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Microearthquake Characteristics in Darajat Geothermal Field, Indonesia

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ABSTRACT

Microearthquake (MEQ) data from three (3) surveys at Darajat show different seismic characteristics. Two surveys were run in 1997 and the last survey was in 2003. The surveys were conducted under differing conditions including survey duration, number and location of injector wells, different injection rates, stimulation through fluid injection and steam production, with or without start-up of power plants and fixed seismic station versus mobile seismic station configurations.

The microearthquakes from the first survey, induced by additional fluid injection, showed good correlation between events and location of injectors, formed organized swarms, with a relatively high number of events per day, and the event distribution was consistent with known structural trends. The second MEQ survey, with no additional injection program, resulted in a scattered event distribution, lower number of events per day and no clear swarm patterns. The 2003 survey showed a new seismic swarm near a new injector location and other events consistent with known structural trends. Overpressures in the reservoir related to the shutdown of Unit I plant generated a sharp response in the NW and central parts of the field. Instead, the opening of DRJ-21 (the largest producing well) at different wellhead pressures induced only a few earthquakes near the well. The most effective microearthquake triggering mechanism in Darajat is related to the increase of pore pressure in the reservoir either through fluid injection or generation of plant shutdown overpressures.

The moment tensor analysis on selected swarms showed that the dominant mode of failure is left-lateral strike slip on N to NE-orientated sub-vertical faults. The analysis of the moment tensor (including the isotropic components of deformation) suggests predominance of double-couple mechanisms with minor volumetric components. This is consistent with high tectonic stress regimes and triggering of active faults. In particular, the lack of predominant implosive components of the moment tensor, typical of heavily exploited geothermal fields, indicates that Darajat may still be significantly underexploited.

1. INTRODUCTION

1.1. Background

MEQ data have been commonly considered as one of the tools for assessing permeability structures in geothermal reservoirs, to monitor the migration pattern of injection fluids and to determine reservoir boundaries. This paper describes the characteristics of MEQ induced by fluid injection and steam extraction and their application in defining the permeability structures (fractures and faults) and migration patterns of the injection fluid. The use of MEQ data for the monitoring of thermal breakthrough has not been systematically applied yet.

1.2. Location

The Darajat geothermal field is located 150 km southeast of Jakarta, Indonesia, and 35 km southeast of Bandung, the capital of West Java (Figure 1). The average elevation of the field is between 1750 – 2000 meters above sea level. Physiographically, the Darajat field lies within an arcuate, 25 km long mountain range (un-named) in West Java, consisting entirely of Quaternary volcanic rocks. The range includes three well-known thermal areas: Kamojang to the northeast, Darajat in the center and Papandayan in the south.

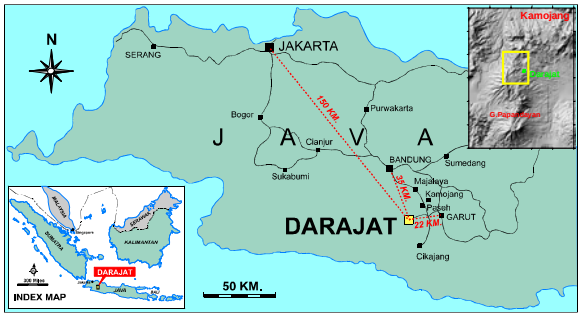

Figure 1: Location of Darajat field

1.3. Source of data

MEQ data were recorded in three surveys conducted in 1997 and 2003 under different field conditions. The various MEQ survey conditions are shown in Table 1.

Table 1: Different condition during MEQ surveys in 1997 and 2003

Survey condition	MEQ Survey		
	April-June 1997	November-December 1997	August-October 2003
Duration (days)	56	31	47
Number of stations	7 (all fixed stations)	7 (all fixed stations)	7 (3 of them are mobile stations)
Number of earthquakes	99	37	127
Number of events per day	1.94	0.45	3
Number of injectors	2 (DRJ-1 & DRJ-7)	1 (DRJ-3)	2 (DRJ-3 & 15)
Total fluid injected (litres)	319,218,620	178,671,267	280,377,254
Activities in the field during survey	Producion,drilling & additional injection (DRJ 7)	Producion,drilling & no additional injection	Production, well testing,shut down of the plant, no additional injection

