

Deep Fracture Structure of the Otake Geothermal Field, Japan, Inferred by Rupture Behaviors of the Largest Event at the Field

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ABSTRACT

There are geothermal systems in the steep slopes around the Shishimuta subsiding zone, which was originated of a caldera volcano. The Otake geothermal field, Japan, is located at the southern margin of the Shishimuta subsiding zone. The geological structure in the Otake geothermal field is characterized by the presence of NW-SE trending fault systems. In August 2025 an earthquake with a magnitude of 4.9 (USGS scale) occurred at the Otake geothermal field. It is the largest event at the field. We made waveform cross correlation and high precision relative relocation of seismicity triggered by the largest event using publicly available seismic data. In Japan, we can effectively use the nation-wide seismic network, seismic station of which are basically deployed in the 20-km mesh. Generally, it is too sparse to analyze fracture structure in geothermal fields. A local volcanic network, however, is working near the Otake field. Therefore, we can make use of the digital waveform data recorded at the seismic station which situated in a few kilometers from the Otake field and study the fracture structure of the field. An empirical Green's function analysis was applied to the largest event of the seismicity, and revealed particular characteristics of the fracture structure in the deeper part of the geothermal reservoir. We developed a kinematic source model for the largest event, The source model as well as accurate hypocenter relocations was effective to image the deep fracture structure of the geothermal reservoir. Please be very careful to use styles throughout the document, so that all the papers will have a similar appearance.

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. Especially for deep geothermal reservoirs, there are very few effective exploration techniques. Thus, micro-earthquake monitoring methods have been employed to explore the deep reservoir. We had been observing microearthquakes in the Hoho geothermal field, northeast Japan (Figure 1b), for ten years since 1982 (Ito and Sugihara, 1985, Sugihara et al., 1991); our studies 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 (Kaneshima et al., 1989). In 1984 we detected a microearthquake swarm at a depth (Sugihara and Ito, 1984) in a steep slope around the Shishimuta subsiding zone. However, such event was scarcely observed for the 1980's measurements in the Hoho geothermal field.

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 August 2025 a microearthquake with a magnitude of 4.9, whose source fault might reach the deep fracture, occurred at the Otake geothermal field. It was the 2nd largest event in Japanese geothermal fields. Asanuma et al. (2014) discussed the 1st largest event seismostatically. We made waveform cross correlation and high precision relative relocation of both background seismicity and seismicity triggered by the M4.9 event.

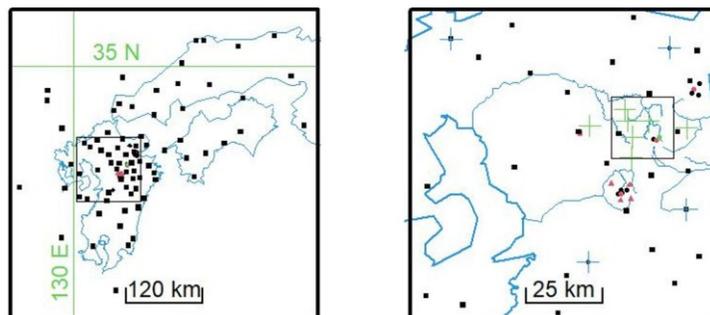


Figure 1: (left) The seismic stations where P-time and/or S-time were read when the M4.9 microearthquake occurred on August 7, 2025. The black rectangle indicate the area of the right map. (right) The seismic stations in the northern part of the Kyushu, Japan. The black rectangle indicates the area of the Figure 2 (left) and the Figure 5 (right).

2. GEOLOGY

There are geothermal systems in the steep slopes around the Shishimuta subsiding zone (Tosha et al., 2021), which was originated of a caldera volcano (Kamata et al., 1988). The Otake geothermal field is located at the southern margin of the Shishimuta subsiding zone (Yano et al., 1987). The geological structure in the Otake geothermal field is characterized by the presence of NW-SE trending fault systems (Fujii et al., 2015).

