PROCEEDINGS, 48th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 6-8, 2023
SGP-TR-224

Fracture Structure of the Kakkonda Geothermal Field, Analyzed Microearthquake Data of the Nation-wide Seismic Network

Mituhiko Sugihara

6-64-12, Kenkyugakuen, Tsukuba, Ibaraki, 305-0817, Japan

mituhiko.sugihara@gmail.com

Keywords: nation-wide seismic network, microearthquake, geothermal reservoir, Kakkonda geothermal field

ABSTRACT

Microearthquake activity has been reported to be one of the potential indicators of fractured structure in many geothermal fields. Typically, microearthquake activity is observed by the local seismic network which was deployed at the geothermal field. In Japan, we can effectively use the nation-wide seismic network, seismic station of which are basically deployed in the 20-km mesh. Hypocenters of earthquakes with magnitude greater than 1.0 are routinely determined to the third decimal place in degree both in latitude and in longitude. The resolution of the hypocentral location is too low to delineate fracture structure. We, however, can relocate microearthquake hypocenters accurately enough to delineate fracture structure. All the digital data from the nation-wide networks have been available for all researchers since June 2002. Generally, microearthquake activity in geothermal fields are characterized by many low magnitude events. Most microearthquakes are analyzed to be point sources. Only a few larger events have the detectable source faults. The nation-wide seismic network provides us the opportunity for re-analyzing the long-term accumulated data. In September 2022 a microearthquake with a magnitude of 3.5 occurred at the Kakkonda geothermal field, in Japan. It is the largest event at the field. We made waveform cross correlation and high precision relative relocation of both background seismicity and seismicity triggered by the largest event. We also developed a kinematic source model for the largest event, The source model as well as accurate hypocenter relocations was effective to image the fracture structure of the geothermal reservoir.

1. INTRODUCTION

Seismic activity has been reported in many geothermal fields and is believed to be one of the potential indicators of fracturing within a geothermal reservoir (Majer and McEvilly, 1979). We have been observing microearthquakes in the Kakkonda geothermal field, northeast Japan (Figure 1), since 1982 (Ito and Sugihara, 1987); our studies have revealed that the outline of the hypocenters of microearthquakes indicates that part of geothermal reservoir where the rocks are highly fractured and the hydrothermal circulation of the geothermal fluid is dominant (Kanesshima et al., 1988, Tosha et al., 1993, Sugihara et al., 1998, Tosha et al., 1998). Aside from that, measurements and control of the geothermal crack reservoir has been successfully performed in a hydrothermal area by employing the downhole AE technique (Niitsuma et al, 1987, Moriya et al., 1994).