2. TECTONIC SETTING OF DARAJAT AREA

The Darajat geothermal field is located on the eastern side of Mt. Kendang, which is part of an arcuate range of Quaternary volcanoes. There are numerous eruptive centers within the range and volcanic activity has occurred in historic times such as the 1840 eruption of Mt. Guntur, and Mt. Papandayan in 1772 (Amoseas Indonesia, 1989). The last eruption of Mt. Papandayan occurred in 2003. The broad tectonic setting of the Darajat – Kamojang region is shown in Figure 2. The most significant structural feature is the Kendang fault, which strikes northeast from Darajat

along the axis of the volcanic range, disappearing on the north side of the Kamojang field, 10 kilometers away. To the west of the Darajat field, the Kendang fault is slightly offset by the Gagak fault, which is considered to be a major permeability target (Amoseas Indonesia, 1998). Permeable zones in the reservoir have been interpreted primarily from drilling records and water-loss surveys and supported by Schlumberger Formation Micro Scanner (FMS) log analysis. Major producing zones have been recognized during drilling by sudden losses of circulation and drilling breaks. The surface lineaments show predominant NE – SW and possible NW – SE strikes (Figure 2). FMS logs also show fracture orientations predominantly NE – SW, and less commonly, N – S.

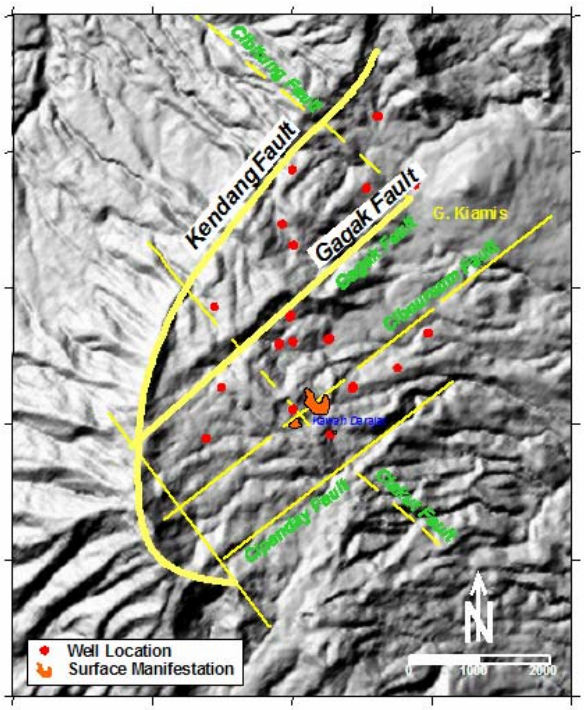

Figure 2: Surface lineaments in the Darajat field

3. MICROEARTHQUAKE CHARACTERISTICS IN DARAJAT AREA

3.1. Station Configurations

The first and second survey in 1997 occupied seven (7) stationary stations, with common installation sites. In the 2003 survey, several stations, out of the total 7 stations, were moved to the eastern side and the northwestern side of the field to provide better angular coverage to the MEQ locations (Figure 3). Maximum seismic network aperture in the 1997 survey was 4.7 km, while in the 2003 survey it was 5.5 km. The greater network aperture in the 2003 survey contributed to increase the depth resolution of the MEQ locations.

