High-resolution microseismic monitoring for water injection in Okuaizu Geothermal Field, Japan

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A continuous water injection test was conducted to halt the reduction of steam production in the Okuaizu Geothermal Field, Japan. Understanding the spatiotemporal behavior of water flow within the reservoir associated with the water injection is essential to ensuring effective steam production. We conducted a high-resolution hypocenter determination using the double-difference method. In this method, relative hypocenter locations are corrected by using time difference in P-wave onsets of seismic event pairs. We found three characteristic seismic clusters associated with the water injection using this method. The creation of microseismic clusters seems to have a qualitative relationship with the distribution of well head pressures in this field, suggesting that microseismic monitoring could be a method for understanding fluid behavior in the reservoir.

1. Introduction

During water injection into geothermal reservoirs, it is important to monitor and control migration of the fluid to avoid cooling of the reservoir and to retrieve steam efficiently. For this purpose, microseismic monitoring has been widely used to estimate the spatiotemporal behavior of reservoirs (e.g., Fehler et al., 1987; Baria et al., 1999). In the Okuaizu Geothermal Field, Japan, water injection test was conducted from June to August 2015 (first test) and from November to December 2015 (second test). We conducted a high-resolution hypocenter determination using the double-difference method (Waldhauser and Ellsworth, 2000) to understand the behavior of the injected water. This precise hypocenter determination has found a slight difference between the location of seismic clusters appeared in the first and second stages. We also analyzed the distribution of total head calculated from well head pressure (WHP) under several assumptions regarding to the condition of water within the well. Using this total head distribution as a proxy of water flow, we evaluated the relationship between the location of hypocenters and the water flow.

2. Injection test and microseismic monitoring

As part of the "Technology to Evaluate and Manage Geothermal Reservoirs" project conducted by the Japan Oil, Gas and Metals National Corporation (JOGMEC) (e.g., Okabe et al., 2016), a continuous water injection test was conducted. The injection rate is shown in Figure 1 with four analysis terms (① - ④). The first test was conducted in the term 1. The second test was conducted in the term 3 after three months from the end of the first test. Five stations on the surface and four stations in boreholes (shown by triangles in Figures 2) have been deployed around the injection well. These stations are three-component broadband accelerometers or velocimeters. Continuous seismic records are transmitted to a National Institute of Advanced Industrial Science and Technology (AIST) server in real time, and hypocenters are routinely determined by manual pick of P- and S- wave arrivals. The residuals in P-wave travel times for the routinely estimated hypocenters are, at most, 100 ms (~10^2-m error in the spatial domain). The lower limit of the

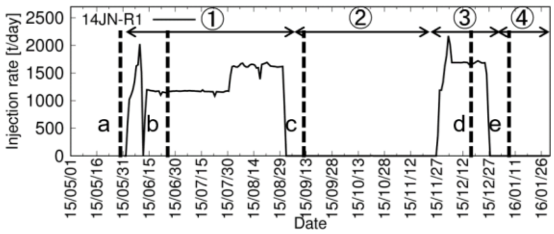

Figure 1 Injection rate per day. The arrows with the number (1-4) represent four analysis terms we employed. The dashed lines with the small letter (a-e) represent the timing that total head pressure (shown in the later section) was estimated.

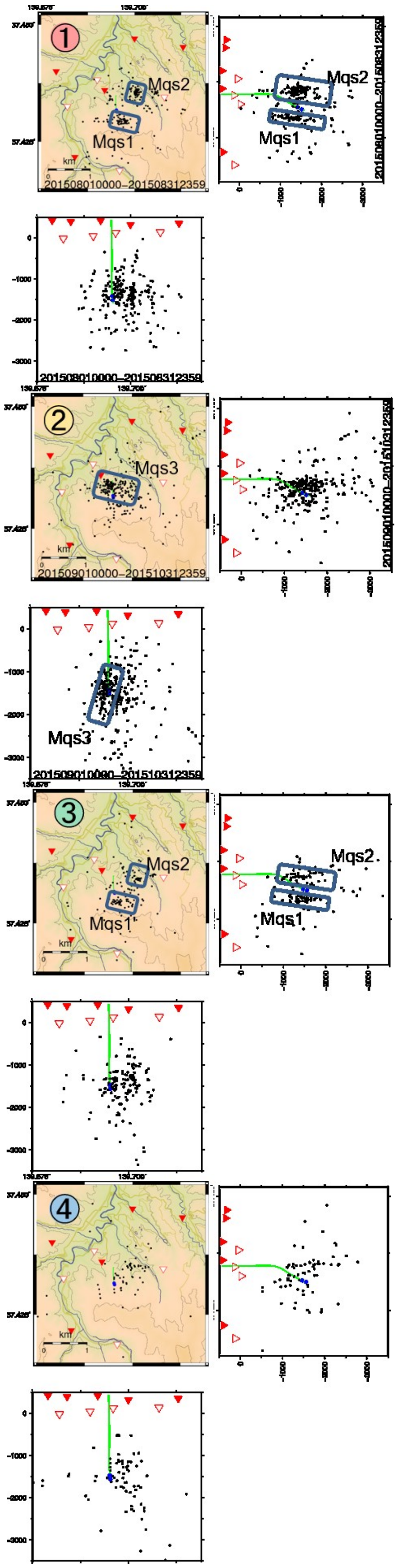

Figure 2 Hypocenter distribution in the term 1-4. The red and white rectangles show sensors on and in the ground.

detectable local seismic magnitude is approximately -2.0.

