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FOCAL MECHANISM FOR DETERMINING FAULT PLANES ORIENTATION IN "GAMMA" GEOTHERMAL FIELD

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ABSTRACT

"Gamma" geothermal field is located in volcanic lines which associated by others geothermal field and controlled by geological processes as well as the activity of geothermal exploitation, so they are indicated by fault planes which became one of micro earthquake triggering factors. Fault planes identification with focal mechanism method towards micro earthquake data has been done by reviewed location and relocation of hypocenters, which used of Single Event Determination (SED) and Double Difference (DD). 211 data of 70.659 hypocenters was recorded by five micro earthquake recording stations in "Gamma" geothermal field during the period of March 2012 to October 2012. 211 hypocenters data is used for SED location determination, 60 data for DD relocation determination, and 4 data for focal mechanism solution. Hypocenters location and relocation of SED and DD methods spread off through northwest to southwest of "Gamma" geothermal field. Based on SED method result, distribution of hypocenter shows the cap rock elevation is located upon 500 meters and the geothermal reservoir is located about 500 meters to -1500 meters (beneath mean sea level point). Afterwards, the SED method result is relocated by DD method so that hypocenters distribution is centered on four fault planes, there are fault planes A, B, C and D which are located between production and injection wells. Determination of all fault planes obtained with focal mechanism solution which reviewed by initial movement of P waves arrival time, it indicate A, B, C fault planes are typed reverse lateral oblique and D fault plane is typed lateral strike slip.

I. INTRODUCTION

West Java has the largest geothermal resources in Indonesia. The Geothermal resources totally reached 6,101 MWe (21.7%), which they are spread in 43 locations in 11 districts. Nowadays the whole capacity have been installed reached 1,057 MWe. [1]

"Gamma" geothermal field is one of the productive fields in West Java. The hydrothermal production optimization becomes very important in geothermal reservoir management which is aims to maximize the potential of geothermal energy then it will be processed into an energy source of geothermal. The Micro seismic approach is one method to be able of characterization fractures in the geothermal field. The Micro seismic approach is expected could provide the information geothermal reservoir condition.

The micro seismic method has been known as a geophysical method that used to identify tiny earthquakes (≤ 3 SR) is generally caused by hydraulic simulation, production / injection and drilling. This method can indicate the distribution of earthquakes zones through the hypocenter location. The hypocenter location could be used to viewing the direction of the flow of fault injection and described the zone with relatively high permeability for the manufacture of new production wells.

The Determination of earthquakes hypocenter location properly has become an essential key at fields in a research of seismology because seismic data can provide initial information the existence of fault or subsurface structures associated with seismic activity itself (Shater, 2012: 1081). The Hypocenter location accuracy is controlled by several factors; they are geometry observer station, reading the exact arrival time, subsurface velocity model, and the study of the geological structure of the study area (Gomberg et al, 1990, in Waldhauser, 2000: 1353). The Determination of earthquakes hypocenter location with a Single Event Determination and Double Difference method are expected to mapping the distribution of the hypocenter based on the existence of a fault that was in the "Gamma" geothermal field.

Focal Mechanism Solution is the result of seismic waveform analysis and recorded by seismogram. The complete characterization of the earthquakes in focal mechanisms can provide the important information that can determine the direction and knowing the shifting fault. Information about the earthquake in a simple way is attractive for structural geological work on the active structure (Cronin, 2004).

II. BASIC THEORY

The Geothermal System

A description of the geothermal system in an area usually made by demonstrating at least five components; they are the heat source, reservoir, reservoir temperature, water sources, and geothermal surface manifestations found in the area. Other components that are often shown in the model are the spread of rock, the type and direction of flow of water in the subsurface. Model of the geothermal system called conceptual models are based on the evaluation of data of geology, hydrology, geophysics, geochemistry and wells data.

In each hydrothermal system, it has unique characteristics, different from each other, not only just from its surface manifestations but also in reservoir characteristics. The uniqueness of each system is the result of the interaction of various factors, including the size and shape of the heat source rocks, structural geology, permeability, topography, surface hydrology (temperature and infiltration).

