Estimation of Permeability using Simple Multi Criteria Decision Analysis in Gümüşköy, Aydın, Turkey

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Multi Criteria Decision Analysis, Weight of Evidence, geothermal reservoir, permeability determination, Gümüşköy, Turkey

ABSTRACT

The aim of this study was to develop a methodology to estimate geological formation permeability in a geothermal system. Permeability is an important parameter for geothermal exploration since it defines the flow capacity of reservoir rocks. However, most of the time it is either not possible to calculate hard rock permeability or it requires time consuming tests and analysis. Thus, a more practical solution was needed to estimate permeability for the exploration studies. In this scope, a Multi Criteria Decision Analysis (MCDA) method was utilized. The case study area was selected as the Gümüşköy geothermal area, which is located in the Western end of Büyük Menderes Graben (BMG).

The methodology was constructed similar to Weights of Evidence (WoE) method, which belongs to a group of multi-criteria decision making methods. MCDA was used to determine favorability of permeable areas by means of giving scores and weights to the input parameters and evidences. Weights were estimated from the measured parameters and the values on well logs were used as predictors. For this purpose, 3 deep wells were utilized with spacing up to 800 meters. The parameters used for permeability estimation included, Lithology, Spinner Log, Caliper Log, Water Loss Test Results, Resistivity Log, Temperature Log, *Formation Micro-Imager* (FMI) Log, Drilling Parameters; Rate of Penetration (ROP), Weight on Bit (WOB), Mud Temperature, and Rock Quality Designation (RQD). A permeability log is evaluated for all possible well locations using the given weights producing favorable zones in one dimension and then extrapolated into a 3D Permeability Model using kriging interpolation. Consequently, permeable zones were modeled from favorability logs generated with MCDA method in 3D and the model was mostly in line with the estimated reservoir depth and thickness.

Introduction

The study area is located in Gümüşköy, Aydın, geologically at the Western side of Büyük Menderes Graben (BMG). Southwestern Turkey, including the Menderes Massive, has been affected by an extensional tectonic regime since Oligocene (Bozkurt and Satir 2000; Bozkurt and Oberhansli, 2001; Gessner et al., 2001). Neotectonic domain of Southwestern Turkey is characterized by a tensional tectonic regime and distributed stress system with the multidirectional extension. Main structures characterizing and shaping this neotectonic domain are the graben-horst systems and their margin-boundary normal faults. The E-W-trending Menderes Graben is divided into several sub-grabens and sub-horsts along its western tip around Ortaklar, Gümüşköy, Argavlı, and Kirazlı (Koçyiğit, 2009).

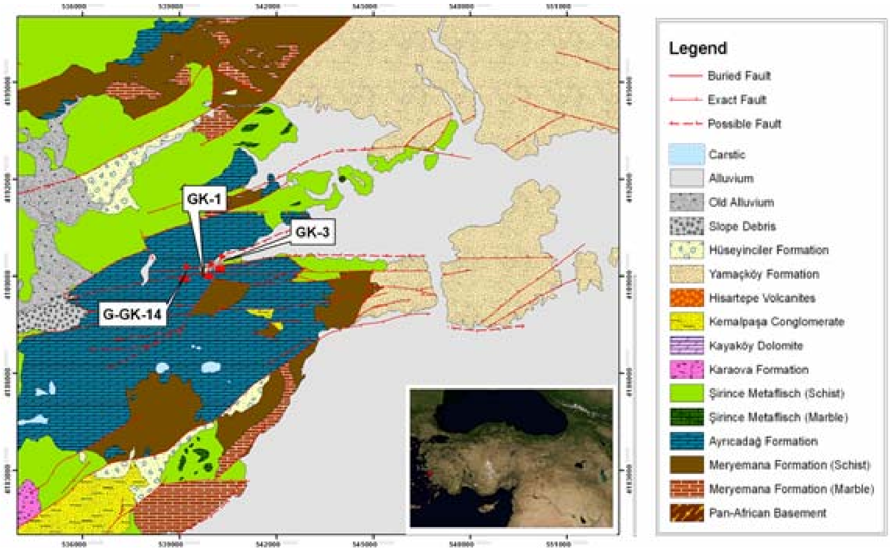

Figure 1. Map showing location and general geology of the study area (Tüysüz and Genç, 2010).

