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Discrete Fracture Network Modeling of Alaşehir Geothermal Field

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ABSTRACT

Understanding of fracture network and fracture characteristic properties is essential for an effective geothermal reservoir management. Discrete Fracture Network (DFN) is one of the widely used approach to characterize fractured reservoirs. DFN modeling approach uses fracture geometry, conductivity and connectivity to create a fracture network. In this study, DFN modeling is used to characterize Alaşehir geothermal reservoir, which consists from heavily fractured marble and schist. Fracture parameters such as fracture permeability, aperture, intensity and fracture radius are conditioned for model calibration. Most of the required fracture parameters are retrieved from different data sources. Stochastic correlations related with known parameters are used to estimate unavailable parameters. The dynamic model results are verified with pressure transient buildup tests conducted in the field. Upscaled fracture properties are in accord with well test analysis and tracer test results. DFN model shows that all wells are interconnected by strong fracture network. Fracture network is validated with a tracer test and reservoir monitoring in the field.

1. INTRODUCTION

Geothermal resources are usually discovered in tectonically active areas. During the tectonic movement of brittle rock blocks, natural faults and fractures are created. Natural fractures constitute the major fluid flow paths in the geothermal reservoirs. Production wells which are drilled into these fractures usually provide high flow rates. The scale of fractures may vary from micrometers to kilometers in length. Most of the conventional geothermal reservoirs in the world produce from naturally fractured systems. In the hot reservoirs that does not have natural fracture system, in other words the reservoir rock which has very limited permeability, EGS (Enhanced Geothermal System) is applicable. In EGS, artificial fractures are created by using hydraulic fracturing technology. However, Alaşehir geothermal field is naturally fractured reservoir similar to most of the geothermal reservoirs in Turkey. Therefore, artificial fractures are not included in this study. The scope of the study is to investigate characteristics of natural fractures. Natural fractures can be quantified by several methods**:** FMI and FMS logs, core analysis, drilling mud losses, fracture outcrop analysis, seismic, well testing, tracer test etc.

All of the aforementioned methods provide certain amount of information about fractures, however they have some limitations. To illustrate, FMI log can be used to determine fracture properties in micro scales but it is limited with wellbore dimension. Similarly, seismic can cover large reservoir volume but small scale fractures cannot be evaluated. Outcrops are used as an analogue to the subsurface. Especially, in wildcat areas where there is no available drilling well data and well test data, outcrops are very useful to estimate characteristic properties of reservoir rock. However, they are not at the reservoir conditions (temperature and pressure) and outcrops may be exposed to weathering and erosion which may lead to wrong interpretation about fractures. In order to take into account large reservoir volume while considering fractures with wide range of scale, there is a need to use modelling approach.

It is challenging to model Naturally Fractured Reservoirs (NFR) because of high uncertainity and anisotropy in their hydraulic properties. Thus, while modeling naturally fractured reservoirs, it is crucial to benefit from multi disciplines such as well test, tracer test, seismic, geology, geochemistry and drilling.

2. MODELLING NATURALLY FRACTURED RESERVOIRS

In order to better understand behaviour of NFR, several studies have been conducted since the early 1900s. Versluys (1915) investigated anisotropic permeabillity by using arbitrarily-oriented bundles of tubes. He stated that high number of arbitrary sets can be reduced to three mutually conductors as Kx, Ky, Kz. Ferrandon (1948) further developed the bundle of tubes model by introducing permeability tensor. He noted that flow contribution of each conductor to total flow rate is proportional to the potential gradient along a unit area of tubes. Snow (1965) considered parallel plate openings, which is called aperture of real fractures. He proposed that discharge of each fracture is proportional to cube of its aperture for a given gradient. This is called cubic law. Long and Witherspoon (1985) proved that fracture geometry fluctuates the fluid flow significantly. They reported the most important fracture geometric parameters as fracture aperture, fracture shape, density, orientation and fracture size. With development of computing power and algorithms in 1980s, the modeling approaches have become the most attractive way for evaluating complex fracture systems. Fluid flow simulation in fractured rocks has been accomplished by using continuum model, dual porosity model and discrete fracture network model.