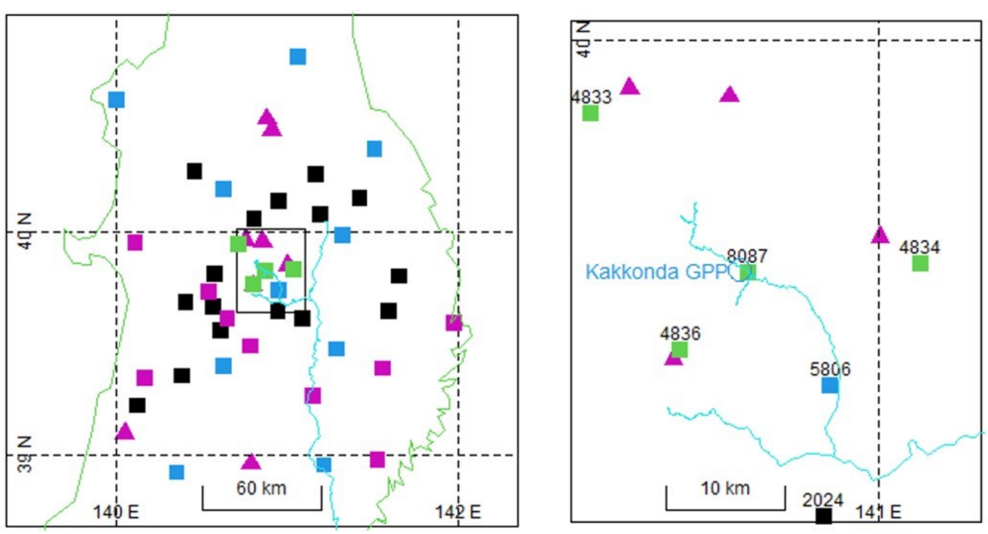

Figure 1: (left) The seismic stations where P-time and/or S-time were read when the M3.5 microearthquake occurred on September 8, 2022. Blue squares denote the JMA nation-wide stations, Black squares denote the NIED nation-wide stations, Red squares denote regional stations, and green squares volcano monitor stations. The black rectangle indicate the area of the right map. (right) Seismic stations around the Kakkonda geothermal field. Red triangles indicate active volcanoes.

Sugihara.

The two studies merged into a project. New Energy and Industrial Technology Development Organization (NEDO) started the project "Deep-Seated Geothermal Reservoir Survey" in 1993. This project consists of a well WD1 and several deep exploration activities in the Kakkonda geothermal field, Japan. There are very few effective exploration techniques for deep geothermal reservoirs. Thus, a micro-earthquake monitoring and a VSP utilizing acoustic emissions from a drill-bit are employed to explore the deep reservoir in this project (Takahashi et al., 1995). In 2014 NEDO started another project to understand the nature of the possible supercritical geothermal system. The low resistivity anomaly is located in an eastern area, slightly distant from the WD-1a well. The National Institute of Advanced Industrial Science and Technology (AIST) deployed a microseismic monitoring network in 2017 to explore seismic structures in and around the low-resistivity anomaly (Okamoto et al., 2022). Their result is a great achievement of a well-designed particular seismic network. On the other hand, to what extent can information of fracture structure be extracted from publicly available data? In this study we tried a few methods to infer the fracture structure of geothermal system using the nation-wide seismic network.

2. NATION-WIDE SEISMIC NETWORK>

More than two thousand permanent stations are included in seismic observation networks in Japan. Those observation stations belong to several networks; the nation-wide network operated by the Japan Meteorological Agency (JMA), the nation-wide network operated by the National Research Institute for Earth Science and Disaster Prevention (NIED) and subregional to local networks operated by national universities and other institutions (Ohtake and Ishikawa, 1995), Some stations are also added to the total network from decades of local volcanic network.

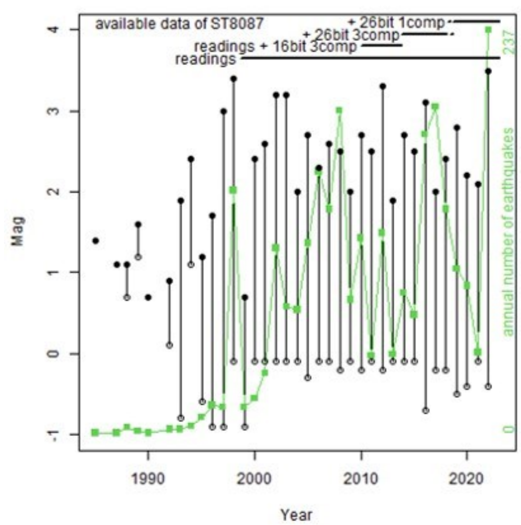

Figure 2: Green line shows change in the annual number of earthquakes which occurred near the Kakkonda geothermal field (the distance from the Kakkonda GPP is less than 5 km). Black closed circles and open circles indicate largest magnitude and smallest magnitude in the year. The numbers are counted in the catalog of JMA.

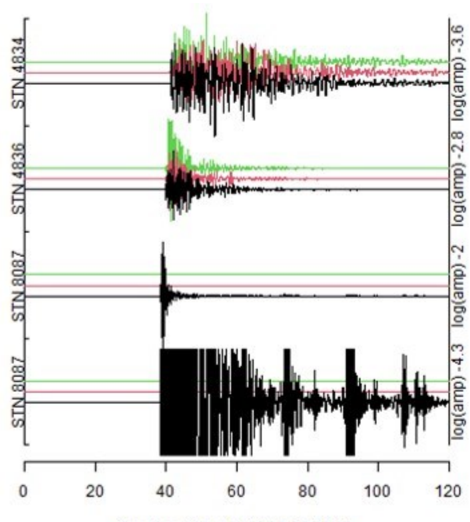

Figure 3: The seismograms of the M3.5 event of September 8, 2022 at three stations (ST4834, ST4836, and ST8087).

