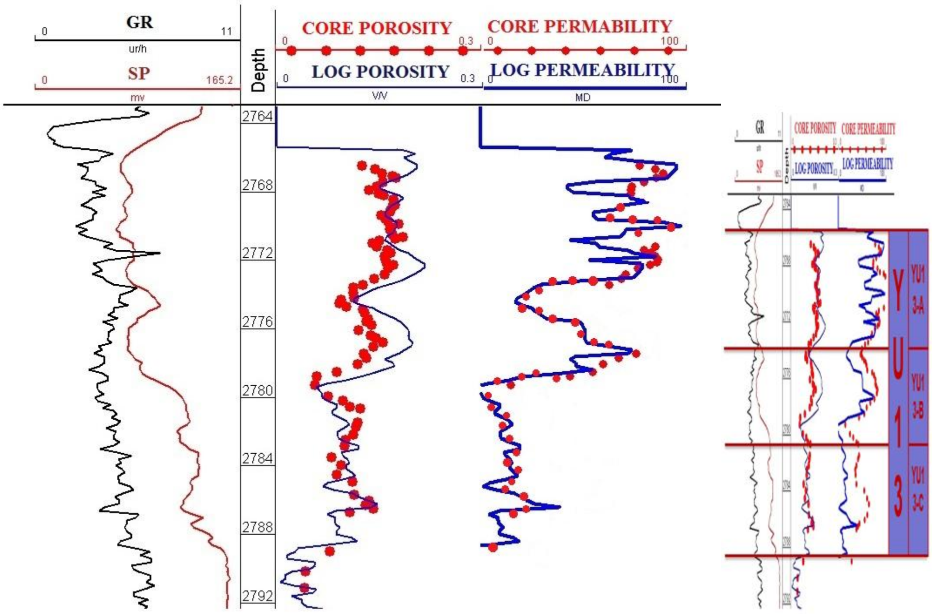

Figure 1. Separation of sub-layers in a reference well

Keeping that in mind, three sets of permeability maps were constructed (figures 2 to 4). The simple Kriging method was used and permeability data for every map and every well were obtained by averaging permeability in a particular sublayer (from YU 1-3-A to C). In recapitulation, the maps constructed for two upper layers show the evident orientation of horizontal permeability and it corresponds to the azimuth of ≈ 45 °. It is very close to the azimuth that was revealed earlier with the petrographic grain analysis (48 °). Furthermore, both those layers have an elliptical shape that stands out as a formation with better reservoir properties and can be linked to the mouth bar structure that was mentioned in the geological depositional model [9].