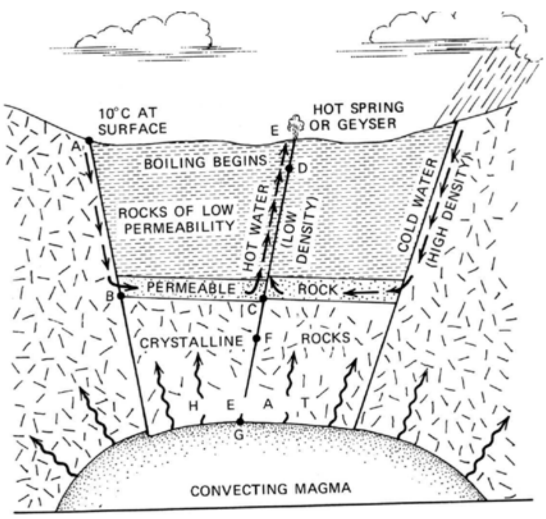

Figure 1 Geothermal System Model [2]

Micro Earthquake

Viewing by characteristics of the micro earthquake can be concluded that micro earthquake is a low magnitude earthquake that is caused by several things, such as hydrocarbons production, injection of fluid into the geothermal reservoir and so on. In general, micro earthquakes can occur due to:

- Weak zone is open or shifting of water injected continuously which results in increased pressure in the rock, resulting in a micro earthquake intensity higher along with increasing injection pressure and volume
- The contact between the cold water with hot igneous rocks (heat source). This occurs when the reservoir rocks directly exposed to water injection
- Reduced pore pressure resulting in closing the pores of reservoir rock due to the loss of pore fluid filler rock (due to fluid production).

This micro earthquake may occur in large numbers and in a short time, and vice versa. This is determined by the local geological conditions. The more weak zones are still closed and the injection of water the more the higher the intensity of the micro earthquake.

The Hypocenters Determination's Method of Single Event Determination

The location of the earthquake is defined by the location of the earthquake hypocenter x_0, y_0, z_0 and t_0. Hypocenter is the physical location of the earthquake, usually expressed in longitude (x_0), latitude (y_0), and elevation below the surface (z_0). When the hypocenter and origin time is determined by the arrival time of seismic phases starting by the first earthquake, the location will be calculated according to the point where the earthquake started.

The first arrival time of seismic waves at each station observations (seismometers) to-i (x_i, y_i, z_i) from the hypocenter (x_0, y_0, z_0) is described in the parameter t. The travel time calculations based on 1D velocity models of the subsurface and t_0 is the time of origin (origin time) described in t^{cal} parameters. Mathematically described as follows:

$$r_e = t - t_0 - t^{cal} \quad (1)$$

whereas

r : residual or error
e: observer station index
t : arrival time
t_0 : origin time
t^{cal} : travel time calculated
$t - t_0$: t^{obs}

When an earthquake occurs at position x_0, y_0, z_0 at time t_0 in e station with position x_e, y_e, z_e time will be recorded the seismic waves which arrived at time ti, then the travel time of seismic waves could be known (x_0, y_0, z_0, t_0).

By the (1) equation is known when the wave's arrival time at the observer station is equal to the amount of travel time and origin time, it will generate residual (error) is zero, it could be estimated that the earthquake's origin time position was right. Mathematical's function least squares (minimum) of the residual or error is:

$$F(X) = \sum_{e=1}^{M} r_e^2 \quad (2)$$

With M is the number of stations and x is the hypocenter parameters that we want to know (x0, y0, z0, t0). Allow the fact that the subsurface structure of the complex made it difficult to determine the model with the same velocity and the real situation due to an error factor of reading arrival time, then the equation (2) is non-linear equations. Simplification is done to solve the above equation by assuming the velocity model is approaching the actual situation and the arrival time readings are correct, so that the difference in travel time is a simple linear function of the difference between calculated and observed hypocenter parameters. Linearization equation (2) is written in the form:

$$r_e = \frac{\partial T_e}{\partial x_0}\partial x + \frac{\partial T_e}{\partial y_0}\partial y + \frac{\partial T_e}{\partial z_0} + dt \quad (3)$$

whereas

t : origin time
T : travel time
e : observer station index
x_0, y_0, z_0: calculated hypocenter location
r : residual or error

When equation (3) arranged for all monitoring stations that recorded the earthquakes it will form a matrix equation residual travel time. The matrix can be written in the equation:

$$J\Delta m = \Delta d \quad (4)$$

J is a matrix with the kernel, or commonly known as the Jacobian matrix, contained the partial derivatives of each station travel time residuals towards the hypocenter parameters (x_0, y_0, z_0, t_0), it size n x 4, where n is indicate the number of monitoring stations and 4 are representations number of hypocenter parameters are sought.