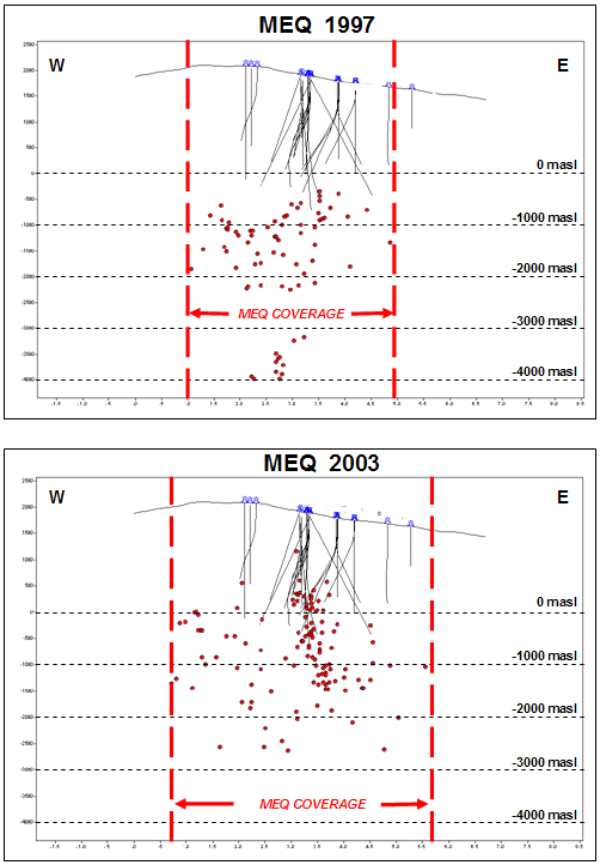

Figure 3: Different MEQ coverage in 1997 and 2003 along W – E cross section

3.2. Microearthquakes induced by fluid injection & steam extraction

Additional fluid was injected during the first survey in well DRJ-7, which is located in the center of the field. This caused an immediate response of events in the northwestern side of the field (Figure 4). The events formed an organized swarm oriented NE – SW and occurred at elevations of 500 to 2000 m bsl. The deepest events, down to 3500 m bsl, occurred in the center of the field. The second MEQ survey, which was conducted without additional injection and immediately after the simultaneous start-up of all wells in the field, did not show seismic swarms. Instead, a scattered pattern of events occurred between sea level and 3000 to 4000 m bsl in the center and at shallower elevation in the southeastern part of the field (Figure 5). Regular injection in a new well (DRJ-15) during the 2003 MEQ survey induced a large number of events in swarms, which propagated in a NE direction. The MEQs occurred from sea level down to 1500 m bsl and were focused along a NE – SW trending structure (Figure 6).

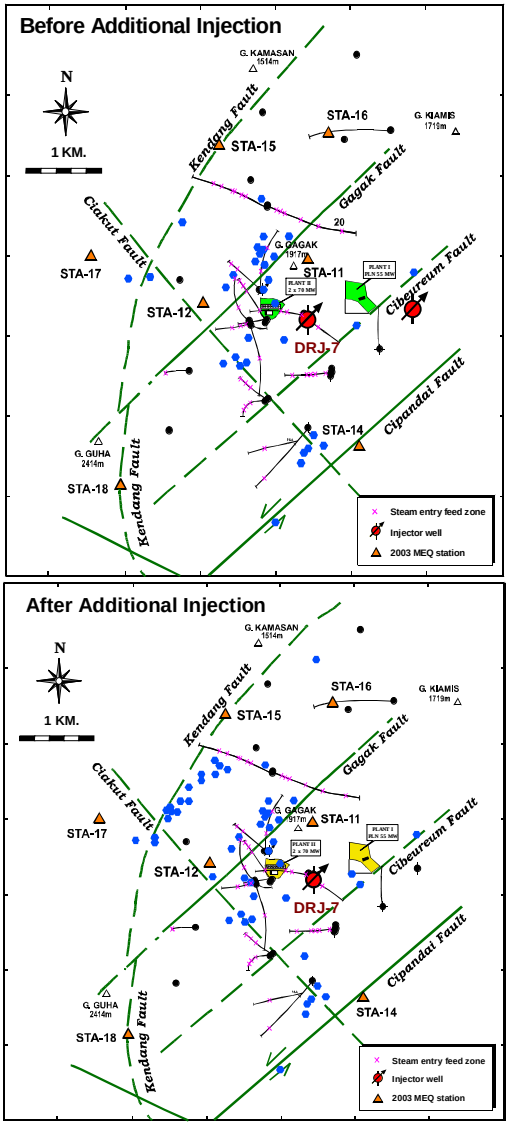

Figure 4: MEQ distribution before and after additional injection through DRJ-7 in 1997 survey