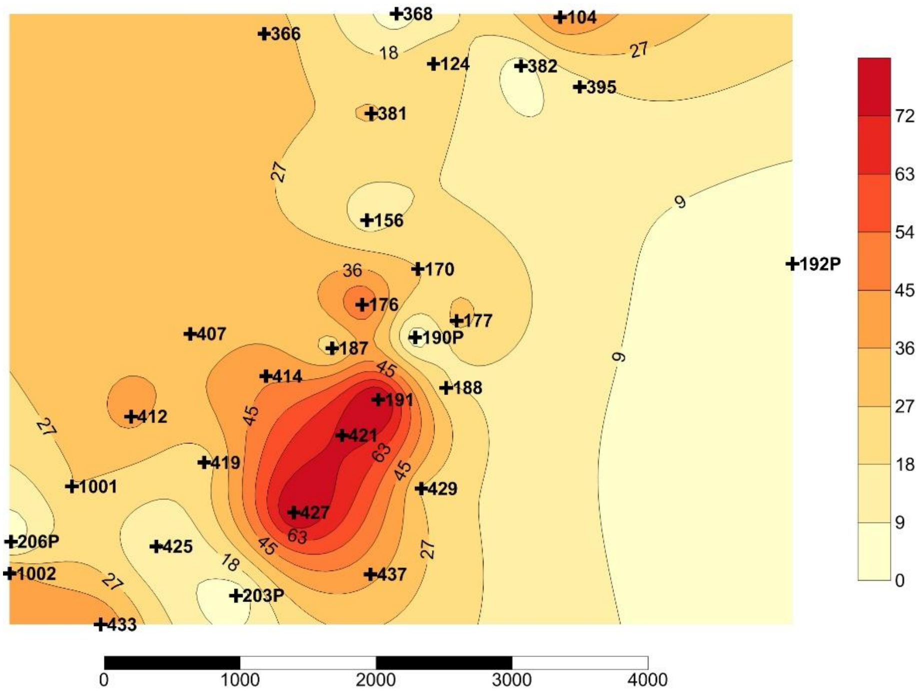

Figure 2. Absolute permeability map of YU-1-3-A (mD)

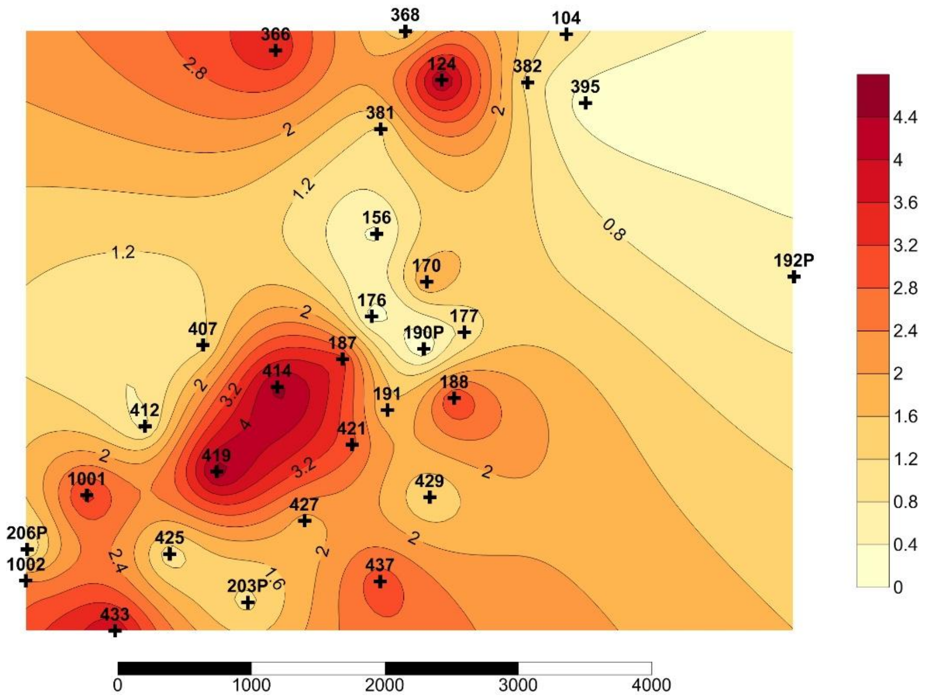

Figure 3. Absolute permeability map of YU-1-3-B (mD)