2.1 Continuum Model

In continuum approach, fluid flow in fractures is considered as similar to fluid flow in porous media. Long and Witherspoon (1985) stated that fracture systems behave like a porous medium as the number of intersected fractures increase. For simplicity, fractures in a rock mass are considered as an equivalent porous medium (EPM), therefore predicted hydraulic properties are averaged values (Lee et al., 1995). It is not possible to distinguish hydralic properties of fractures from that of porous media in continuum model. The advantage of continuum approach is that simulation takes short run times compare to other approaches

2.2 Dual Porosity Approach

The concept of fluid flow in double porosity system was first delineated by (Barrenblatt et al. 1960) and (Warren and Root, 1963). Barrenblatt et al. (1960) conducted laboratory studies on fissured strata and they proved that description of transient flow of liquids in fissured system with homogeneous porous system leads to wrong interpretations. According to Barrenblatt et al. (1960), fissures have greater width compare to pores, thus permeability of fissure system is much greater than that of pores. However, matrix porous media occupy much more volume than fissures. Double porosity model was first used in a numerical simulation of oil reservoir by Kazemi et al. (1976). Dual porosity model is a representative model for fractured and vuggy geothermal reservoirs. However, it does not meet all requirements of high flow rates found in geothermal wells. In addition, in tracer test evaluation, multi fractural model has better match than Double porosity model.

2.3 Discrete Fracture Network

Discrete Fracture Network (DFN) model describes fluid flow in fractures by considering fracture geometry and connectivity. Unlike dual porosity model and continuum approach, DFN takes into consideration the contribution of individual fracture to the total system. Therefore, DFN model represents fractured systems more realisticly and it enables us to examine effects of individual fracture parameter on flow respond. The DFN concept was started in 1980s for both 2D and 3D systems (Long et al. 1982; Andersson, 1984; Dershowtz and Einstein, 1987). The disadvantage of DFN is that it requires fracture geometry to describe flow behavior. There is a need for definition of fracture geometry within acceptable range of uncertainty. Einstein and Baecher, (1983) proposed statistical methods to decrease geological uncertainty. They sampled field data and plotted their cumulative density function. Joint spacing was verified as exponential distribution with 5 % confidence level. Trace length showed lognormal distribution. Orientation data was recorded to behave as exponential distribution. With new correlations and algorithms, DFN approach has been continuously developed and applied in natural fracture reservoir and hydraulic fracturing operations such as development of enhanced geothermal system (EGS) and shale oil and shale gas. In this study, DFN modeling of Alaşehir Geothermal Field is constructed by using a special software, FracMan7.6 academic version.

3. CHARACTERISTICS OF ALAŞEHİR GEOTHERMAL FIELD

Alaşehir geothermal field has become the most attractive target for geothermal exploration activities and constructing power plants for the last decade. The field lies on a Alaşehir Graben that is 6-10 km wide for the particular study area and it becomes wider through Aegean Sea in Western Turkey. More than 100 wells have been drilled in the field by six different operator companies. There are 6 binary power plants and a combined flashing-binary power plant are actively generating electricity from the field with total installed capacity of 210 MWe. Meteoric origin reservoir fluid is liquid dominated and Paleozoic aged reservoir rock consists from marble, mica schist, calcshist and quartz. The field has reservoir temperature ranges from 140 ^{o}C to 250 ^{o}C, average gross and net reservoir thickness are reported as 1200 m and 650 m respectively by Gurel, (2016).

This study includes 13 km^2 area of the field and only 10 production wells are included in DFN modeling. However, injection wells are also included in the remaining part of the study for further reservoir characterization.

4. METHODOLOGY

The study started with gathering data for static model construction. Reservoir parameters are retrieved from different data sources such as seismic, outcrops, drilling mud loss, well test, tracer test, geochemistry and well correlations. FracMan7.6 creates fractures stochastically based on their distribution function. In FracMan, fracture set can be generated based on geometric, geocellular, geologic, trace map, stratigraphic methods. In this study, fracture set is generated by using geocellular method. In geocellular method, fractures are generated into specified grid blocks. FracMan requires fracture features to generate fracture set. These features include fracture orientation, location, intensity, size, permeability, aperture and shape.

Once the static model is constructed, stochastic fractures are generated. After that, wells are conditioned with dynamic analysis. The static model is reconstructed and populated with updated data until dynamic well test results (i.e. pressures recorded during the well test) are matched with actual well test data. As the dynamic model calibration is achieved, fractures are upscaled. The dynamic model results are compared and populated with interference test results, tracer test results and geochemical interpretations for further reservoir characterization.