The permeability within the Menderes Massive rocks is highly variable. The hard, brittle lithologies have acquired secondary permeability through active graben tectonism in the region (Simsek, 2003). The carbonates of the Menderes Massive rocks are highly fractured and karstified and act as an aquifer for both cold ground waters and thermomineral waters depending on the location. Fractured parts of granodiorite, gneiss and quartz-schist units of the Menderes Massive act as aquifers for low-salinity cold ground waters, hot waters and for thermomineral waters. These rocks form the reservoir for waters to be heated at depth and fractures and faults provide a means for circulation and rise of the heated waters to the surface (Gemici and Tarcan, 2002). Schists and phyllites have relatively low permeability. The Neogene terrestrial sediments, which are made up of alluvial fan deposits including poorly cemented clayey levels, have very low permeability as a whole and may locally act as cap rocks for the geothermal systems. Clayey levels of the Neogene sediments occur as impermeable barrier rocks. Sandy to gravely and limestone levels of this Neogene unit contain minor aquifers (Tarcan et al, 2005).

Permeability is an important phenomenon in geothermal systems, which needs to be identified in detail. Permeability measures the ability of fluids to flow through rock or porous media which is significant for determination of geothermal reservoirs. It is related to the type of the rock, fracture systems, schistosity and bedding. Permeability can be either be directly calculated by Darcy's law or derived from hydraulic conductivity;

$$\kappa = \upsilon \frac{\mu \Delta x}{\Delta P} \tag{1}$$

$$\kappa = k \frac{\mu}{\rho g} \tag{2}$$

Where:

- ***κ** is the permeability of a medium (m^2)*
- ***k** is the hydraulic conductivity, m/s*
- ***v** is the superficial fluid flow velocity through the medium (m/s)*
- ***μ** is the dynamic viscosity of the fluid (Pa s)*
- ***ΔP** is the applied pressure difference (Pa)*
- ***Δx** is the thickness of the bed of the porous medium (m)*
- ***ρ** is the density of the fluid, kg/m^3*
- ***g** is the acceleration due to gravity, m/s^2*

Reservoir Rocks of Menderes Massive geothermal systems are karstic marbles and fractured Schists-Gneiss contact zone. Hydraulic conductivities for karstified marbles and fractured metamorphic rocks in literature vary from to 1 x 10^{-5} to 2 x 10^{-2} m/s, and from 8 x 10^{-9} m/s to 3 x 10^{-4} m/s, respectively (Tarcan & Gemici, 2010). Unfractured schists and phllites of the Menderes Massive rocks are both basement rocks and cap rocks of the geothermal systems. Hydraulic conductivity coefficients (k) of these rocks in literature vary between 3 x 10^{-14} m/s - 2 x 10^{-10} m/s corresponding to relatively impermeable (Tarcan and Gemici, 2010). According to Darcy's Law permeability values for karstic marbles and fractured metamorphic rocks of Menderes Massive geothermal systems were calculated based on known hydraulic conductivities and found to be ranging from 2 mD to 466 mD (Viscosity of water at 150ºC was taken as 0.023 Pa.s and density was taken as 1 kg/m^3).

Methodology

Since the calculated values of permeability for the reservoir rocks in Gümüşköy area were within a wide range, they could not be used directly for locating reservoir zones. Thus, rather than defining the exact permeability of rocks, a practical approach was needed to estimate favorable zones for high permeability. For this purpose, a multi criteria decision analysis (MCDA) technique was utilized.

Multi criteria decision making (MCDM) refers to making decisions in the presence of multiple, usually conflicting, criteria. Measurements in MCDA are derived or interpreted subjectively as indicators of the strength of various preferences. Preferences differ from decision maker to decision maker, so the outcome depends on who is making the decision and their goals and preferences (Saaty, 2005). Previously, MCDA were used to predict the probable undiscovered geothermal systems through investigation of spatial relation between geothermal occurrences and its surrounding geological phenomenon in Western Anatolia (Tüfekçi et al, 2010).

In this study, an adapted MCDA methodology was constructed based on principles of Weight of Evidence (WoE) for determining favorability of permeable areas. WoE is a multi criteria decision making method. It can be defined as a framework for synthesizing individual lines of evidence, using methods that are either qualitative (examining distinguishing attributes) or quantitative (measuring aspects in terms of magnitude) to develop conclusions regarding questions concerned with the degree of impairment or risk (Good, 1991). In general, qualitative methods include presentation of individual lines of evidence without an attempt at integration, or integration through a standardized evaluation of individual lines of evidence based on qualitative considerations. Quantitative methods include integration of multiple lines of evidence using weighting, ranking, or indexing as well as structured decision or statistical models (Linkov et al. 2009).

