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Dynamic Modeling of Microseismic Activities in a Geothermal Field

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ABSTRACT

In this study substantial microseismic activities have been recorded over 9 years of monitoring depending upon surface operations conducted, such as new production and reinjection wells added to the exploitation operation around the license area, and connection to new power plants. After examination of data obtained some relations between surface operations and subsurface activities are inferred. Large data obtained over 9 years are modeled dynamically in 3D and it helped to better understand and evaluate the changes occurring underground.

1. INTRODUCTION

Salavatlı geothermal field in Turkey has been developed and operated in the last 15 years, and during this period 5 power plants with a total power generation capacity of 72 MWe were installed. In order to monitor the reinjection fluid pathways first tracer testing, then micro-earthquake monitoring were used.

The first power plant was commissioned in 2006, and the second in 2010 when a 9 station seismic network was deployed around the license area and monitoring of microseismic activity was started. Application of high-precision micro-earthquake hypocenter location has continued until today and will proceed in the future. In the last decade, observing microseismic events across different networks has also started in three more geothermal fields under exploitation in Turkey, and is currently continuing.

Geothermal resources derive their capacity for fluid and heat transport mainly from fracture systems. Microseismicity occurring on fracture systems might identify large faults and fractures which provide fluid storage and recharge capacity to sustain a geothermal reservoir.

Large microseismicity has been observed mainly in the exploitation area and 1-3 km depth of the injection and production intervals in Turkey. As for geological structures, the activity is observed near fault systems. Important geological features might be elucidated by microseismic monitoring that has indicated events with the start of field operations in the exploitation areas where seismicity has not been observed previously.

During the nine years of observation at Salavatlı geothermal field, microseismic activities occurred in the area delimited by the low resistivity anomaly within which all the wells have been drilled. Reinjection wells are located around the margins of this anomaly.

2. GEOLOGICAL SETTING

Extensional tectonics and subsequent horst-graben morpho-structures are the key feature of western Anatolia, and the main geological factors which determine the anomalously high heat-flow controlled by the deep structures (Tezcan, 1979).

The grabens are the surface expression of extensional structures which can be very deep. In the Büyük Menderes Graben, the wells stratigraphy points out a general structure having the Miocene sedimentary units overlying the crystalline basement (Menderes Metamorphic Massif), which in turn is deformed by thrusting (showing in some places high-grade rocks like gneisses onto low-grade metamorphic rocks). Combinations of antithetic faults and minor horst-graben within the main graben give rise to a great structural complexity, which is a favoring geological factor for the up-flow of geothermal fluids from deep crustal levels.

The Büyük Menderes Graben is an E-W trending, roughly 200 km long tectonic valley, which stretches from the Aegean Sea to near Denizli (Fig. 1). A major south-dipping normal fault system bounds the northern margin of the Graben, juxtaposing Neogene sediments against the (mostly Paleozoic) Menderes metamorphic massif. Information about the thickness of Neogene basin infill, through the wells stratigraphy and geophysical investigations, suggests that the displacement along the steep normal faults of this system may exceed 3 km. Transverse faults (ranging from NNW-SSE to NE-SW) dissect the Graben margins and commonly extend into the Menderes Massif.

A geological map of the Field is shown in Fig. 2. The field is divided into two parts by main gravity faults as can be seen from this map. Metamorphic basement and Miocene sedimentary units outcrop at north of this divide; while, only Pliocene and Quaternary deposits are outcropping in the south. Miocene units located as filling NW-SE oriented old grabens over the Metamorphic basement at NW quarter of the area. However, the Pliocene deposits obviously are filling the ENE-WSW oriented young graben system.

Salavatlı Field is located along the morphological boundary between the almost flat valley floor of Menderes River, to the south, and a northern faulted block, made of Neogene sedimentary units which gives rise to a dense set of eroded and tectonically dissected low hills. The transition between the flat area and these relieves corresponds to the northern tectonic boundary of the aforementioned Büyük Menderes graben. In this sector, the graben widens and the flat valley floor measures some 6 km in a N-S direction.