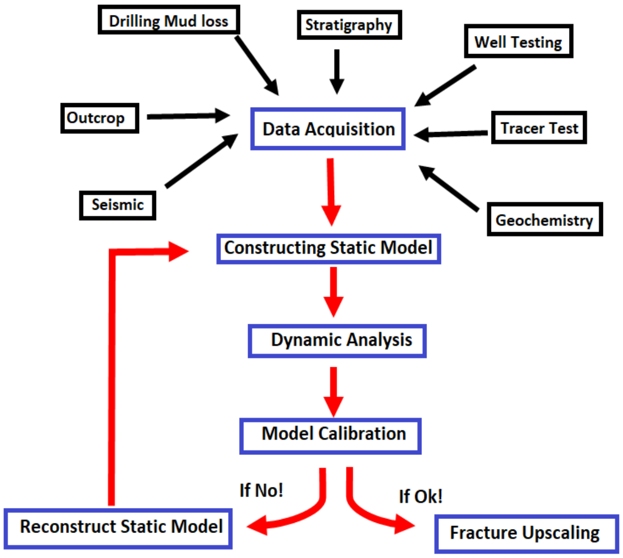

Figure-1: Work Flow Diagram

4.1 Data Attainment for DFN Model

Required fracture properties for DFN modeling can be obtained from several data sources such as outcrops on the surface, drilling mud loss, core sample, seismic data, well testing, and geochemistry, geology and well logs. These sources have different data quality and measurement scale (Figure 2).

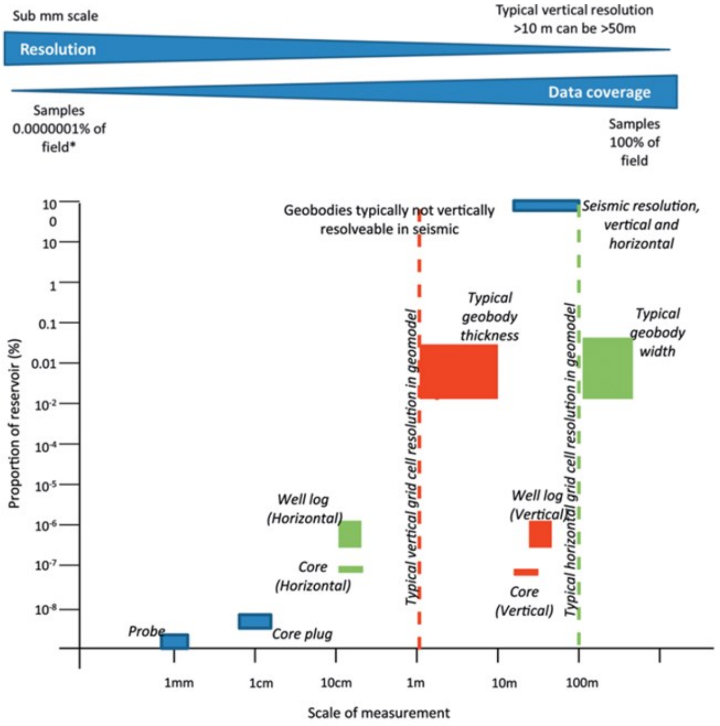

Figure-2: Quantification of Data Quality of Variety Sources (Hower et al., 2018)

4.1.1 Outcrop Analysis and Seismic Study

In geothermal exploration phase, it is difficult to obtain information about characteristics of subsurface rock without drilling a well in a given field area. One of the easiest way of obtaining information about reservoir rock is to analyze outcrop rock which is already available on surface. Outcrop ris usually considered as analogue to reservoir rock. In outcrop studies, fractal analysis has been found efficient and useful by several scientists to estimate reservoir characteristics such as fracture permeability, fracture porosity and aperture. Gurel et al., (2016) studied fractal of outcrops in Alaşehir geothermal area to characterize subsurface reservoir rock. In their study, fracture density, permeability and effective porosity were calculated by using box counting method and equations proposed by Miao et al., (2015). Apart from small scale fractured outcrop, large scale faults are also available in Alaşehir geothermal area. Ciftci, (2007) reported high angle normal rock faults and low angle North dipping detachment faults in the southern part of the graben. He noted that low angle (0-20°) North dipping detachments bound the southern margin of the graben and they constitute the contact between Menderes Metamorphic and sedimentary overlain rocks. In this study, dip angle of fault calculated from wells correlation. Total mud loss depth of two wells which are believed to target the same fault are used to estimate dip angle. Dip angle of north dipping fault is calculated as 10 °.

4.1.2 Drilling Mud Loss

One of the strongest indication for existence of natural fractures in geothermal reservoir is the partial or total mud loss during drilling. Mud losses provide a good insight about fracture characteristics before conducting a well test. Investigation of the fracture width and permeability from mud loss data can be found in Akin, (2013). He used the cubic equation proposed by Huang et al. (2011) coupled with an artificial neural network model (ANN).

4.1.3 Interference Test

A multi-well interference test was conducted in Alaşehir geothermal field. Akin (2015) designed and implemented an interference test which included four wells to assess the reservoir characteristics. The study reported that there is a good communication between wells and result of the test was given in detail. Permeability and porosity values were used as the initial value for DFN modeling.