Matrix Δm is the model which we want to know, contain the hypocenter position (x, y, z) and time of the earthquake (t_0) 4 x 1. Parameters and Δd is obtained from observations (data), in the form of residual seismic wave's arrival time at the station observer (Tobs) with size n x 1

The models could be obtained by changing the matrix to matrix inversion by multiplication inverse Jacobian matrix (J-1) so that the completion of the above matrix inversion is given by the equation:

$$[J]^T[J]\Delta m = [J]^T\Delta d \tag{5}$$

$$[J^T J]^{-1}J^T\Delta m = [J^T J]^{-1}J^T\Delta d \tag{6}$$

$$\Delta m = [J^T J]^{-1}J^T\Delta d \tag{7}$$

$$J = \begin{bmatrix} \frac{dT_1}{dx} & \frac{dT_1}{dy} & \frac{dT_1}{dz} & \frac{dT_1}{dt} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \frac{dT_M}{dx} & \frac{dT_M}{dy} & \frac{dT_M}{dz} & \frac{dT_M}{dt} \end{bmatrix} \tag{8}$$

$$\Delta m = \begin{bmatrix} dx \\ dy \\ dz \\ dt \end{bmatrix} \tag{9}$$

$$\Delta d = \begin{bmatrix} r_1 \\ r_2 \\ \cdots \\ r_M \end{bmatrix} \tag{10}$$

$$x_0 + dx = x \tag{11}$$

$$y_0 + dy = y \tag{12}$$

$$z_0 + dz = z \tag{13}$$

$$t_0 + dt = t \tag{14}$$

whereas,

x_0, y_0, z_0 : calculated hypocenter location
dx, dy, dz, dt : hypocenter location correction
t_0 : origin time
t : origin time correction

The equations are calculate the travel time and origin time by the distance between the location of the station with the approximate location of the hypocenter is combined with a model of a pre-determined velocity. After we have calculated the difference in travel time calculation results t^{cal} with the travel time on the observation Tobs (obtained from wave arrival time tp / ts or travel time $t_p - t_0$), so that the residual value will be obtained which is proportional to the distance and time difference (dx, dy, dz , dt) of the earthquake.

The hypocenter location correction will be continued by iteration until the residual travel time observations and calculations is near to zero.

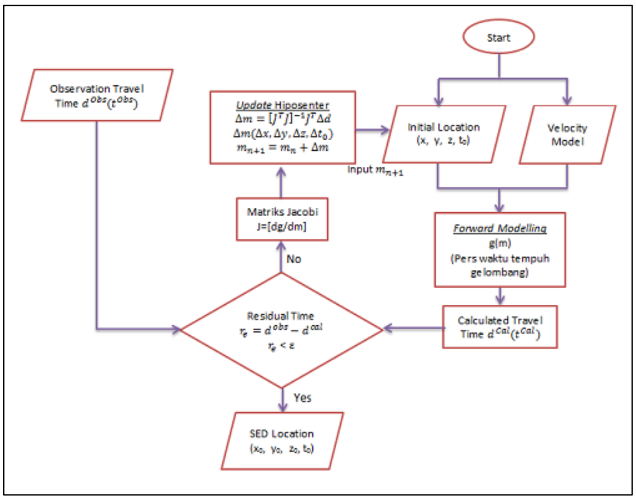

Figure 2 *Single Event Determination Flowchart* [3]

The Hypocenters Relocation's Method of Double Difference

The double difference is the Double difference method is the development of a Single Event Determination method using earthquake pairs differences of travel time, which in this study is derived from the data catalog. Waldhauser and Ellsworth (2000: 1353) said that if the distance between the location of the hypocenter separated the two events is smaller than the distance of the station towards the event and the velocity varied, then the path traversed by the seismic waves from the source to the station is the same in almost all track. In this case the difference between the wave travel time for two events observed in one station could be considered approximately equal between events with high accuracy.