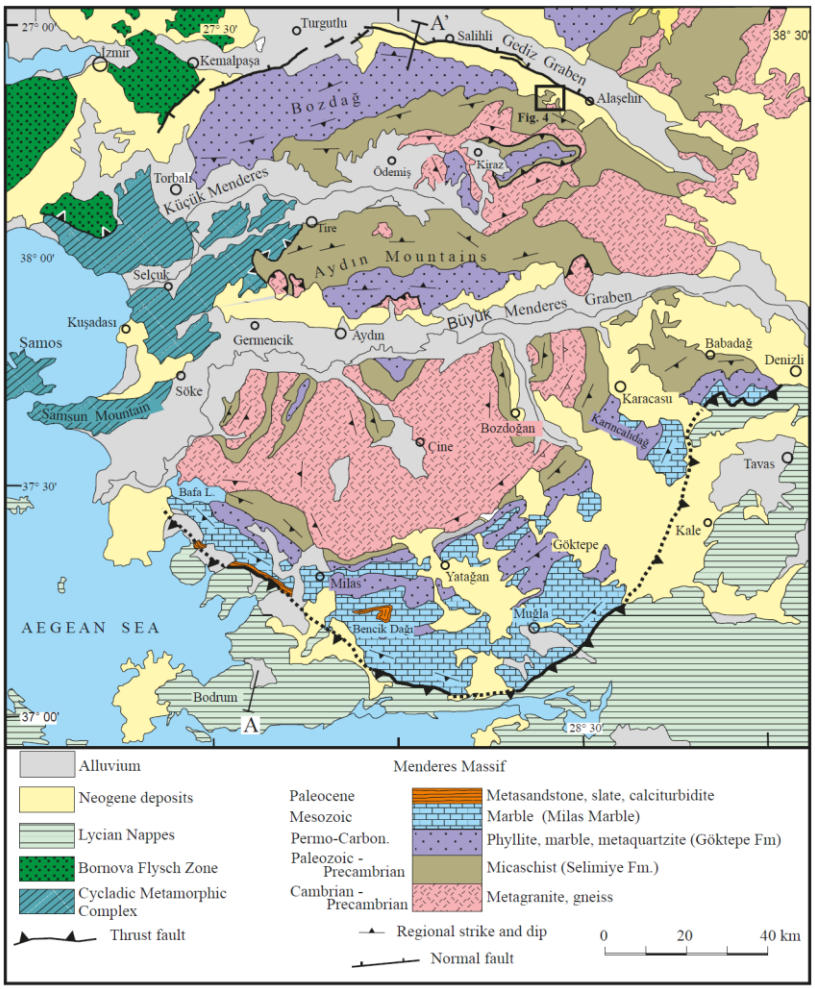

Figure 1: Geological map of Menderes Massif and B. Menderes Graben (Gülmez et al, 2019).