Evidences were identified both for conventional rotary drilled full scale wells (GK-1, GK-3) and smaller size cored wells (G-GK-14). Weights were estimated from the measured parameters and

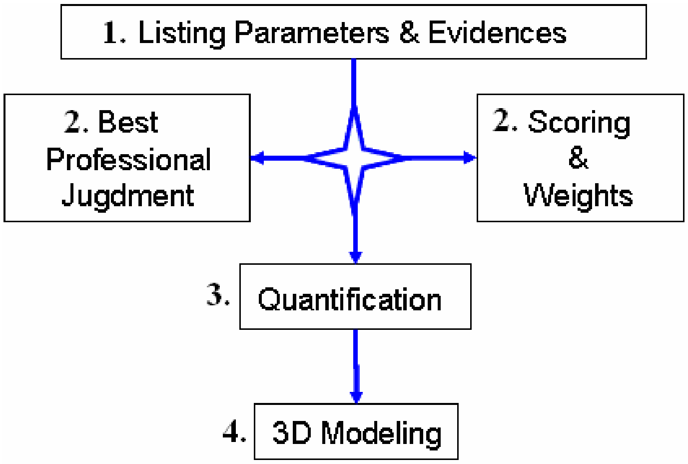

Figure 2. Outline of Methodology (Modified from Linkov et al. 2009).

the values on well logs as predictors. Rather than using statistical approach weights were assigned manually by best professional judgment. A permeability log is generated for all possible well locations using the given weights producing favorable zones in one dimension and then extrapolated into 3D Permeability Model using Kriging interpolation.

1. Listing Evidences

Evidences used in this study are summarized below;

- ***Lithology:*** Marble, recrystallized limestone, gneiss-schist contact zone
- ***Flow Zones*****:** Corrected Spinner log, Caliper log
- ***Water Loss Data:*** Rapid AND Extreme Cooling, Rapid OR Extreme Cooling
- ***Formation Micro-Imager (FMI):***Presence of faults, Fracture density
- ***Rock Quality Designation RQD:*** Fracture Density (A substitute of FMI for cored wells)
- ***Temperature Gradient:*** Fracture related vertical convection connectivity
- ***Drilling Parameters:*** ROP, WOB, Mud Temperature, Mud Loss

The parameters used for rotary drilling were lithology, spinner log, caliper Log, water loss test results, resistivity log, temperature log, *Formation Micro-Imager* (FMI) log, and drilling parameters. For the cored wells Rock Quality Designation (RQD) was the equivalent of FMI.

2. Best Professional Judgment & Scoring

Lithology was defined from both cores and cuttings from drilling. In Gümüşköy Geothermal Area major lithological targets were marble, recrystallized limestone, and highly fractured gneiss-schist contact zone. Most of the carbonate rocks are known to be porous and permeable. However, the score of fractured Gneiss-Schist Contact was higher than other carbonate rocks since it is within a tectonic origin cataclastic zone, which increases the original permeability metamorphic rocks at a noticeable amount (Table 1 & Table 2).

Flow zones were determined based on spinner logs. A correction was applied to spinner log by simply multiplying with caliper log to eliminate roughness effect of the open hole. Thus, more accurate calculation of the inflow to the well bore was acquired. Inflow values were classifies as high, moderate and low depending on the amount of shift in the spinner log and the corresponding vertical length (Table 1).

Well diameter was also used as evidence which indicated some level of permeability and for this reason the zones of contraction and expansion were determined. Drilling mud looses its water through the formation forming mud cakes where there are permeable zones with lithostatic pressure less than the pressure of drilling fluid. Thus, drilling mud or bentonite sticks to the well bore causing a constriction. Most permeable zones create expansion rather than constriction. Permeable formations collapse due to the effect of the drill bit and drilling fluid which yields an increase in the well diameter (Table 1).

Water Loss Test is a dynamic measurement for determining zones where fluid is penetrating into the reservoir by injecting relatively cold water in the well bore. These zones result from conducting successive temperature and pressure (PT) surveys in the well bore. The amount and rate of cooling represent permeable areas. A rapid and high amount of cooling indicates the most favorable zones. Either rapid cooling or high amount cooling zones are also favorable. Slow and slight cooling indicates low permeability (Table 1).