With these assumptions, the difference in travel time between the two earthquakes were recorded at the same station could be considered as a function of the distance between the hypocenters. So it minimize the error correction of velocity model without using the station.

The travel time residual differences between the two events observation and calculations (Δd) is defined as follows:

$$(r_{e\,k}^{ij}) = (t_k^i - t_k^j)^{obs} - (t_k^i - t_k^j)^{cal} \tag{15}$$

Whereas

i, j :index of neighborhood event
k : observer station index

The hypocenter distance of i and in observation station is described in equation 15. Hypocenter i and j are to be relocated together to repair the distance between the two hypocenter.

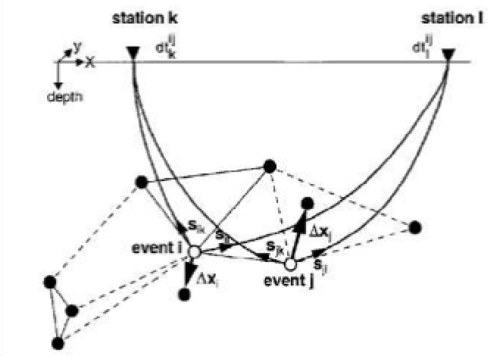

Figure 3 Illustration of Double Difference Method [4]

The hypocenter positions correction will continue to iterate until the residual travel time observations and calculations is near to zero. In this study the double difference method using hypoDD program (Waldhauser, 2001).

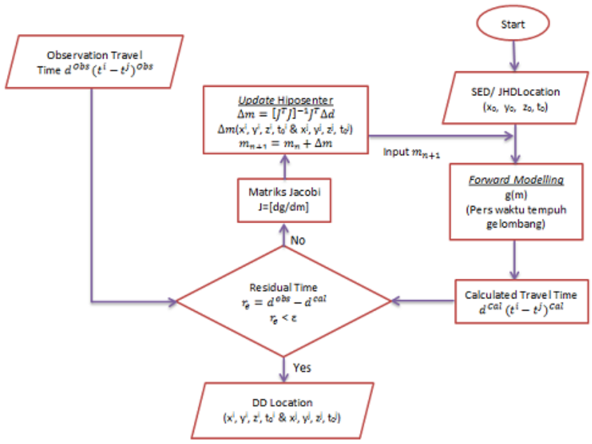

Figure 4 *Double Difference Flowchart* [5]

III. METHOD

Seismic data recording using five micro seismic recorder stations that MEQ-1, 3-MEQ, MEQ-4, MEQ-MEQ-5 and 6 are placed based on the configuration of the three circle method. The circle method uses the assumption that the case is a homogeneous subsurface, and is still valid in a heterogeneous medium but must be in horizontal layer. This will be easily extended in the case of the Earth is round (Afnimar 2009 in Annisofira, 2013). This configuration is suitable for determining local earthquake hypocenter due to local earthquakes generally which are in a seismic recording station configuration.

Table 1 Coordinates and Elevation of Micro Earthquake Station Recorder in "Gamma" Geothermal Field

Micro earthquake Station	Elevation	Coordinate UTM (48)	
		Longitude (Easting)	*Latitude (Northing)*
MEQ-1	1531	806xxx	920xxx
MEQ-3	1658	809xxx	921xxx
MEQ-4	1140	807xxx	921xxx
MEQ-5	1365	807xxx	920xxx
MEQ-6	1286	810xxx	920xxx

IV. RESULT

The distribution of earthquake hypocenter based on micro-based at cross section AB in figure 5. The vertical cross-section AB through distribution of hypocenter location is associated with the elevation of the northeast to the southwest of micro-earthquake data, so as to indicate the presence of permeable and impermeable zones allegations on each trend hypocenter location. Distribution of the location of the hypocenter forms a stretch of track from the northeast to the southwest. Hypocenter distribution in the northeast are in the mountain areas of geothermal systems Kamojang, hypocenter distribution in the north is at the geothermal system Geothermal Field "Gamma", while the hypocenter distribution in the southwest direction is in the area of Kendal Mountain geothermal system.