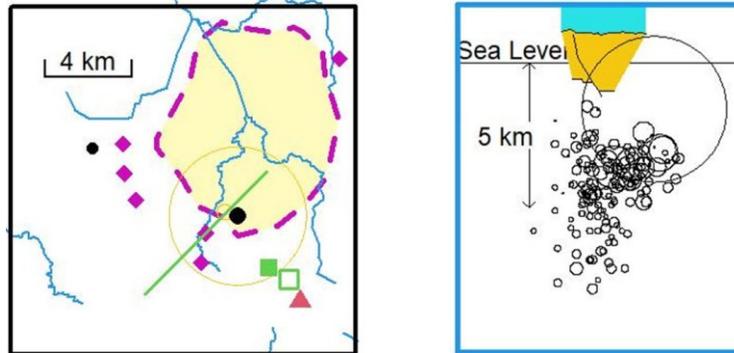


Figure 2: (left) Shishimuta caldera and six geothermal power plants which are shown by magenta diamonds. A green solid rectangle is the station v.kja2 and a green open rectangle is the station v.ksgm. A green NE-SW line shows the cross-section line of the right figure. (right) The cross-section, which pass through the Otake GPP, showing the geology and hypocenters of the M4.9 event and the aftershocks.

3. SEISMIC OBSERVATION

More than two thousand permanent stations are included in seismic observation networks in Japan. Those observation stations belong to one of the two nation-wide networks, several subregional networks or several tens of local volcanic networks. 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 the Japan Meteorological Agency (JMA). All digital data from these networks and earthquake catalogs are available through internet for all researchers. Using the data Sugihara (2023) studied the fracture structure of the Kakkonda geothermal field, and Sugihara (2025) studied the Ogiri geothermal field.

The broad band nationwide seismic network (F-net) as well as the high-sensitivity nationwide seismic network (Hi-net) have been established and operated by National Research Institute for Earth Science and Disaster Prevention (NIED). There are four F-net stations in the northern part of the Kyushu island (Figure 1, right).

In Japan, we can effectively use the nation-wide seismic network, seismic station of which are basically deployed in the 20-km mesh. Generally, it is too sparse to analyze fracture structure in geothermal fields. A local volcanic network, however, is working near the Otake field. Therefore, we can make use of the digital waveform data recorded at the seismic station which situated in a few kilometers from the Otake field and study the fracture structure of the field. The seismic station v.kja2 is the nearest to the Otake field (Figure 2 left). The seismic station v.ksgm is also near to the Otake field, however, it has been unhealthy since 2023 April 28th (Figure 3 left). Both the seismic station belongs to the JMA Kuju volcano network.

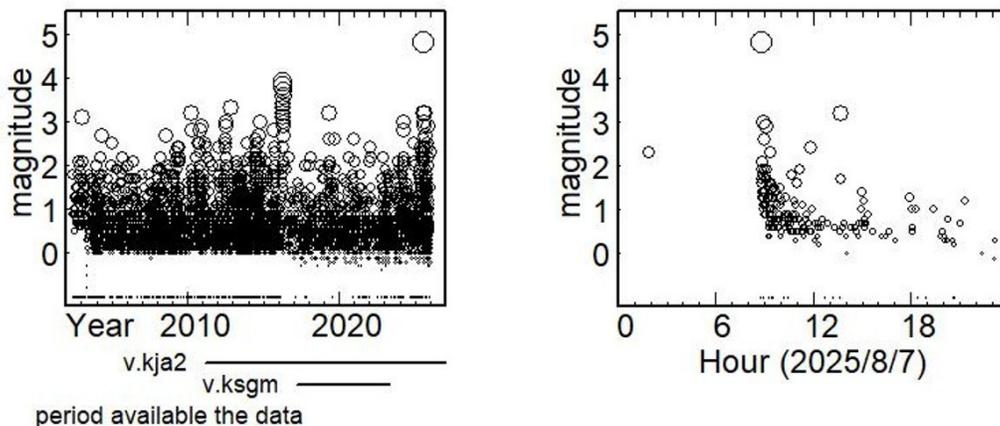


Figure 3: Event magnitude as a function of time. Each event occurred at the place whose distance from the Otake GPP is less than 5 km. (left) The period is 2002/6/2 – 2025/12/31. (right) on the day 2025/8/7.

4. METHOD AND RESULT

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 main large event. The largest earthquake in the Otake field is the M4.9 event of August 7, 2025 (Figure 2, Figure 3). The M4.9 event followed typical aftershocks (Figure 2 right and Figure 3 right). 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 Wallace, 1995).