Rock resistivity is inversely proportional to porosity but there is not an exact correlation between porosity and permeability. Rocks with a similar porosity but different permeabilities are very common in a reservoir. Carbonate rock data especially shows scattering and poor correlation between permeability and porosity. Thus, resistivity can be related to permeability by considering the water saturation and flow parameters. When flow parameters were correlated with the resistivity logs 30 Ωm was found to be an acceptable limit for reasonable permeability (Table 1 and Table 2).

FMI images were acquired from the well bore below casing depth for GK-1 and GK-3. In GK-1, 3,154 measurements were assigned into 6 dip sets as; 1,976 bed boundaries, 26 unconformable beds, 1,101 conductive fractures, 12 resistive fractures, 18 induced fractures and 21 faults. Similarly in GK-3, 2279 measurements were assigned into 6 dip sets as; 1,356 bed boundaries, 56 unconformable beds, 833 conductive fractures, 5 resistive fractures, 20 induced fractures and 9 faults. Since the amount of data to analyze is quite large the well was divided into segments with 100m spacing and conductive fractures were counted in every interval. The scoring was conducted based on data density (Table 1). Additionally, a score was given to the location where faults exist based on FMI data and well log interpretations.

Rock Quality Designation (RQD) is a parameter defining the strength of rocks and fracture framework. RQD can only be measured in cored wells and is used as a substitute of FMI in this case study. RQD and permeability are inversely proportional.

Temperature gradient is also considered as an indicator of permeability. Most of the time the temperature gradient is not constant in every section of the well bore. Zones having less then the earth's average geothermal gradient (3.3°C/100m) placed after zones with high gradient is mostly attributed to vertical connectivity (convection) within the formation. This effect can be interpreted as a permeability indicator. However, since background geothermal gradient is usually higher than 3.3°C/100m, this value was taken as a conservative limit beyond typical conductivity effects.

Drilling Parameters used for permeability estimation were Rate Of Penetration (ROP), Weight on Bit (WOB), drilling fluid losses and drilling fluid temperature changes. Sudden increase in ROP without increasing WOB is mostly related with a loose formation, karstic cavity or highly fractured zones, all of which can be related with high permeability. Drilling fluid losses and sudden drilling fluid temperature changes also related to fluid-loss zones and inflow zones respectively both of which could be related to high permeability. Meanwhile, it is important to adjust drilling fluid temperature changes with respect to depth data for circulation time related delays, since these values are measured up at the well head at the time of arrival of circulated fluid.

Table 1. Score & Weights for Rotary Wells.

Parameter	Evidence	Score	Grade (%)	Impact (%)	Corrected Impact (%)	Final Weight
Lithology	Marble	1	0,50	15%	15,00%	0,075
	Re-Crystalline Limestone	1	0,50			0,075
	Gneiss-Schist Contact	2	1,00			0,150
Inflow (Spinner)	High Inflow (f/50m > 0.15)	3	1,00	15%	15,00%	0,150
	Moderate Inflow (0.05<f/50m<0.15)	2	0,67			0,100
	Low Inflow (0.02< f/50m <0.05)	1	0,33			0,050
Caliper	Contraction (>10%)	5	1,00	10%	10,00%	0,100
	Expansion (>20 %)	3	0,60			0,060
	Expansion (<20 %)	1	0,20			0,020
Water Loss Test	Rapid AND Notable Cooling effect	2	1,00	15%	15,00%	0,150
	Rapid OR Notable Cooling effect	1	0,50			0,075
Resistivity	x ≤ 30 Ohm.m	1	1,00	5%	5,00%	0,050
FMI (Fracture)	# >100	4	1,00	10%	10,00%	0,100
	70 < # < 100	2	0,50			0,050
	# <70	1	0,25			0,025
FMI (Fault)	Exists	1	1,00	10%	10,00%	0,100
Gradient	x < 3,3C/100m	3	1,00	9%	9,00%	0,090
	3,3C/100m < x < 8,5C/100m	1	0,33			0,030
ROP - WOB Mud Loss	Sudden increase in ROP	1	1,00	5%	5,00%	0,050
	Mud Loss	1	1,00	3%	3,00%	0,030
	Mud Temperature Δt >%50 values	1	1,00	3%	3,00%	0,030
	TOTAL			**100%**	**100%**	**1,000**

Table 2. Score & Weights for Cored Wells.