The networks are basically independent of one another, but they carry out on-line exchange of observation data to some extent. Currently, several hundreds of hypocenters per day are located by JMA. JMA developed a new method to identify multiple concurrent earthquakes for Seismological Bulletin of Japan and applied this method to earthquakes in the vicinity of Japan. The probability of detection of earthquakes compared with the bulletin is almost 100 % (M>=1.0) at inland and shallow areas (Tamaribuchi et al., 2016). All digital data from these networks and earthquake catalogs are available through internet for all researchers. The seismic activity in the Kakkonda field is shown in Figure 2. The activated seismicity in 1988 is caused from magma and/or magmatic water intrusion under the Iwate Volcano, 13 km east of the Kakkonda field (Doi et al., 2000). Generally annual number of events and magnitude range have been same level from 2002 onward. The seismic station ST8087 started operation in 1999, and has provided digital waveform data since 2010 (Figure 2). Comparing the seismographs (Figure 3) importance ST8087 is predominantly important for seismic study in the Kakkonda field.

3. DATA AND RESULTS

3.1 The seismic swarm of January 16, 2016

The seismic station 8087 have been healthy and provides 26-bit 3 component seismograms during (1) the period from October 8, 2014 to February 3, 2019 and (2) the period from May 22, 2019 to August 30, 2019. Figure 4 shows the typical seismograms of the seismic swarm, which occurred on January 16, 2016. Six events were detected and located by JMA; however, more events can be seen in seismogram of the station 8087 (Figure 4).

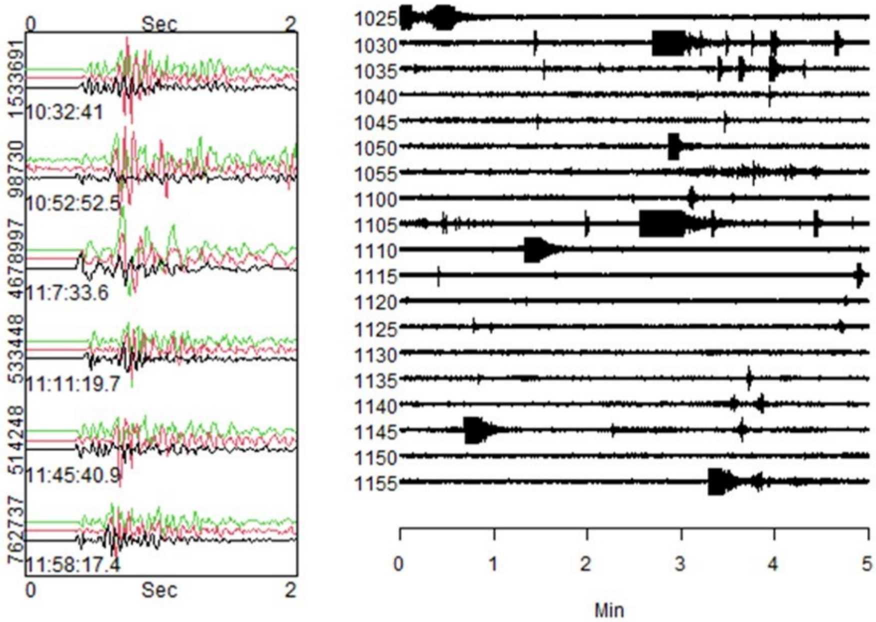

Figure 4: Plot of seismograms of the swarms occurred on January 16, 2016 in the Kakkonda geothermal field.