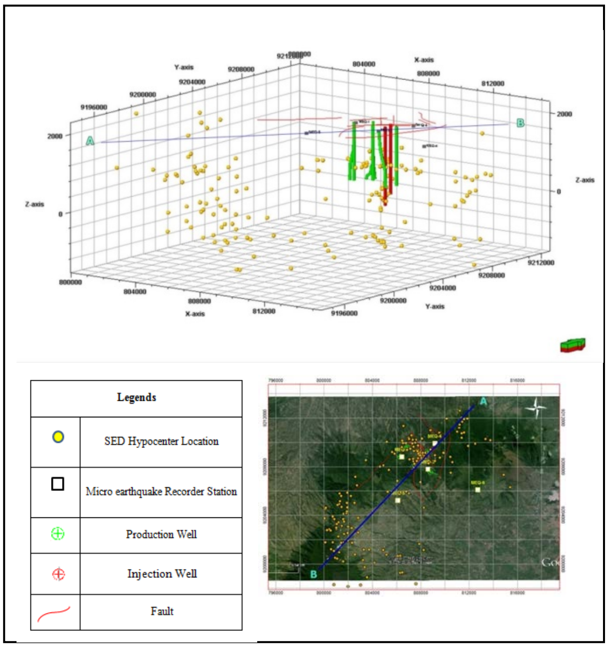

Figure 5 AB's Vertical Cross Section of SED Location Hypocenter

In figure 6, the hypocenter distribution is seen by its hypocenter elevation. The hypocenter distribution which caused of Kamojang's mountain seismic activity was located in elevation at 1460 meters to -1450 meters below mean sea level point and it have the same geothermal system with "Gamma" geothermal field but slightly hypocenter distribution and the less of information about the hypocenter fault it couldn't be explained of the earthquake's focus. Whereas the hypocenter distribution of seismic activity that caused by Kendal's mountain has a fairly extensive geothermal system, it located at an elevation of 2250 meters to -1500 meters below mean sea level point, it indicated by the hypocenter distribution was random and has no pattern activity, that is made possible by a deeper fault or increased by a heat source such as magma which is punctuated by regional tectonic aspects such as the results of a previous study conducted by Anik (2010).

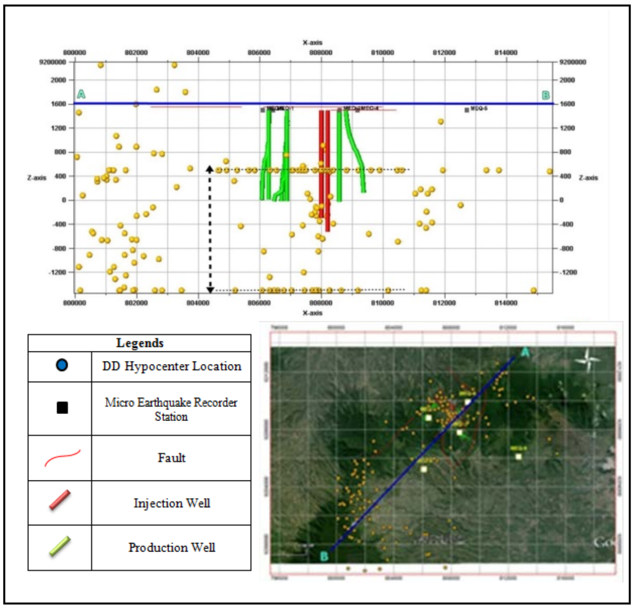

Figure 6 AB's Vertical Cross Section of SED Location Hypocenter viewed by South Direction