4.1.4 Geochemistry

Chloride is considered as a nonreactive and conservative chemical component and it is not controlled by reservoir temperature. Unlike other components, Chloride does not tend to precipitate in the reservoir and surface conditions. Especially, in flashing type power plants Chloride content of the reinjection brine increases continuously. Therefore, elevation in Chloride concentration of production wells can be considered as the indication of arrival of reinjection fluid which makes Chloride a natural tracer. In Alaşehir geothermal field, Chloride is used to understand the effect of reinjection wells on production. Another component tracked for reinjection path is CO_2 decline in production wells.

4.2 Model Construction

4.2.1 Static Model

In constructing the static model for a particular field area, Fracman 7.6 required fracture parameters which are fracture aperture, permeability, length, orientation and fracture density. These parameters are usually considered as distribution instead of taking average value (Figure-3). Therefore, the static model is populated from different data sources to make it more reliable. The Enhanced Beacher model is used to generate fractures in constructing static model of Alaşehir reservoir. In FracMan7.6, geocellular fractures are generated based on grid blocks. There are ten production wells in the DFN model. Each well was assumed to produce from a rectangular shape boundary with 1200 m length-side and the height of the particular area is taken as the penetrated thickness of the metamorphic. Input parameters are given in (Table-1). The constrained area is divided into 10x10x10 (1000 grids) for each well (Figure-4). Stochastic fractures are generated in these grid blocks based on the fracture parameters introduced to the software. (Figure-4).

Table-1: Input Fracture Properties for Static Model

	Mean Fracture length (m) (exponential)	Mean Volumetric Fracture Intensity(1/m) (exponential)	Reservoir pay zone (m) Uniform distribution	Mean Permeability(md) Lognormal distribution	Mean Fracture Aperture(mm) Exponential distribution
Well X-1	20	0.06	200	1360	1.6
Well X-2	20	0.065	300	570	1.3
Well X-3	25	0.073	56	3600	1.6
Well X-4	25	0.06	214	5600	1.5
Well X-5	20	0.08	50	216	1.5
Well X-8	25	0.065	117	220	1.6
Well B-1	25	0.045	250	340	1.8
Well B-2	25	0.055	586	420	1.7
Well W-2	20	0.055	170	500	1.6
Well C-3	25	0.06	200	38	1.6