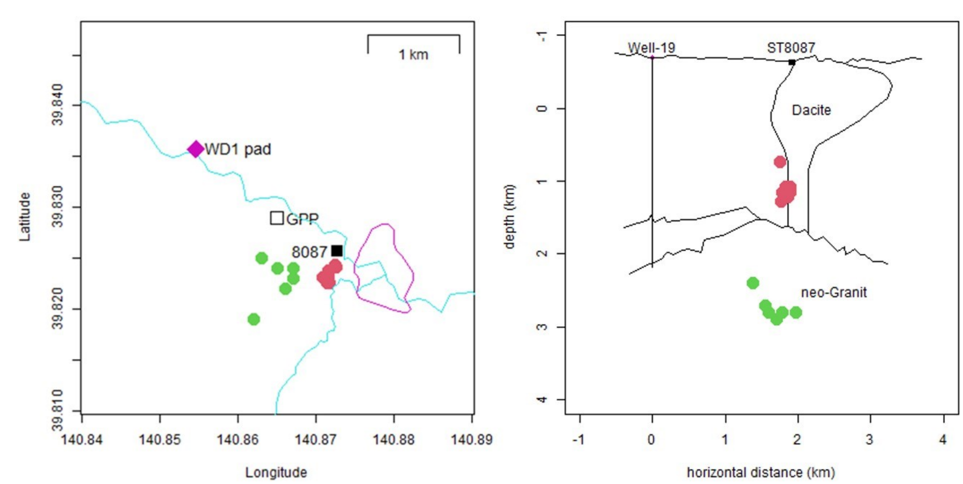

Figure 5: (left) Epicenter distribution of the swarm which occurred on January 16, 2016. Green solid circles indicate the location determined by JMA. Red circles indicate relocated solutions. (right) Cross-section of hypocenters along the NW-SW axis. Well-19 was drilled from the same drillpad as WD1.

Sugihara.

The triaxial hodogram method makes it possible to determine source locations by a single station data. Measuring the P-wave arrival direction and the P-S arrival time delay, then follow the assumed ray path from the observation point to the source point. Figure 5 shows the result.

Doi et al. (1995) pointed out that the microearthquake distribution shows the decrease in distribution of fractures below the cordierite isograd, which is nearly coincides with the upper boundary of the Kakkonda neo-Granit. Relocated seismic sources look inside the fractured zone (Figure 5).

3.2 The largest M3.5 event and the aftershocks in September, 2022

Nearly all large earthquakes are followed by a sequence of smaller earthquakes, known as aftershocks, which are apparently related to the fault plane that slipped during the event. The largest earthquake in the Kakkonda field is the M3.5 event of September 8, 2022 (Figure 2). The M3.5 event followed typical aftershocks (Figure 6). The distribution of aftershocks is often used to infer the fault area. In general, the fault area is estimated from the extent of the aftershock zone after 1 to 2 days (Lay and Walace, 1995).

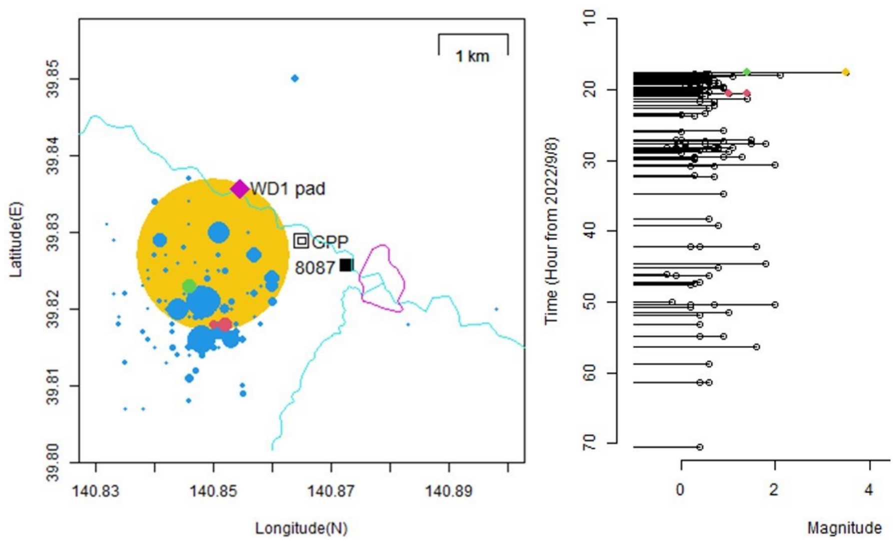

Figure 6: (left) Epicenter distribution of the earthquake in Kakkonda for the period of 48 hours after the M3.5 main shock on September 08, 2022. The main shock is also indicated by yellow solid circle. A green solid circle indicates the second aftershock, and two red circles indicate a pair of similar earthquakes. Each circle indicates the size of the fault size inferred from the empirical relation between Magnitude and the fault area scale (Lay and Wallace, 1995). (right) Event magnitude as a function of time.