The study isn't analysis of the permeable zones outside Geothermal Field " Gamma ". Hypocenter distribution of the vertical cross section AB with SED method chosen the hypocenter distribution in the "Gamma" geothermal field. The hypocenter distribution on " Gamma " geothermal field system is characterized by the distribution of the hypocenter location between the production wells and fluids injection on the cap rock / clay cap estimation impermeable zone at an elevation of over 500 meters and is located at a reservoir zone between 500 meters to -1500 meters below mean sea level point that indicated by the arrow (in view of the hypocenters who have the same elevation). Cap rock is argillic alteration zone or altered rocks zones due to hydrothermal fluid interaction with rocks that change form igneous rock origins into a impermeable rock. This zone is dominated by the influence of the interaction of the fluid in the form of injection that is given by injection in two wells "Gamma" Geothermal Field is characterized by the hypocenter distribution between the injection wells. The existence of transfer activity by fluid injection and production wells in the "Gamma" Geothermal Field reservoir led to some event that is the hypocenter focus is located adjacent to the position of the well in the reservoir. The hypocenter affects the active fault zone in the weak "Gamma" geothermal field is an indication for reservoir management. However, SED method on the micro seismic data can't explain the influence of the focus hypocenter of the existence of active faults in the Gamma" geothermal field because the certain of hypocenter trends were not located in around of active faults , so it is necessary in order to determine the distribution of the hypocenter relocation hypocenter by the presence of active faults .

In figure 7 is a topographical map of "Gamma" geothermal field. The hypocenter distribution by the DD method in cluster 2 "Gamma" geothermal field follows the pattern of fault seems to be the effect of the centralization of some hypocenter, it is caused by the position of the injection wells that are among some of the fault that controls "Gamma" geothermal field, in other words, the injection process on Geothermal Field "Gamma" is associated with the movement of the fault is the source of the micro earthquake.

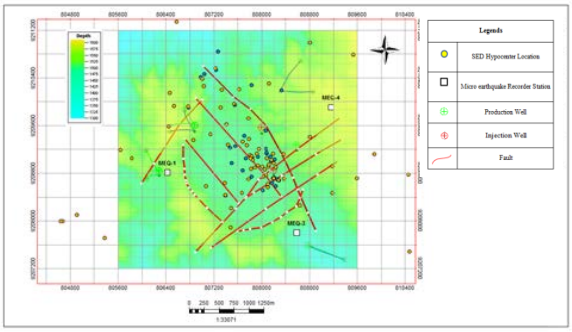

Figure 7 The Hypocenter Distribution of SED and DD on "Gamma" Geothermal Field Topographic Map.

The distribution of the hypocenter distribution used the modeling 3-D of faults lineament in figure 8. The modeling 3-D of faults lineament has been cut several hypocenters in below the "Gamma" geothermal field surface.

At Figure 8 point (a) is shown in modeling 3-D of faults lineament . At figure 7 the point (b), (c) and (d) respectively fault A, B and C are cut the hypocenter distribution around the injection wells. This indication of the fluid activity movement is dominated by fluid injection activities, they are influenced by the presence of the fault. While the figure 8 point (e) which is the fault D hypocenter distribution, it cut around the production wells. This indication of the fluid activity movement is dominated by fluid production activities that affect the existence of the fault.

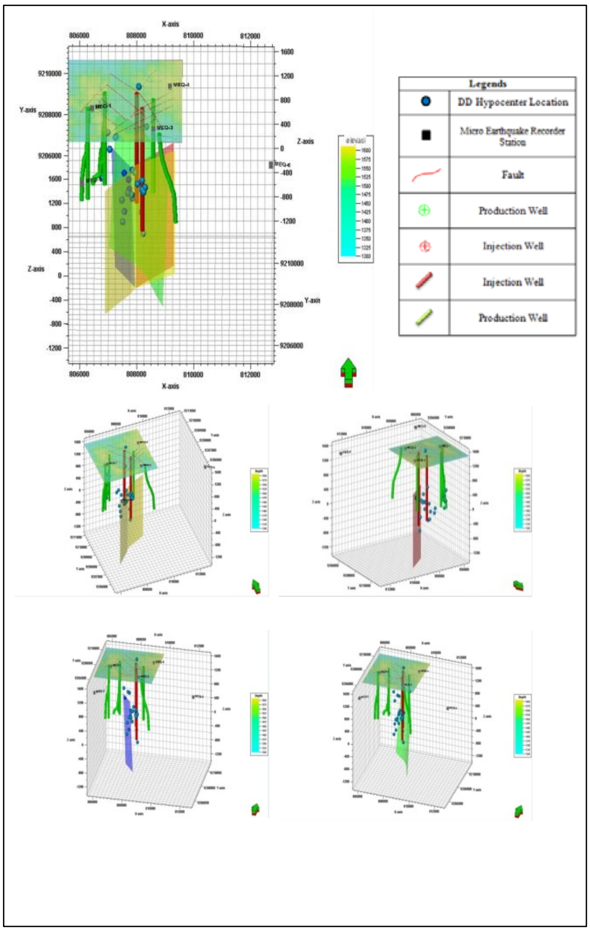

Figure 8 The DD Hypocenter Position 3D vertical fault direction. a) Overall view. b) Fault A (yellow). c) Fault B (red). d) Fault C (blue). e) Fault D (green)