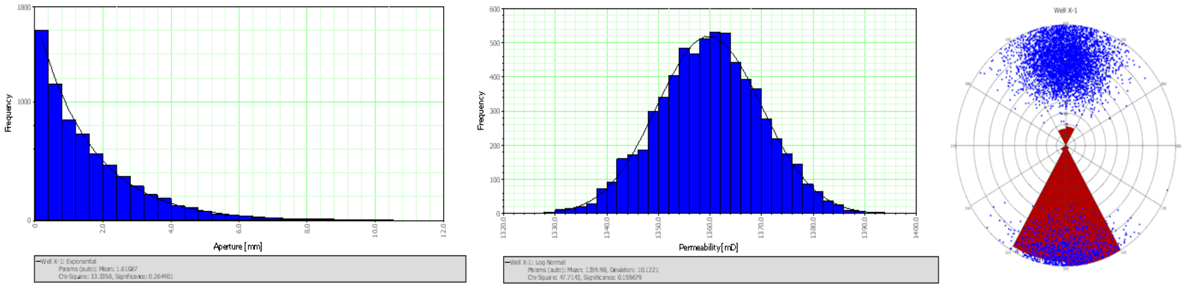

Figure-3: Fracture Permeability, Aperture and Orientation

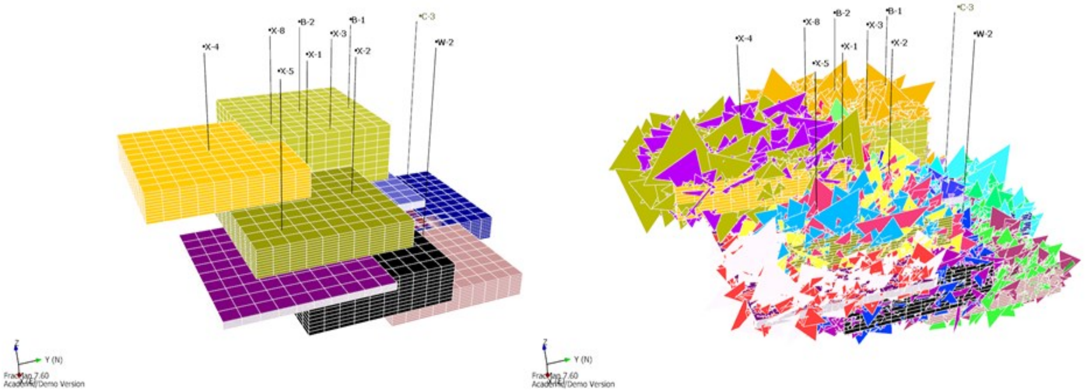

Figure-4: Grid Blocks and Stochastic Fractures

4.2.2 Dynamic Model Analysis and Calibration

FracMan 7.6 enables us to simulate fracture sets for a transient test of single phase and slightly compressible fluid. The software provides the flow calculation for both injection and production events. Galerkin's finite element method is used in fluid flow calculation. The method subdivides fractures into smaller triangular elements (Figure-5). The networks between these triangular elements are generated by meshing process for fluid flow simulation. In well test simulation, mesh size, initial pressure, fracture set, production pay zone, test duration and fluid properties need to be specified. Small mesh size provides more accurate simulation results but the simulation run time takes longer. In this study, mesh size is taken in the range of 20 to 50 meters based on fracture density and pay zone thickness which affect the simulation run time. Fluid properties are calculated from empirical correlations.

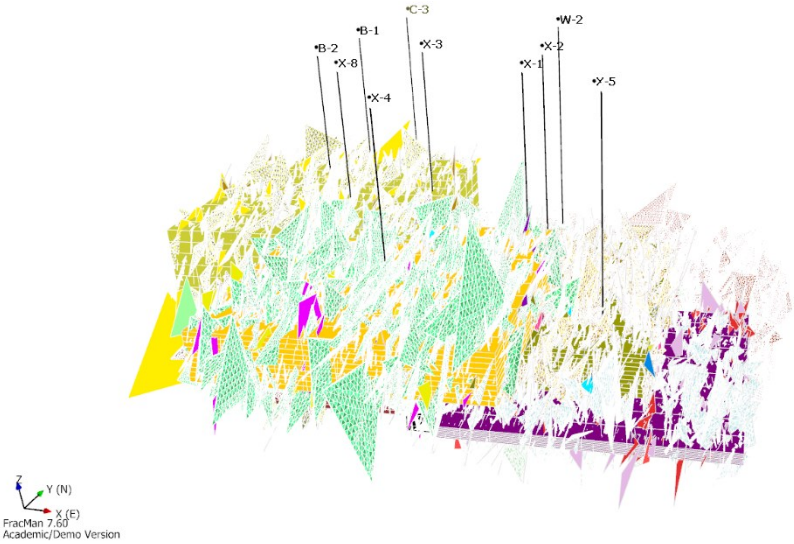

Figure-5: Meshed Fractures

The dynamic model calibration is achieved by tuning fracture length, fracture aperture and fracture density (Figure 6). Fracture permeability is taken as the results obtained from pressure transient well test analysis and it was not considered as a tuning parameter. In order to test goodness of fit between simulation result and actual test data, chi-square test is applied.

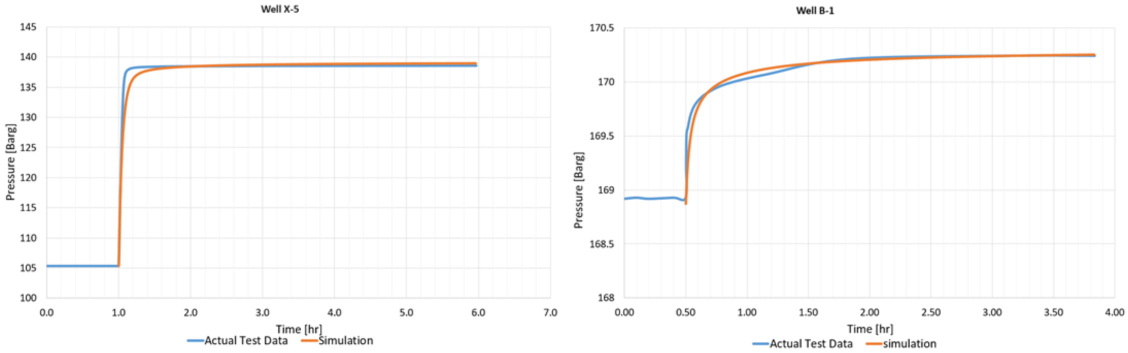

Figure-6: Buildup Test Matches

FracMan 7.6 provides number of analyses on grids and fractures to upscale fracture properties. The analyses included in this study are cluster analysis, pathway analysis and Oda analysis.

The main target of cluster analysis is to identify compartmentalization by processing fracture sets and find out isolated groups of self-connected fractures. Fractures set of each well is selected and cluster analysis was performed. In the analysis, minimum number of fractures in a cluster was considered as 20. The total number of clustered fractures and total volume of clustered fractures are given in (Table-2). There was no identified compartmentalized fracture set in this particular study area in Alaşehir field. CO_2 decline (Figure-7) and elevation in chloride concentration of production wells (Figure-8) are also indications of strong well interconnections.