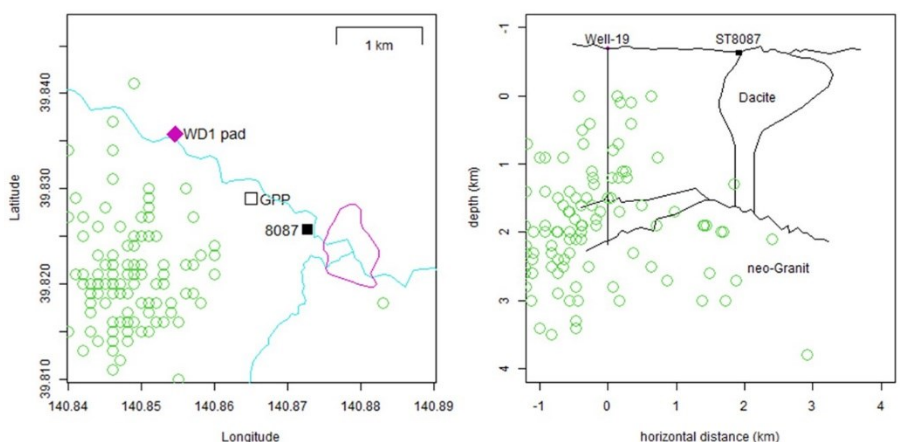

Figure 7: (left) Epicenter distribution of the aftershocks which occurred for the period of 48 hours after the M3.5 main shock on September 08, 2022. Green open circles indicate the location which were routinely determined by JMA to the third decimal place in degree both in latitude and in longitude. Cross stripes appearance is caused by the insufficient accuracy. (right) Cross-section of hypocenters along the NW-SW axis. Well-19 was drilled from the same drillpad as WD1.

Generally, the hypocenter distribution used to show an en echelon arrangement of microearthquake swarms trending NNE-SSW along the Kakkonda river which flows in a NW to SE direction. JMA detected and located 130 aftershocks, Roughly the aftershocks occurred in the usual seismic zone.

Unfortunately, horizontal two components of the 8087 station have not been observed since August 31, 2019. Therefore we cannot apply the triaxial hodogram method to relocation. We applied other methods to analyze the M3.5 event and the aftershocks to study fracture structure of the Kakkonda field.

4. DISCUSSION

In Japan, we can effectively use the nation-wide seismic network, seismic station of which are basically deployed in the 20-km mesh, for such analysis. Hypocenters of earthquakes with magnitude greater than 1.0 are routinely determined to the third decimal place in degree both in latitude and in longitude. The resolution of the hypocentral location is too low to delineate fracture structure. We, however, can relocate microearthquake hypocenters accurately enough to delineate fracture structure. Source location methods can also be categorized into absolute location and relative location types. The absolute location method estimates the individual location of seismic sources. However, small detection errors caused by background noise greatly affect the estimation of absolute location. Moriya et al. (1994) applied the precise relative location method which had been proposed Poupinet et al. (1984). They identified earthquake doublets as a pair of similar earthquakes and evaluate their arrival-time difference more accurate than sampling rate. We found an earthquake doublet in the aftershocks of the M3.5 event and evaluated arrival-time differences. (Figure 8).