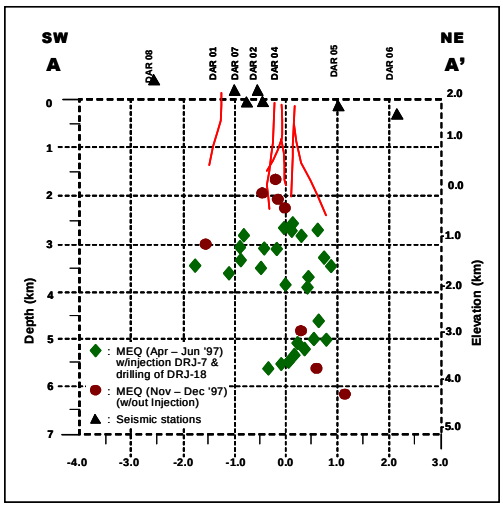

Figure 5: NW – SE cross section through center of the field show MEQ distribution up to 4 km m bsl in 1997 survey

3.3. Microearthquakes induced by shut down of plant in 2003 survey

The shutdown of Darajat Unit I power plant induced less-focused seismic patterns. Orientation was NW – SE, at elevations from 500 to 1500 m bsl in the northwestern and central parts of the field (Figure 7).

3.4. Moment Tensor Analysis

The moment tensor provides a general description of the equivalent force system of an earthquake. It expresses the relative strengths and orientations of the three force dipoles (pressure, tension and intermediate) of an earthquake.

Different approaches were applied for 1997 and 2003 data. Selected swarms based on the similarity of the waveforms from 1997 data set were used for the calculation of composite (double-couple) focal mechanisms (Geosystem, 1997). The selected swarms were located in the central part and in the NW area of the Darajat field. The result of focal mechanism from the swarms in the central area indicated a left-lateral strike slip movement along a NE trending fault (strike 65°) and in the NW area the results were still consistent with a left lateral slipping fault trending in the NE direction (strike 63°) (Figure 8).

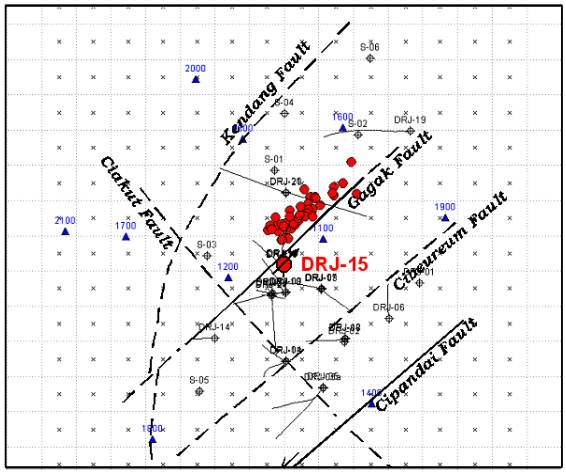

Figure 6: MEQ caused by injection DRJ-15 during 2003 survey

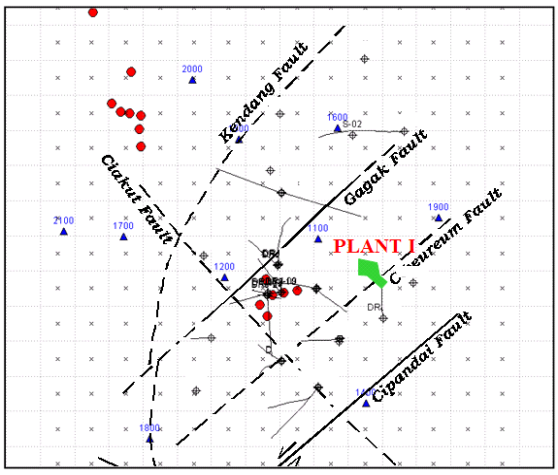

Figure 7: MEQ induced by shutdown of power plant I

The 2003 MEQ data were also selected based on the similarity of waveforms by calculating the cross correlation matrix of the recorded waves (around the P onset time) and

selecting the events with correlation coefficient greater than 55% and with overall good signal/noise ratio. Two swarms were finally chosen for the moment tensor analysis, i.e. the swarms related to injection in DRJ-15 and the swarm related to the shutdown of Unit I plant (Figure 6 and Figure 7 respectively).