Rupture process of such large event can be estimated by the empirical Green's function method (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. Larger events can be deconvolved with the smaller event whose waveform is similar to the larger. Regarding the M4.9 event the waveforms observed by the high-sensitivity seismometers are rather complicated for the analysis. Instead of the Hi-net data we used the F-net data. Figure 4 (left) shows the waveforms of the M4.9 event and the aftershocks whose magnitude is larger than 2. Comparing the waveforms the M2.9 event is most similar to the M4.9 event. For each station we assumed a source-time function consisting of a single pulse duration T . We calculated the waveforms for various values of T , compared them to the waveform of the mainshock, and selected the value that reproduced a computed waveform most similar to the observed mainshock as the apparent rupture duration. Figure 4 (right) shows the case of $T=70$ ms at the F-net station n.tkdf.

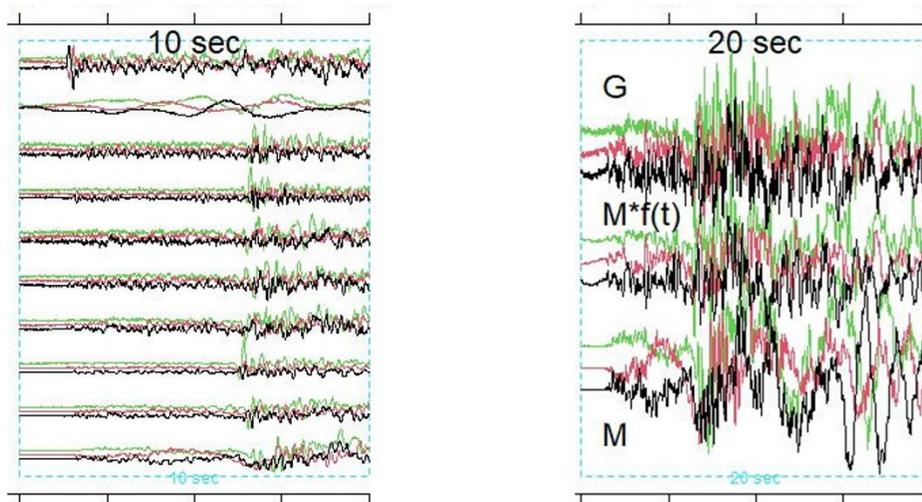


Figure 4: (left) 10 sec waveforms recorded at the F-net station n.tkdf. The bottom line is the waveform of the M4.9 event and the others are the aftershocks whose magnitude is larger than 2. (right) 20 sec waveforms at the F-net station n.tkdf. The bottom is the observed waveform of the M4.9 event (M). The top is the observed waveform of the M2.9 event (G).

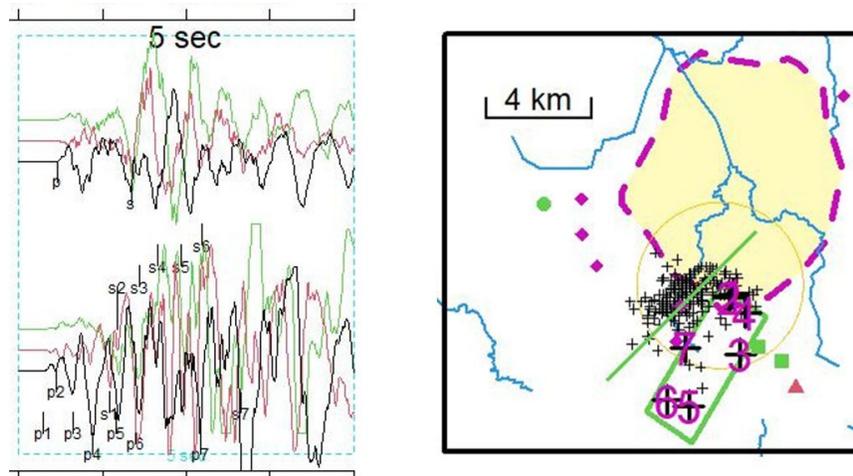


Figure 5: (left) Comparing the waveform of the M4.9 event and the M2.9 event observed at the station v.kja2, even sub-events can be seen in the waveform of the M4.9 event. P-time and S-time are shown for each sub-event. (right) The location of the source of the sub-events. The numbered black cross indicate the source of the sub-event. The green rectangle shows the source fault of the M4.9 mainshock. It was inferred from the location of the sub-events.