Parameter	Evidence	Score	Grade	Impact (%)	Corrected Impact (%)	Final Weight
Lithology	Marble	1	0,50	25%	35,71%	0,179
	Re-Crystalline Limestone	1	0,50			0,179
	Gneiss-Schist Contact	2	1,00			0,357
Water Loss Test	Rapid AND Extreme Cooling	2	1,00	0%	0,00%	0,000
	Rapid OR Extreme Cooling	1	0,50			0,000
RQD	RQD< %25	4	1,00	10%	14,29%	0,143
	RQD<%50	2	0,50			0,071
	RQD %50-75	1	0,25			0,036
Faults	Exists	1	1,00	15%	21,43%	0,214
Gradient	x < 3,3C/100m	3	1,00	10%	14,29%	0,143
	3,3C/100m < x < 8,5C/100m	1	0,33			0,048
Mud Loss Mud Temperature	Start Point	2	1,00	10%	14,29%	0,143
	Partial Loss Zone	1	0,50			
	Total Loss	1	1,00			
	Mud Temperature Δt > %50 values	1	1,00	0%	0,00%	0,000
	TOTAL			**70%**	**100%**	**1,000**

3. Quantification

In the quantification stage, some very simple algebra was utilized to calculate the final weights of the evidences. A score was given to each evidence that was based on best professional judgment. Then a grade was assigned depending on percent share within its parameter category and an impact percent was given to each parameter. Missing evidence for the wells was extracted from calculations and a corrected impact percent was calculated. Well logs were generated for each evidence based on the final weight. Favorability log was generated by simply adding all available logs and converted into percent range in order to keep consistency between different wells.

4. 3D Modeling

After completion of 2D permeability logs for the wells, a 3D permeability model was generated. A Regular 3D grid was constructed without taking the structural framework into account since the structural information is integrated into favorability logs. Zoning and layering was conducted based on data density and the well logs were rescaled up to a precision of 2m. Kriging interpolation was selected as a modeling algorithm for 3D distribution of the well data. Kriging is a group of geostatistical techniques to interpolate the value of a random field at an unobserved location from observations of its value at nearby locations (Cressie, 1990). Kriging is made for interpolation of a single realization of a random field (permeability), while regression models are based on multiple observations of a multivariate dataset. The Kriging algorithm is favorable for revealing asymmetrical and anisotropic distribution of data in the geo-field and it is commonly used as the 3D interpolation method to convert the insufficient and random-arrayed data set into sufficient grid data set.

Results

Favorability logs were calculated by assigning final weights to each parameter. Thus, for the conventional wells GK-1 and GK-3, 9 different well logs and for the cored well G-GK-14, 6 different logs were created. Then, the final favorability log was generated by adding all existing logs and normalizing calculated values into a range from 0 to 1 (Figure 3).

The maximum favorability for the wells GK-1, GK-3, and G-GK-14 was calculated to be 0.62, 0.45, and 0.36, and mean favorability values was calculated to be 0.22, 0.12, and 0.16 respectively. This showed that the permeability is decreasing towards the East and the West of GK-1 well. In other words, GK-1 stands at the up flow zone of the geothermal system.