For the 2003 data, moment tensor analysis, which involves volumetric changes (i.e. opening and closure of cavities), was applied. The symmetric moment tensors was obtained by fitting *P*-, *SH*- and *SV*-phase polarities and *P:SH*, *P:SV*, and *SH:SV* amplitude ratios using linear-programming methods (Julian, 1986; Julian and Foulger, 1996).

Eight (8) moment tensors were calculated for the first swarm (Figure 9). The P (compression) axes are mostly horizontal and orientated approximately NW-SE whilst the T (tension) axes vary from sub-horizontal and NE trending to sub-vertical. The overall NE orientation of the swarm and the known location of the Gagak fault in this area, shows evidence that the fault is activated in a NE orientation.

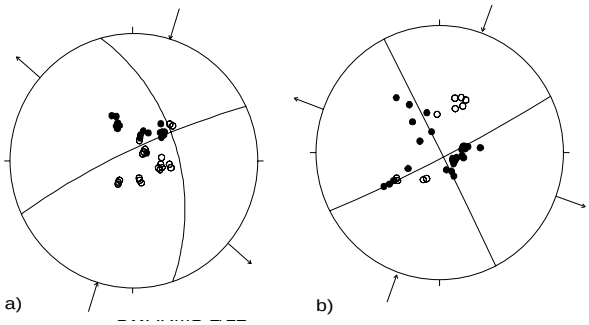

Figure 8: Composite fault plane solutions for the swarms recorded in central (a) and NW area (b) of Darajat (1997 data set). Solid circles represent compression (up) and open circles tension (down).

Three (3) moment tensors could be obtained from the second swarm which relates to the shutdown of Unit I plant (Figure 10). All moment tensors had P axes orientated sub-horizontally and trending NW-SE and T axes orientated sub-horizontally and trending NE. This result is consistent with the first swarm.

Figure 11 shows the results on a "source-type" plot (Hudson et al., 1989). This plot depicts the moment tensor in a form that is independent of source orientation. All simple shear-faulting mechanisms, whether strike-slip, normal or reverse, plot at the central point labeled DC (= double couple). The vertical coordinate k ranges from –1 (–V) at the bottom to +1 (+V) at the top of the plot, and indicates the magnitude and sign of the volume change involved. Mechanisms with explosive (volume increase) components lie above the horizontal line through the central point DC, and mechanisms with volume decreases lie below it. Pure, spherically symmetric explosions plot at point +V and pure implosions plot at –V. The left-right coordinate T ranges from –1 on the left (+CLVD) to +1 on the right (–CLVD) side of the plot, and indicates the type of shear involved, with simple shears lying on the vertical line T=0 through the central point DC and more complex pure shears lying to the right or left of this line. In particular, opening (closing) tensile cracks, which involve both shear and volumetric deformation, lie at the point +Crack (–Crack). The points ±CLVD and ±Dipole represent mathematically idealized force systems whose possible physical significance is not clear, but probably related to the opening and closure of cracks in the presence of compensating fluid flow.

Most of the events generated from DRJ-15 (B, C, D, E, F and G) form a coherent array extending from the DC point towards the +Dipole point (Figure 11, top). The further these events plot towards the +V point, the larger their explosive component. Events B, D and G clearly have significant explosive components. These six events are each most simply interpreted as predominately shear-faulting events on N- to NE-orientated planes, with an additional explosive component (volume increase) related to the injection of fluids in DRJ-15. Event A is consistent with a similar interpretation, but with an implosive component. Only event H appears to have a different mechanism and this is consistent with the opening of a sub horizontal fracture.

The characteristics of the few selected events generated by the shut down of power plant Unit I are shown by the source-type plot of Figure 11 (bottom). Events A and B display characteristics similar to the swarm generated by injection in DRJ-15 and to this generating mechanism should be related. On the other hand, event C, which was located towards the NW end of the swarm, is significantly different from events A and B. In the source-type space event C plots on the right-hand side of the diagram, and has a small explosive component. Its moment tensor could be interpreted as the sudden closure of a pressurized crack, accompanied by an increase in pressure within it. Since event C was generated as a consequence of the shut down of power plant Unit I, which apparently produced an overpressure in the reservoir, this hypothesis seems to be consistent.