Table-2: Cluster Analysis Result

	X-1	X-2	X-3	X-4	X-5	X-8	W-2	B-1	B-2	C-3
Number of Clustered Fractures	15963	16287	3112	6949	2587	6316	7596	5419	6825	6598
Total Volume of Clustered Fractures, m^3	818982	712821	267316	538404	147329	530631	431857	437356	731095	566625

By performing pathway analysis, geometric connections between wells can be identified. FracMan7.6 is able to compute geometry of the connected fractures between sources and sink wells defined by users. The software reports geometry of shortest and the highest conductance pathways between wells such as path length, number of fractures and total volume of fractures. The pathway analysis for wells near to each other performed and result is given in (Table 3). These results are similar to swept fracture volume calculated in tracer test (Figure-10)

Table-3: Paths Analysis Result

	Shortest Flow Paths			**Highest Conductance Paths**	
	Fracture Length	**Number of fractures**	**Fracture Volume,m^3**	**Number of fractures**	**Fracture Volume,m^3**
X-1 to X-2	657	12	324	223	36765
X-1 to X-3	1020	21	291	215	21150
X-1 to X-4	1373	24	226	200	30524
X-1 to X-5	708	16	72	100	11847
X-1 to X-8	1522	24	296	278	49533
X-4 to X-8	885	12	181	79	20475
X-4 to X-5	2535	38	718	153	25451
X-8 to X-3	830	16	281	212	29940
X-8 to B-2	520	12	15	127	44853
B-2 to X-3	1005	16	623	467	68956
B-2 to B-1	2620	42	726	1229	137729
B-1 to C-3	657	10	75	118	14138
B-1 to W-2	1931	23	376	98	11932
C-3 to W-2	1965	21	760	20	24663
X-3 to X-2	1485	27	628	915	70243

FracMan7.6 has Oda analysis to account for directional permeability variation. The analysis calculates permeability tensors in x, y and z directions for each grid block

Oda analysis results are given in (Table-4). It was found that vertical permeability of wells in Western of the particular study area is higher than permeability of X and Y direction. Wells located in Eastern of the field have higher permeability in direction of X and Y. It can be concluded that Western of the field produces from deeper depths while the flow contributions of horizontal directions are dominant in Eastern wells. Fracture permeability was found similar to interference test results. Mean fracture porosity is less than 3 % for all wells. There are no significant porosity variations in the field.

Table-4: Oda Analysis Result

	Well-X1	**Well-X2**	**Well-X3**	**Well-X4**	**Well-X5**
Number of Grids	1000	1000	1000	1000	1000
Max Porosity,%	7.1	4.1	5.8	3.4	4.3
Min Porosity,%	0.2	0.3	0.6	0.2	0.2
Mean Porosity,%	2.9	1.5	2.6	1.37	1.4
Max Permeability in X direction	1861	627	2169	878	1005
Min Permeability in X direction	56	11.4	170	18	21
Mean Permeability in X direction	429	81	657	235	203
Max Permeability in Y direction	6207	3301	6680	3068	5022
Min Permeability in Y direction	329	65	1186	202	102
Mean Permeability in Y direction	2155	417	3257	1218	984
Max Permeability in Z direction	5793	3133	6672	3179	4903
Min Permeability in Z direction	328	61	1170	207	102
Mean Permeability in Z direction	2026	398	3068	1149	927

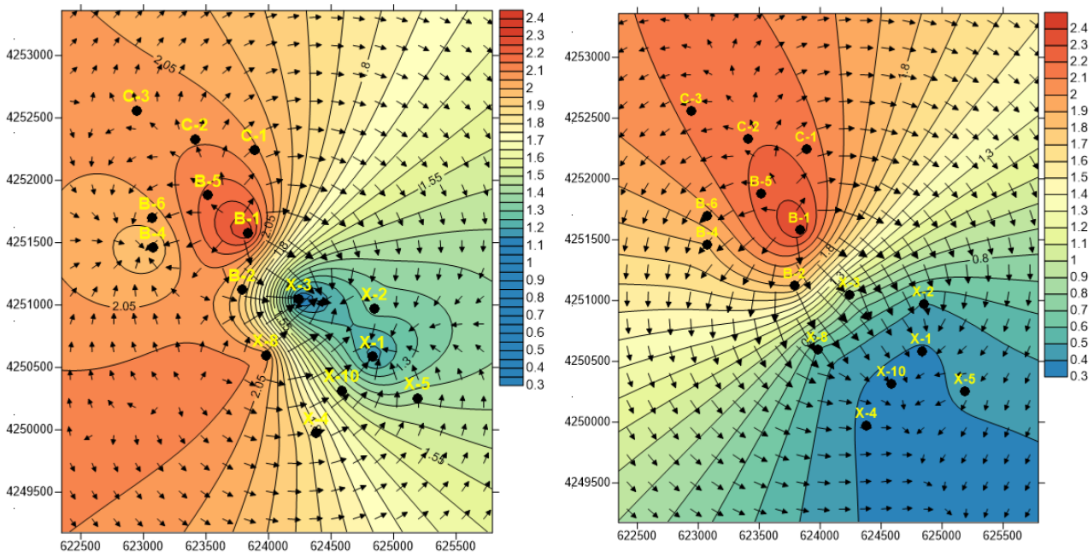

Figure-7: CO₂ Gas Weight % (Left: May 2016 Right: January 2017)