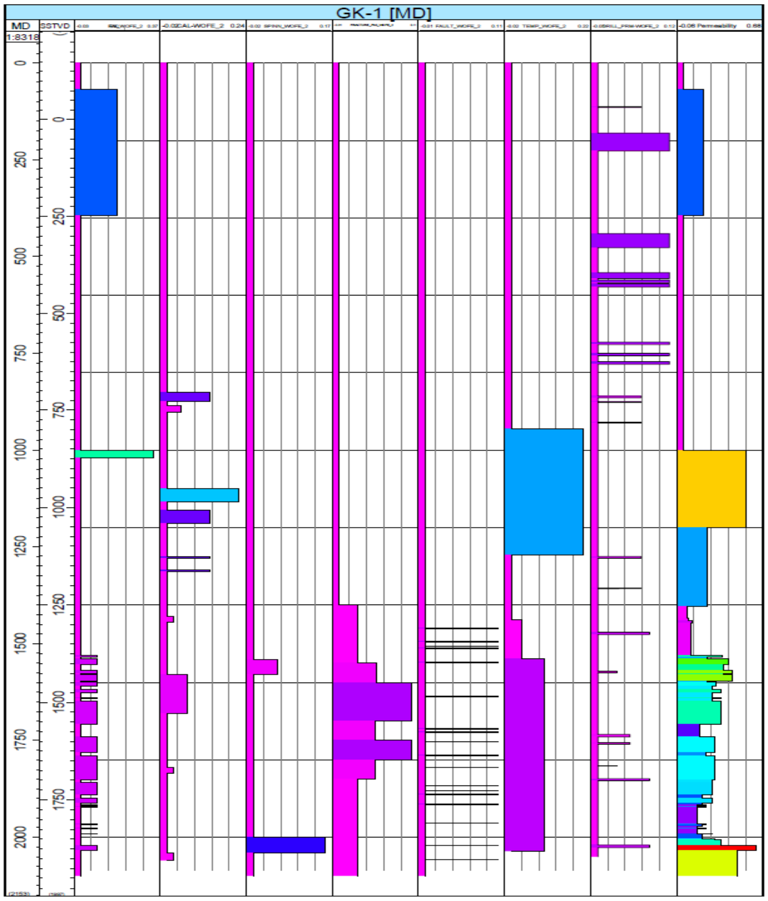

Figure 3. Favorability Logs for each evidence and final permeability log for GK-1.

Seven different horizons and permeable zones were outlined by correlating 3 wells. A first permeable zone was at the uppermost section which corresponded to the Mesozoic Re-crystalline Limestone. This zone was thinning towards East. Below that, there was an impervious zone at GK-1 which loses continuity towards both at sides. A second permeable zone was around -800m and -1100m depth. This zone corresponds to highly fractured gneiss schist contact which is a tectonic cataclastic zone.

A third permeable zone corresponds to Paleozoic Marble between -1300m and -1600m depth. Most permeable zone was observed below - 1850 m at GK-1 and lateral extension can not be traced at the other wells. G-GK-14 is not deep enough to penetrate into that permeable zone. GK-3 was more or less at the same depth of GK-1 but that zone should be located at deeper sections. Most of the permeable zones mentioned above were under structural control and located were E-W and NE-SW trending fault systems coincide.

Flow rates of the wells are directly related to the permeability of the inflow zone. Therefore, a second study was performed as a means to crosscheck with MCDA permeability zones. For this study, spinner surveys for GK-1 and GK-3 used (corrected for caliper sectional area) a partial flow calculation from bottom to top along the well bore and adjusted to yield the total measured well flow. The flow rates of GK-1 and GK-3 were 60lt/s and 42lt/s respectively. For GK-1 two major inflow zone were determined from spinner logs and corresponding permeability were investigated (Figure 5). The amount of inflow from each zone were calculated proportional to the MCDA weights of the spinner log and it was found that 75 % was coming from the lower section and 25 % from the upper section. There is another permeable zone noted from the well data between -850m and -1050 m but since it was behind the production casing it had no effect to the flow rate.

The situation for GK-3 was more interesting than GK-1. There were 5 major inflow zones below the casing and one behind the casing. Unlike GK-1, GK-3 was perforated between 1028m (Measured Depth: MD) and 1131m (MD) depth from 5 sections with 6 meters perforation length. The partial inflow from the perforated zone was 34% of the total flow. The inflow zones were correlated with permeability log and their percent share in the total flow were calculated (Figure 6).

As mentioned in the previous sections 3D modeling of permeability was conducted using Kriging interpolation. Maximum favorability was calculated as 0.6 and mean favorability was 0.2. The model was filtered to show favorability higher than the mean value (0.3 was taken as an example) and 3 different reservoir (deep, interim reservoir and shallow) levels have been visualized (Figure 7). In general the model was successful and the distribution of permeable zones was mostly inline with estimated reservoir depth and thickness.