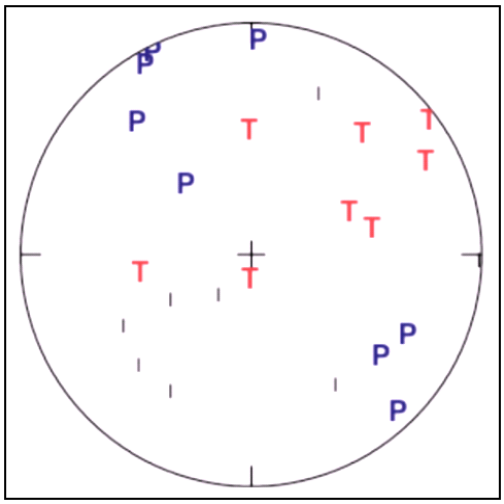

Figure 9: Equal area upper-hemisphere plot showing pressure (P), tension (T) and intermediate (I) axes of the moment tensors for the earthquakes induced by injection in DRJ 15.

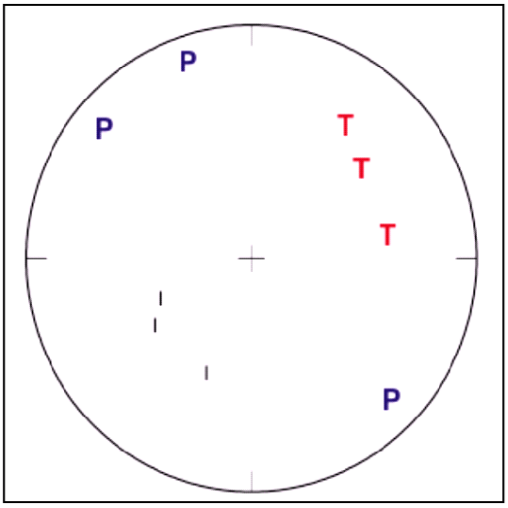

Figure 10: Equal area upper-hemisphere plot showing pressure (P), tension (T) and intermediate (I) axes of the moment tensors for earthquakes from swarm induced by shut down of power plant I

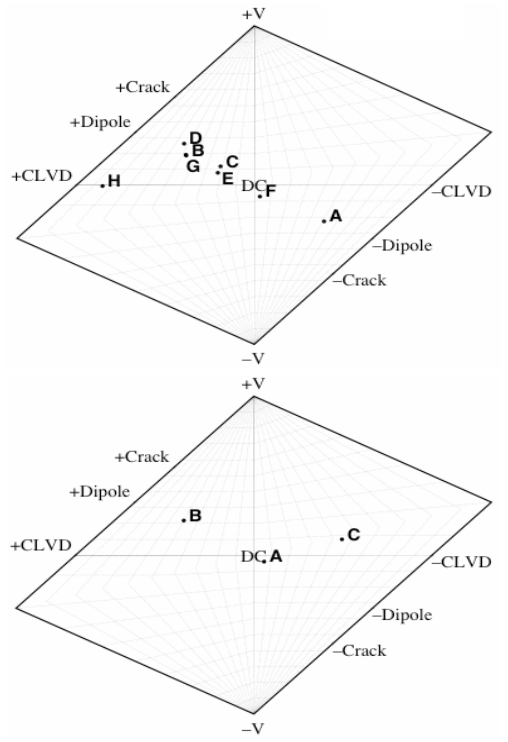

Figure 11: Source-type plot depicting moment tensors of earthquakes in a manner independent of source orientation (top: seismic swarm induced by injection in DRJ-15; bottom: swarm induced by shut down of power plant I).

4. DISCUSSION

The lack of seismic activity during the second 1997 survey may confirm the hypothesis regarding fluid-related seismicity recorded in the first 1997 survey. During this survey, a well-defined MEQ alignment was observed in the N – NW part of the field and this activity may have been related to additional injection into well DRJ-7, which is located in the center of the field. The scattered seismic activity in the center can also be interpreted as related to the injection of fluids even if it is not defining clear structural trends.

The total absence of seismicity in the NW area during the second 1997 survey, when no significant new injection took place, is a confirmation of the fluid triggering mechanism of those microearthquakes. The deep events, which occurred in the central part of the field, may also confirm the hypothesis of a combination of natural and production induced seismic activity in this part of the field (Geosystem, December 1997). The other factors that may have affected the occurrence and distribution of events are the location of injectors, the total amount of fluid injected in the ground and the field disturbances during the survey (Table 1).