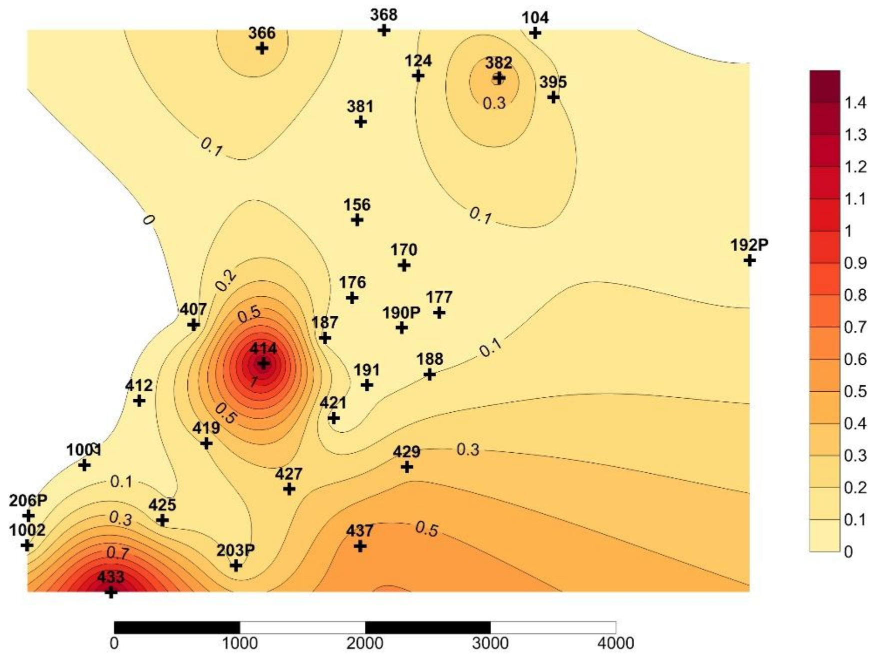

Figure 4. Absolute permeability map of YU-1-3-C (mD)

3.2 Tracer injection analysis of injection wells 156, 190P and adjacent production wells

In order to study the macroscopic reservoir characteristics of this field, an inter well tracer test was performed. The test started in September 2003 and took several months. Two injection wells were selected (156 and 190P) in which two different tracers were injected. Water injection was planned to increase with time and the amount of tracer injected ranged from 43 to 162 m3/day for well 156, while injection for well 190P started with 500 and finished with 1111 m3/day. The samples of water produced were taken in the predetermined periods and analyzed for indicators and their concentration. The first appearances of measurable indicator concentrations were observed in 8 to 15 days after the injection.

The largest amount of tracers was recovered in connection between 156 – 170 and 190P – 170 and comprised 55.7% and 43.93%, respectively (figure 5). It can be concluded that well 170 has a major impact on filtration in the investigated part of the formation. It has the highest values of a relative filtration flow: 68.08% in the direction towards 156 and 53.55% towards 190P. It can be explained by the proximity of well 170 to injection well 156 or by the difference in flow-rates for different injection wells (up to 7 times). Also, both injection wells and the adjacent producer are surrounded with a low permeability formation from NW and SE and one more injector (393) in the north that can also influence flows from 156-170 and 156-177. This influence can also be proved by the fact that both tracers were first sampled at about the same time in well 170. It can be claimed that the maximum velocities correspond to the direction of maximum permeability obtained in the previous analysis. Many other parameters influence the water front. One of them can be a pressure profile in the reservoir, the fact that the wells can be positioned in the part of the reservoir with poor qualities and hence a small production and diffusivity factor.