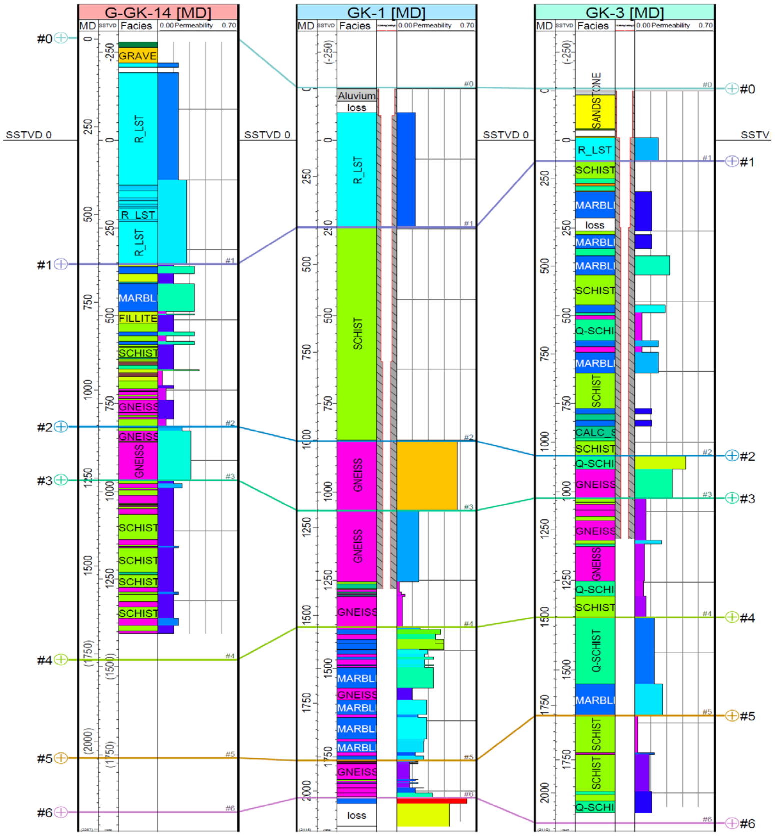

Figure 4. Correlation of Permeability Logs for 3 wells.

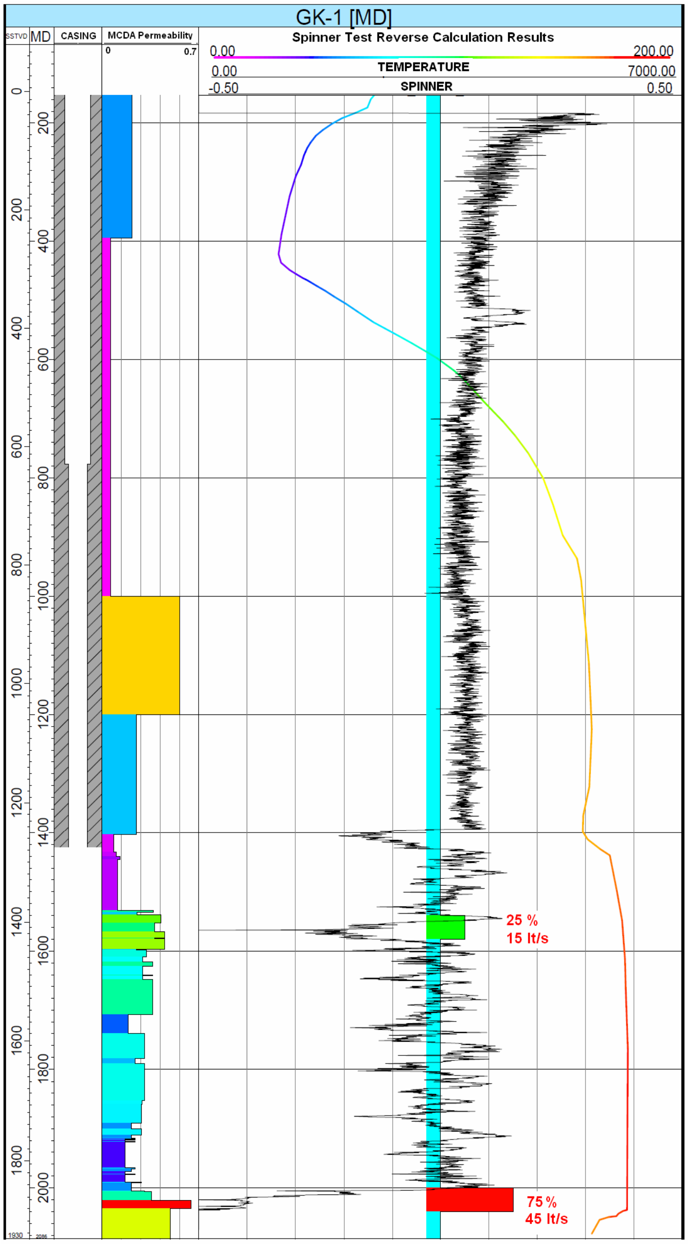

Figure 5. Correlation of Permeability log with PTS survey for GK-1.