The waveform of the M4.9 event observed at the nearest station v.kja2 looks very complicated, however, we can see the several similar waveforms overlapped (Figure 5 (left)). Comparing with the waveform of the M2.9 event (event G in Figure 4) we can detect seven sub-events. The source location of the sub-event can be inferred by the triaxial hodogram method, which makes it possible to determine source locations by a single station data (e.g. Moriya et al., 1994). Measuring the P-wave arrival direction and the P and S arrival times, then we can infer the origin time and the source location of the microearthquake (Figure 5). Figure 5 (right) show the source location of the sub-events. The 1st sub-event occurred at the northmost point, where the M4.9 event was routinely determined by JMA. The 7th sub-event, which is the largest, occurred at the southernmost point.

5. DISCUSSION

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. Near the Otake area, two 3-component seismometers are installed (Figure 2 (left)). Therefore, we estimate the source parameters by the least square regression method. We can locate microearthquake hypocenters accurately enough to delineate fracture structure. Unfortunately, the station v.ksgm has been unhealthy since April 28th 2023. Generally, precision of the result of single station analysis is worse than the result of two stations. However, we can improve precision of the analysis by using better velocity structure model.

We have ever made the tomographic inversion of P-wave velocity structures beneath the Hoho geothermal field (Sugihara and Ito, 1989). Recently the seismic tomography of the Otake-Hatchobaru geothermal fields was made based on finite difference calculation of complex travel-times (Yoshikawa et al., 2005). In this study we used the P-wave and S-wave velocity structures for whole Japanese Islands which are given by Matsubara et al. (2022).

Microearthquake swarms occurred in the depth of the Otake area on 1st November 2025 (Figure 6). Adding the swarm data we will revise the P-wave and S-wave velocity structure at the Otake field. Ray paths of P and S waves from the swarms covered the deeper region, thus velocity model will be revised. The new velocity model will result in lower uncertainty for locations of the microearthquakes and the rupture process of the M4.9 event.

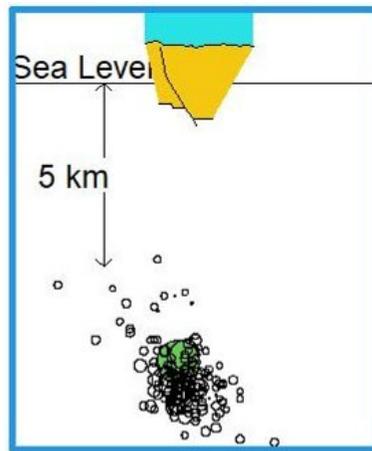


Figure 6: The cross-section, which pass through the Otake GPP, showing the geology and hypocenters of the M2.9 deep event and the aftershocks on the day 1st November 2025.

6. CONCLUSION

In August 2025 an earthquake with a magnitude of 4.9 (USGS scale) occurred at the Otake geothermal field. It is the largest event at the field. We made waveform cross correlation and high precision relative relocation of seismicity triggered by the largest event using publicly available seismic data.

An empirical Green's function analysis was applied to the largest event of the seismicity, and revealed particular characteristics of the fracture structure in the deeper part of the geothermal reservoir. We developed a kinematic source model for the largest event. The source model as well as accurate hypocenter relocations was effective to image the deep fracture structure of the geothermal reservoir.

Strictly definite conclusion as to the deep fracture structure cannot be drawn yet because analysis including the other potential data is still underway. However, a prospect to the deep fracture has been proved.

ACKNOWLEDGMENTS

We used the JMA Unified Earthquake Catalog available at <http://www.hinet.bosai.go.jp/?LANG=en> (last access on 31 January 2026), and seismograms from Hi-net by NIED available at <http://www.hinet.bosai.go.jp/?LANG=en> (last access on 31 January 2026). Part of this work was done using R (<https://www.rproject.org/>, last access on 31 March 2022).

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