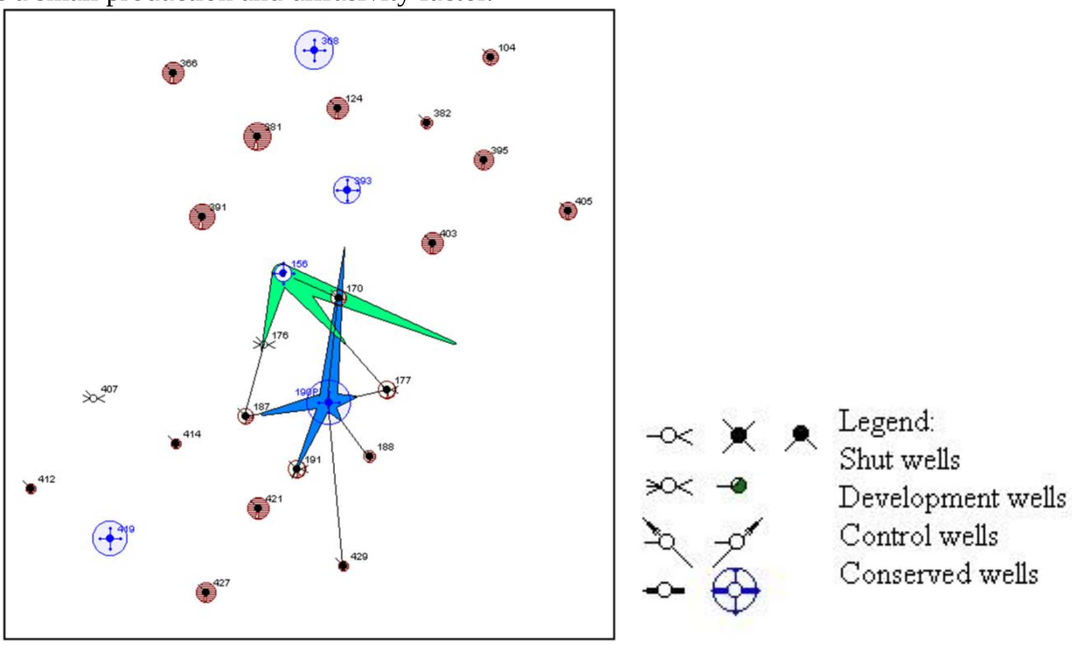

Figure 5. Tracer flow pattern

4. Results

4.1 Anisotropic model sensitivity analysis

In order to understand the anisotropic reservoir behavior, pressure distribution, water front shape, time of water breakthrough, well placement and pattern, a simple conceptual model was constructed with parameters being closest to field K. A grid with 100x100x 5 cells was formed, while anisotropy in the perpendicular direction was introduced by multiplying kx with 0.5 (the value most frequently revealed with petrophysical data). Well spacing was set to be 500 m. Relative permeability curves, PVT data, initial reservoir pressure and vertical anisotropy were taken from literature [9]. Two different sensitivity analyses were performed:

- Well grid orientation influence on water breakthrough in the anisotropic reservoir
- Comparison of five spot and different segregated well patterns in terms of oil production

In both cases, five wells were used: four production wells and one injection well. They also had the same control parameters and perforation program, only their position changed.

4.2 Well grid orientation influence on water breakthrough in the anisotropic reservoir

The idea was to rotate a well grid and to monitor water breakthrough. A rotation step was chosen to be 15 ° with a range from 0 (parallel) to 45 °. An injection well was placed in the center of the reservoir. Around it, a five-spot well pattern was made with four more production wells. Rotation was performed around the injection well.

Next, figure 6 shows that the parallel orientation of the five-spot well pattern towards the maximum permeability direction is most appropriate and has a potential to provide the most effective sweep area, while postponing water breakthrough.

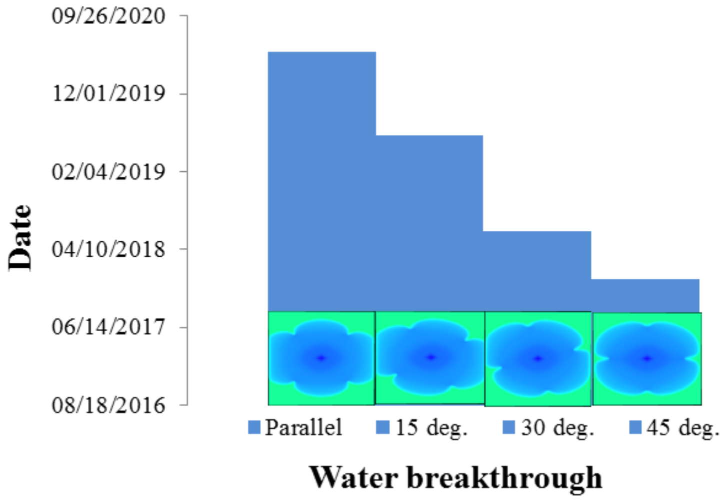

Figure 6. Comparison of different well-anisotropy orientations

4.3 Comparison of five spot and different staggered well patterns in terms of oil production from the anisotropic reservoir