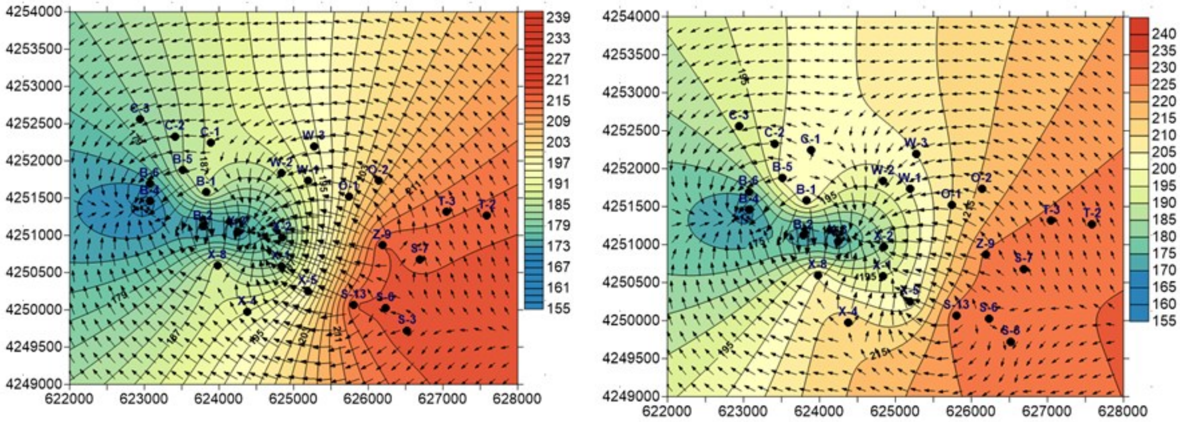

Figure-8: Chloride Concentration (ppm) (Left: November 2015 Right: May 2017)

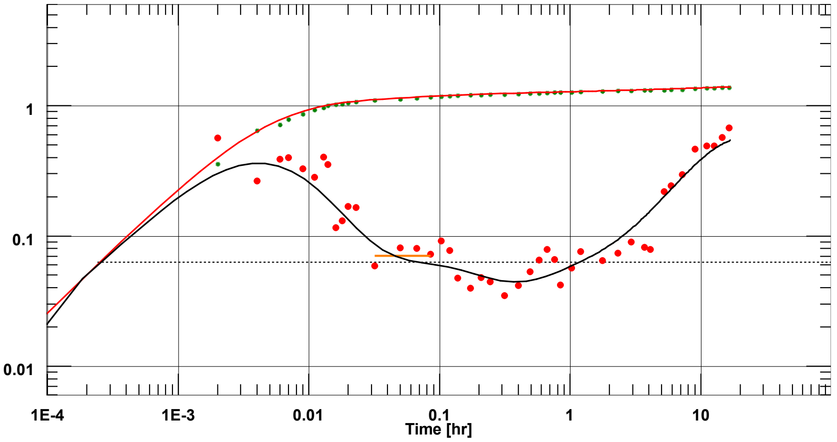

Figure-9: Pressure Buildup Test Log-Log Analysis

Table-5: Pressure Buildup Test Results

Parameters/Well ID	X-1	X-2	X-3	X-4	B-1	K-3	Units
Wellbore Storage, C	0.639	0.171	0.436	0.1	0.97	0.3	m^3/Bar
Skin Factor	1.59	1.27	1	3.07	-3.6	-3.6	Dimensionless
Permeability*thickness kh	96.5	35.5	278	570	34	0.88	Darcy*m
Omega	0.286	0.00753	0.00194	0.011	0.0155	6.50E-05	Dimensionless
Lambda	1.10E-07	1.23E-07	4.98E-08	3.98E-08	1.57E-05	4.80E-05	Dimensionless