In 2003, the response of seismicity to the new injector (DRJ-15) was clearer than for the first 1997 survey. A fairly large number of MEQs occurred in the first days following the beginning of injection, with up to more than 10 events per day. The events were distributed along a NE trending structure that coincides with the known Gagak Fault location. The distribution of this seismic swarm should indicate the migration paths of the injected fluids along the Gagak fault. In particular, the trend of MEQs tends to propagate in the NE direction rather than SW suggesting the possible existence of a permeability barrier. Tracer data support this hypothesis since tracers injected in DRJ-15 are normally not recovered from the wells in the centre of the field.

The start of well testing for DRJ-21 showed a minor seismic response and only a few events occurred near the bottom of the well. These microearthquakes can be related to a sudden local decrease of the steam pressure.

The response of MEQ activity following the shutdown of the Unit I plant was consistent even if less clear in terms of related tectonic structures, than the injection-triggered events. The events occurred simultaneously in the center and northwestern part of the field and formed a less defined NW – SE alignment.

Moment tensor analysis shows that the greatest principal stress is approximately NW and sub-horizontal. However, this orientation is commonly orientated a few tens of degree oblique to the orientation of the Gagak fault as inferred from the hypocenter distribution and the surface lineaments. This suggests that the individual events may have occurred on en echelon faults orientated somewhat more northerly than the epicentral zone as a whole.

Other than confirming the existing permeability structures, the integrated MEQ distribution from all surveys also provided additional permeability trends in other parts of the field (Figure 12). This information greatly assisted in locating the well targets and has successfully provided high flow rate wells.

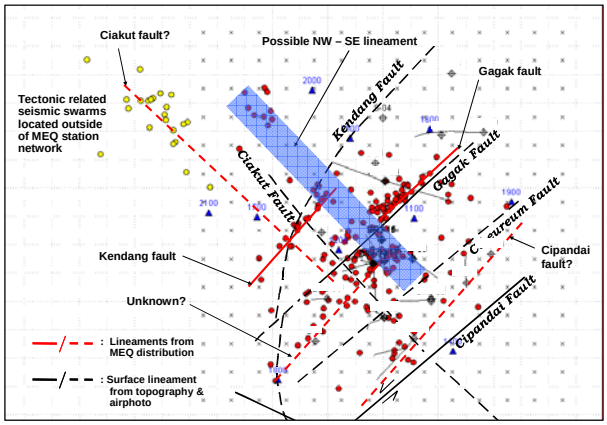

Figure 12: Integrated structure map based on MEQ, air photo & topography

5. CONCLUSIONS

A larger number of events and more organized seismic swarms occurred when fluid injection took place during the MEQ surveys. The sharp decrease of steam extraction (i.e. overpressure in the reservoir due to the shutdown of the plant) showed an immediate response in terms of number of induced MEQs distributed over a wide region. The opening of a high flow-rate production well (i.e. sharp decrease of pressure) showed a minor response in terms of seismic activity. Pore pressure increase in the reservoir (i.e. fluid injection or plant shutdown overpressure) represents the most effective mechanism leading to the generation of microseismic activity in the Darajat geothermal field.

The moment tensor analysis on selected swarms indicates that the dominant mode of failure is left-lateral strike slip on N to NE orientated sub-vertical faults. Shear deformation is predominant (i.e. double-couple) with minor volumetric components which are consistent with the generating mechanisms (volume increase or overpressures due to injection of fluid in DRJ-15 and shut down of power plant Unit I, respectively). The predominance of shear components of the deformation indicates triggering of movement along active faults in high stress regimes rather than significant volumetric changes of the reservoir. Implosive moment tensor components in particular are typical of highly exploited fields such as The Geysers (Ross et al., 1999), a condition which does not seem to be yet developed in Darajat.

The analysis of MEQ data in Darajat geothermal field allows a better management of the reservoir through an appropriate selection of injector locations, a better understanding of the microseismicity source processes and their relationship with the generating causes, the determination of fluid migration paths and the definition of zones of enhanced permeability.

6. ACKNOWLEDGEMENT

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