The fact is that the anisotropic formation causes elliptical pressure distribution around the well, and with that, a drainage area of the same shape. On this basis, the idea that the parallel five-spot pattern that gave the best results in the previous analysis can achieve even better results if it is transformed into a staggered pattern that corresponds to the actual anisotropy was applied. The methodology was as follows: by changing the ratio of 2d/a from 1/5 to 5 (one being a parallel five-spot pattern), attention was focused on finding the ratio that, with field K anisotropy, leads to the biggest oil production.

As it can be seen in figure 7, different ratios induce different production levels; this is related to the elliptical distribution of the water front and its influence on the sweeping area. On the basis of the conclusion that production is highest within the ratio range from 0.5 to 1, one more simulation was performed for 2d/a ratio of 0.75. Finally, it resulted in the most optimal well distance.

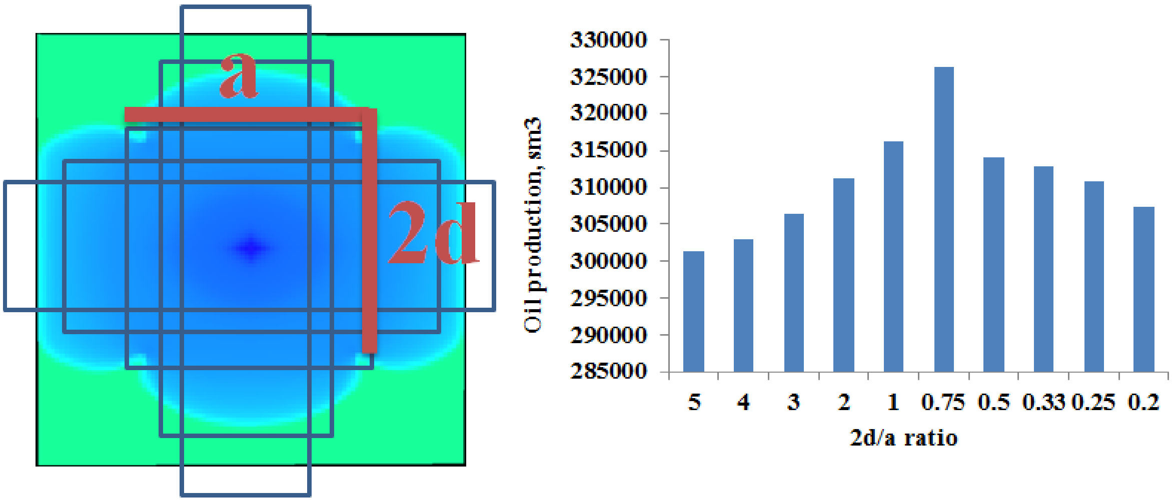

Figure 7. Schematic representation of well patterns and their results

5. Conclusion

Upon the detailed study, the data analyzed provided an insight into permeability distribution in both the orthogonal and vertical direction, microscopic and macroscopic scale, changes in that permeability and gave an answer to three important questions regarding its anisotropy. The knowledge about the presence, direction and magnitude of anisotropy was used to adjust the model that can be further used to optimize oil production by water flooding. Summing up all the results obtained with this study allows making several conclusions:

- The incorporation of anisotropy into the history matched model of the field and comparison with the isotropic one showed improvement in matching, which was interpreted as one more proof of anisotropy presence
- Several sensitivity simulation runs revealed that a staggered well pattern and parallel orientation of a well grid were most appropriate for anisotropic reservoirs development and exploitation.
- Governed by the above- mentioned principles, optimization of water-flooding program was performed by changing several producing wells into injectors. The result was a total oil production increase by 2% and a well oil production increase up to 18.2%.

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