After determinate the hypocenter distribution in the DD method "Gamma" geothermal field, we have to analyze the focal mechanism solutions based on local fault, it is necessary grouping based hypocenters distribution that was around the fault. The hypocenter distribution around the fault is very representative to the reference focal mechanism analysis. The analysis of focal mechanisms is reviewed based on the data arrival time at each hypocenter wave at each micro seismic recording station.

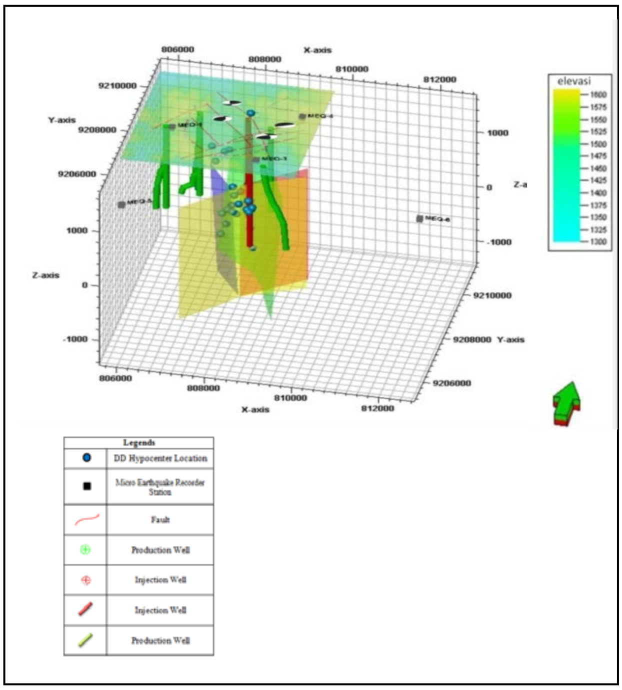

Figure 8 Beachball diagrams in 3-D Hypocenter Distributions.

Based on focal mechanism solutions obtained describe in the diagram balls, fault A, B, and C with reverse-oblique fault types and fault D with strike-slip fault types. As has been discussed previously in DD hypocenter relocation analysis identified the fault, the fault activity around the injection fluid A, B and C show the orientation of the fault with reverse-oblique fault types and fluid production activities surrounding in fault D shows the orientation of the fault with a strike-slip fault type.

Table 2 Fault Indicated of Focal Mechanism Solution

Fault	Focal Mechanism Parameter			Balls Diagram	Fault Type
	Strike (Φ)	*Dip* (δ)	*Rake* (λ)		
Fault A	303.92°	66.52°	27.78°		*Reverse left-lateral oblique*
Fault B	183.67°	8.68°	57.03°		*Reverse left-lateral oblique*
Fault C	207.41°	37.24°	123.91°		*Reverse right-lateral oblique*
Fault D	48.67°	26.52°	162.91°		*Right-lateral strike-slip*

V. CONCLUSIONS

From the research that has been done, it concluded as follows:

1. The distribution of hypocenter associated with each other at the same elevation in the "Gamma" geothermal field geothermal system that located between the production wells and injection wells on the cap rock / clay cap as being impermeable

zone at an elevation of over 500 meters, while the geothermal reservoir estimation permeable zone is located at an elevation of 500 meters to -1500 meters below mean sea level point.

2. The distribution of hypocenter with the DD method "Gamma" geothermal field in cluster 2 follows the pattern of fault. The orientation of the fault is indicated by the focal mechanism solutions at fault identified fault types A and B with the left-lateral reverse fault oblique, fault C with the right of reverse fault-lateral oblique, and D fault with right-lateral fault type of strike-slip, where the position of the well injection was near the fault with reverse-oblique type and position of the production wells located near the fault with strike-slip type.

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