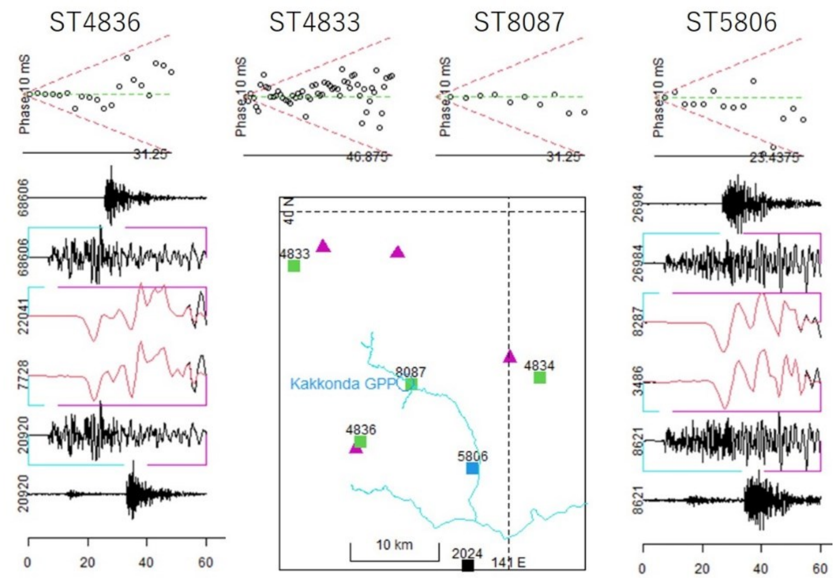

Figure 8: The phases of the cross-spectrum of the doublet are shown on the first line. Red dotted lines indicate the time delay of +-10 milli-seconds. Observed similar waveforms of the doublet were shown for the ST4836 and the ST5806.

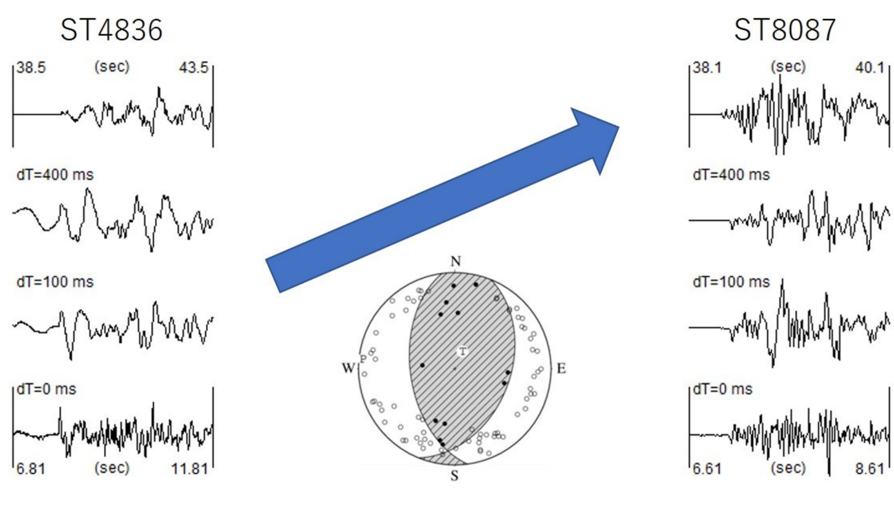

Figure 9: Waveforms of the M3.5 event are shown on the top row. Waveforms of the empirical Green's function are shown on the bottom row. Synthesized waveforms are shown in the middle rows. Apparent rupture duration time is longer at ST4836 than at ST8087, therefore the rupture direction is estimated as the blue arrow. The fault plane solution of the M3.5 event was determined by JMA. First motion polarities of the P-wave are indicated in the lower hemisphere projection.

Sugihara.

Another potential method uses empirical Green's function (Lay and Wallace, 1995). Sugihara et al. (1998) applied the method to the M0.6 event of the swarm which occurred in the Kakkonda field. The M3.5 event can be deconvolved with the M1.4 event (Figure 9).

5. CONCLUSIONS

In Japan, we can effectively use the nation-wide seismic network, seismic station of which are basically deployed in the 20-km mesh, for such analysis. Generally, it is too sparce to analyze fracture structure in geothermal fields. Some stations, however, are also added to the total nationwide network from decades of local volcanic network. Therefore, we can make use of the digital waveform data recorded at the seismic station which situated in a few kilometers from the geothermal field and study the fracture structure of the geothermal field.

ACKNOWLEDGEMENT

We used the JMA Unified Earthquake Catalog available at http://www.hinet.bosai.go.jp/?LANG=en (last access on 29 January 2023), and seismograms from Hi-net by NIED available at http://www.hinet.bosai.go.jp/?LANG=en (last access on 29 January 2023). Part of this work was done using R (https://www.rproject.org/, last access on 31 March 2022).

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