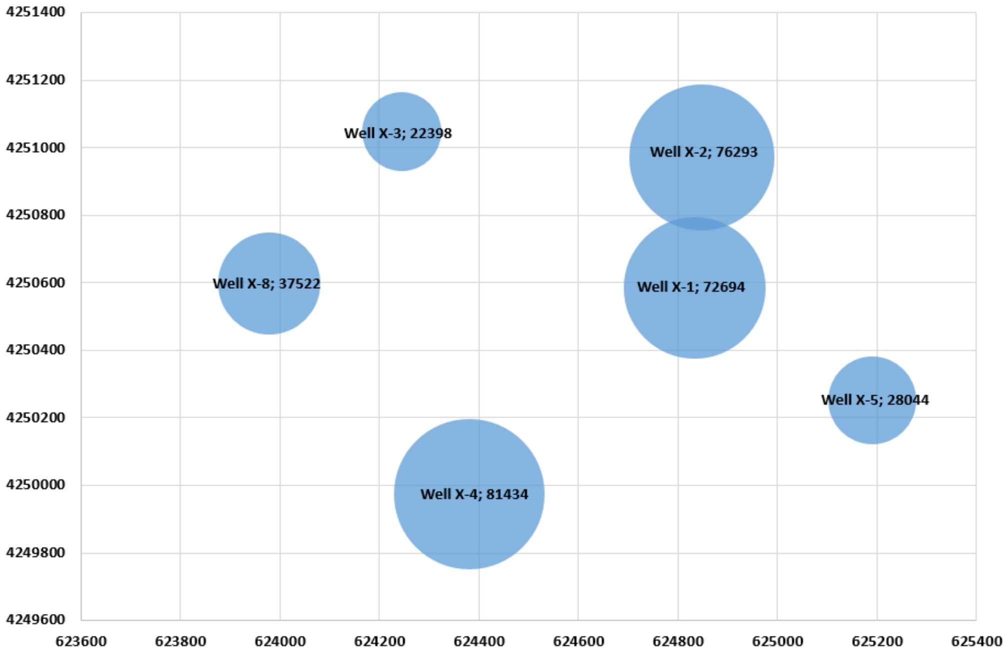

Figure-10: Swept Fracture Pore Volume from Tracer Test

Table-6: Interference Test Results

Parameter	**W-1**	**W-2**	**W-3**	**W-4**
Wellbore storage coefficient, C, m^3/Pa	$4.35x10^{-11}$	$9.64x10^{-10}$	$4.78x10^{-8}$	$2.37x10^{-6}$
Wellbore storage coefficient ratio, C_i/C_f	0.0424	0.0928	0.01	5.52
Alpha	1.1	32	45.6	7.43
Skin	-17.6	-16.0	-7.44	-17.1
Permeability – thickness, kh, m^3	$5.63x10^{-13}$	$6.04x10^{-16}$	$1.64x10^{-12}$	$7.23x10^{-12}$
Porosity – c_t -h, 1/Pa	$1.34x10^{-6}$	$2.39x10^{-4}$	$5.61x10^{-4}$	$6.08x10^{-4}$
Omega	$4.27x10^{-4}$	$1.31x10^{-9}$	$8.62x10^{-9}$	0.0265
Lambda	$2.98x10^{-4}$	0.00867	$1.52x10^{-6}$	0.00152
kx/ky	$1.21x10^{-7}$	$5.3x10^{-4}$	0.180	0.27

5. RESULTS AND DISCUSSIONS

- Fracture pore volume calculated in DFN modeling for each well is in good agreement with tracer swept pore volume calculated from moment analysis.

- Fracture porosity was calculated as ranging from 1.5 % to 3 % in DFN modeling. However, average porosity of outcrop analysis changed from 3 % to 12% in Gurel et al. (2016). The reason of discrepancy may be due to that overburden and confining pressure at reservoir conditions is higher than that of outcrops on surface. Outcrops of reservoir rock may also be exposed to weathering, which may develop secondary porosity.

- Fracture aperture was found to change between 1 mm to 2 mm in DFN modeling. However, Akin (2013) used cubic law in drilling mud loss data and calculated fracture aperture as ranging from 0.3 to 0.4 mm. FracMan7.6 has a convergence problem in performing mesh operation if volumetric fracture density is higher than 0.08. Thus, fracture aperture was increased to higher than 1 mm to obtain a match with actual test data. FMI logging is a very useful method to measure fracture aperture, fracture density, dip direction and dip amount. However, in conventional geothermal wells, FMI log is rarely taken in Turkey. There was no reported FMI log data for Alaşehir Geothermal field.

- There was no compartmentalization fracture set in DFN modeling. Tracer test, geochemical components and interference test also agree with this claim.

- In DFN dynamic analysis, shortest flow paths between wells were significant. Early tracer concentrations observed in tracer test is probably related with these shortest flow paths.

- Detachment fault and high angle normal faults were found as intersected from tracer test.

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