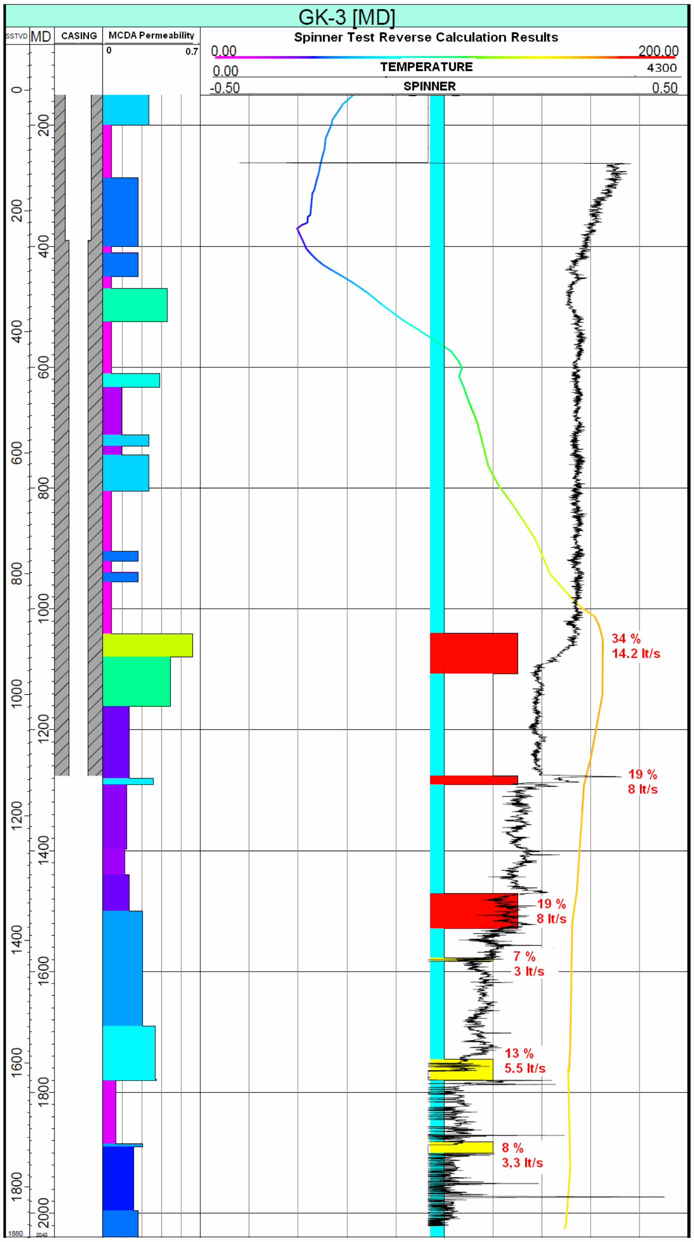

Figure 6. Correlation of Permeability log with PTS survey for GK-3.

Discussions and Conclusions

The aim of this study was to define permeable zones form well logs by utilizing MCDA. The favorability logs were generated by assigning weights to the related well logs by best professional judgment. The model started from 1D interpretation along the well bore, continued with 2D correlation of wells and finalized with 3D interpolation. The result was a 3D permeability model which was mostly in line with the estimated reservoir depth and thickness. The results were satisfactory and gave estimation for the possible reservoir zones. The method does not calculate the exact permeability of rocks; however it can be used in the areas where

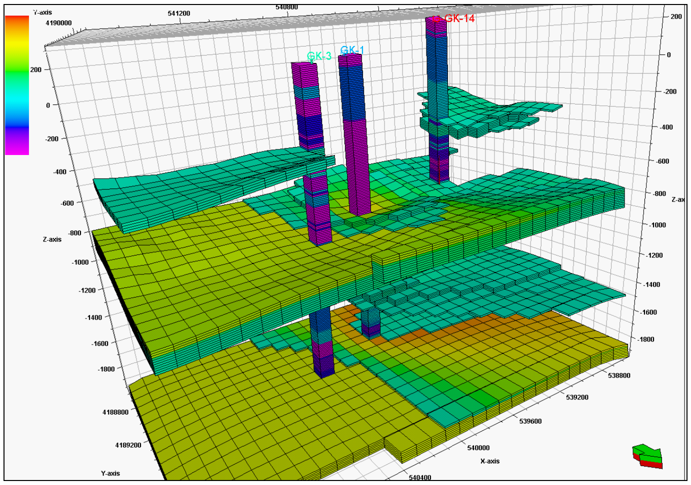

Figure 7. 3D Permeability Model showing favorability values grater than 0.3.

calculation of hard rock permeability is not possible. Since the method is subjective, every parameter should be carefully evaluated before assigning during scoring parameters. One handicap of the model may be the effect of fault zones on permeability. Thus, cataclastic zones related to tectonic activity should be carefully investigated as they can be closely related to high permeability. The methodology is simple and useful for exploration purposes and it can be enhanced with integration of lithological and structural model in 3D during interpolation process and calibrating the results with geophysical data.

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