3. High-resolution hypocenter determination

We employed the double-difference (DD) method to determine precise locations of the microseismic events associated with the injection test. Clusters of microseismic events were identified by cross-correlation of the waveforms (e.g., Schaff et al., 2004) of the up-down (UD) component in the 40–80 Hz frequency range of the borehole sensors. The relative difference in the P-wave arrival times in a cluster was calculated on the basis of the cross-correlation to create the input for the DD method. The spatial residuals were on the order of 10^1 m after the hypocenters were relocated; the centroid of a cluster was that for the routine hypocenter determination.

Two seismic clusters (Mqs1 and Mqs2) appeared during the both injection tests (the analysis terms 1 and 3). The locations of seismic events in Mqs1 and Mqs2 in the analysis terms 1 and 3 were slightly different each other. In the analysis term 3, seismic events tended to occur the periphery of the clusters. This tendency implies that microseismic events triggered by water flow evolved further in the analysis term 3 compared to the analysis term 1. Another seismic cluster (Mqs3) appeared after the end of the first injection test (the analysis term 2). However, this cluster did not appear after the end of the second injection test (the analysis term 4). Further information can be found in Okamoto et al. (2018).

4. Distribution of total head

Distribution of total head near the injection well was estimated by WHP of wells in the Okuaizu Geothermal Field (Figure 3). We employed this distribution as a proxy of characteristics of water flow in subsurface. The gradient of total head is considered to be a direction of water flow. In the calculation of the total head from WHP, we assumed that water table locates at the well head and hydrostatic condition can be applied within the well. These assumptions are rather strong. For example, in general, water table dose not always locate at the well head, there is a mixed phase of water within the well, and thermal effect should be considered, which we did not considered. However, we assume that qualitative character could be obtained from this simple calculation.

The total head distribution was calculated at five timing (a-e) shown in Figure 1. The total head distribution shows roughly three patterns (named

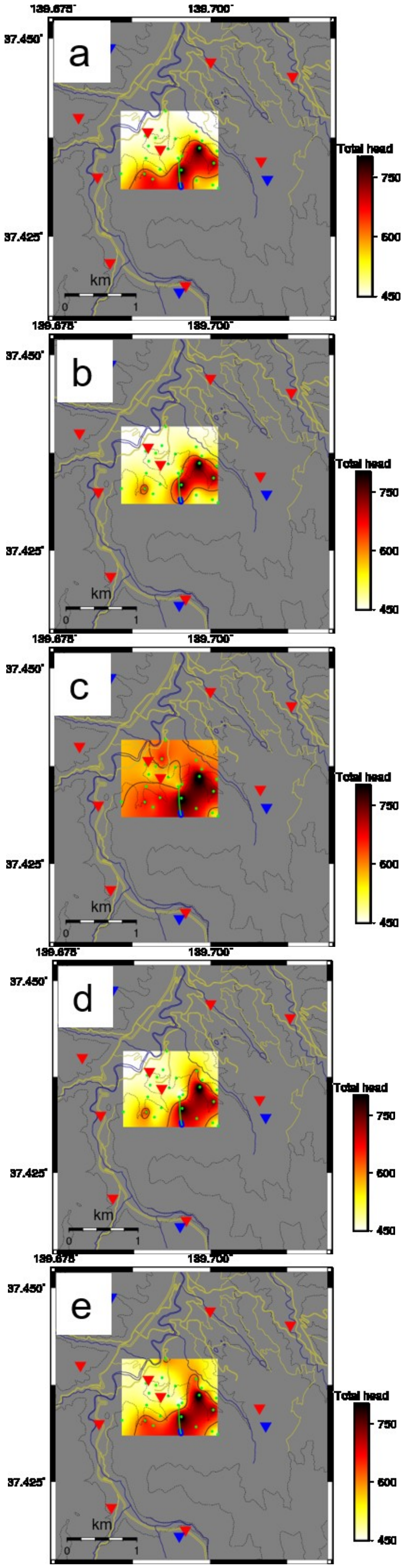

Figure 3 Distribution of total head estimated from WHP (the wells are represented by the green circle) (a) before the start of the first injection test, (b) during the first injection test, (c) between the end of the first injection tests and the start of the second injection tests, (d) during the second injection test and (e) after the end of the second injection test. The green line shows the injection well.

Group 1 – 3). Group 1 is Figures 3a and e, Group 2 is Figure 3b and d, and Group 3 is Figure 3c. A region of high total head extended along a SW-NE direction in Group 1, when the water injection was not proceeded. On the other hand, a region of high total head appeared only around the injection well and its NW area in Group 2, when the injection test was proceeded. A region of high total head extended a wider area in Group 3, when the first injection test was terminated.

5. Discussion

Three patterns in distribution of total head (Group 1-3) could be related to the patterns of occurrence of seismic clusters. Mqs1 and Mqs2 seem to appear when the total head distribution is Group 2. The locations of Mqs1 and Mqs2 correspond to regions where large gradient of the total head exists. Meanwhile, Mqs3 likely appears when the total head distribution is Group 3. A region of large gradient of the total head may correspond to the location of Mqs3. There are no characteristic seismic clusters when the total head distribution is Group 1. Thus, the precisely determined microseismic events could correlate with the patterns of water flow estimated from WHP. Here, we should note that the total head was calculated under the strong assumptions (water table locates at the well head and hydrostatic condition can be applied into the well). Therefore, the gradient of total head does not necessarily correspond with water flow. Though, we consider that the distribution of total head could indicate a qualitative characteristic of water flow.

6. Summary

We determined hypocenters of microseismic events using the double-difference method, and three major seismic clusters were identified. Distribution of the total heads estimated from WHP showed a qualitative relationship of injected waters with the creation of the seismic clusters. It is suggested that the monitoring of microseismic events qualitatively helps us to understand water behavior in the subsurface. More robust estimation of water flow from WHP is needed for further interpretation of our results from the microseismic monitoring with respect to water flow.

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