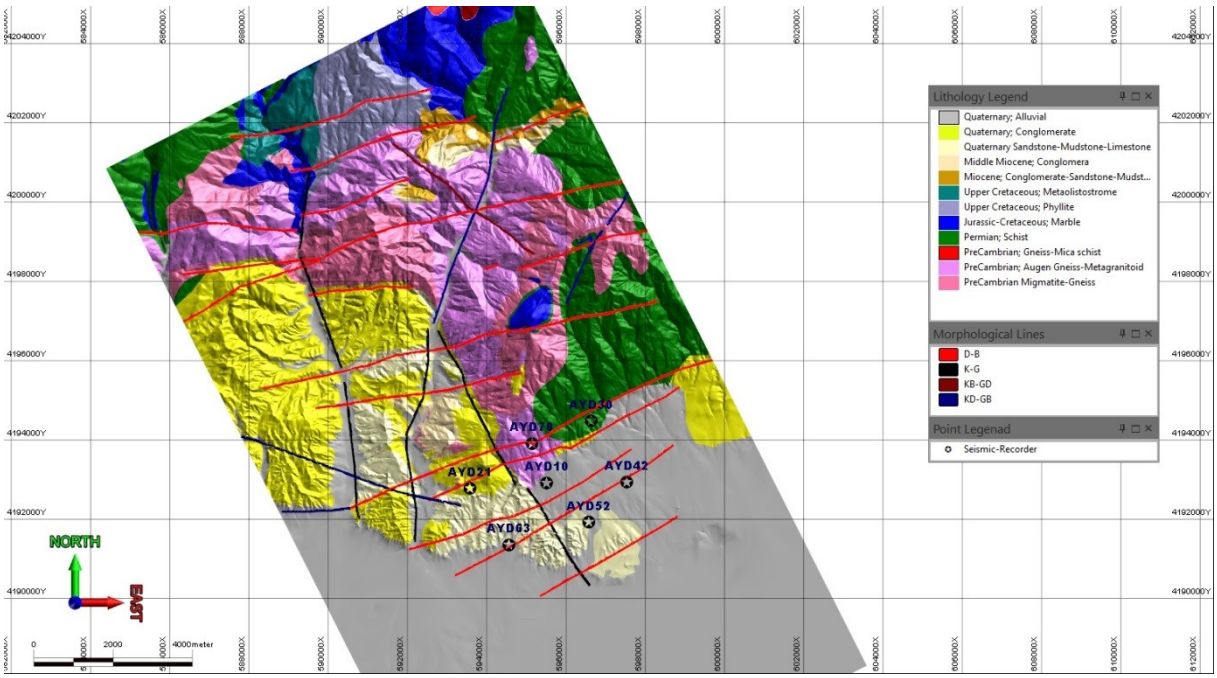

Figure 2: Geological map of Salavatlı area and seismograph network.

3. DATA ACQUISITION AND PROCESSING

3.1. Installation

Originally, this project aimed at monitoring seismic activity in the Salavatli geothermal field and locating reinjected water close to the AS-2 reinjection well. Data were collected in the Salavatli geothermal area starting from May 23 2010 using a temporary seismic network covering an area of 20 km^2. The seismograph network originally was comprised of 9 stations (Fig. 2). The seismic network was put into operation in two deployments using Güralp CMG 6T digital three-component broadband instruments. The recording was continuous with a sample rate of 100 samples/s (Gürbüz et al., 2011).

3.2. Data processing

Data used in this study was recorded by the temporary local seismic network. Data from the temporary local network was downloaded directly from the instrument and later transferred to a computer. This helped to obtain continuous data during the experiment. Every one hour, data was written to a file and was extracted from an external hard disk to a PC computer with gcf format. This data was converted to sac from gcf format before transferring the data to SEISAN data analysis program (Gürbüz et al., 2011).

3.3. Velocity model

A crustal velocity model was constructed to locate the events. For velocity construction various sources were used. There are well logs from all the wells in the study area. Each geological unit with depth is given up to basement rock. The depth of basement varies between wells. The basement becomes deeper in the south towards the Menderes River. For the crustal velocity model, also P and S wave velocity information is needed. The Turkish Petroleum Company had done seismic reflection study in the region. Information obtained from this study was used to estimate the velocity of layers obtained from the well logs (Ciftci et al., 2010 and Gürbüz et al., 2011).

3.4. Location of Earthquakes

Vertical components of all stations were displayed and local earthquakes were sought. After selecting local earthquakes, picking of the arrival times was done using the SEISAN program based on adequate signal-to-noise ratio irrespective of the frequency of the seismic arrival. Accuracy of observed arrival times depends mainly on P and S – wave arrivals were read and located using HYPO71 program (Gürbüz et al., 2011).

4. RESULTS

First results of the seismic monitoring of reinjection in the northern part of Salavatli Geothermal Field indicated some clear trends of the fluid motion complying with the first aim of monitoring reinjection. The most visible pattern is the western and northwestern distribution of the microseismic events (Fig. 3). These occurred especially at the depth range of 0-2 km. Deeper seated focii are regularly distributed in the region and appear as mostly natural seismic background. On the other hand, shallower events took place around the reinjection location and especially in the west and northwest surroundings. However, these parts of the area consist of the hanging wall of the main structure, Graben Fault. According to the distribution pattern of triggered shallow seismic events, reinjected waste water seems to disperse towards outside of the geothermal system, looking to escape from main reservoir zone (Gürbüz at al., 2011).

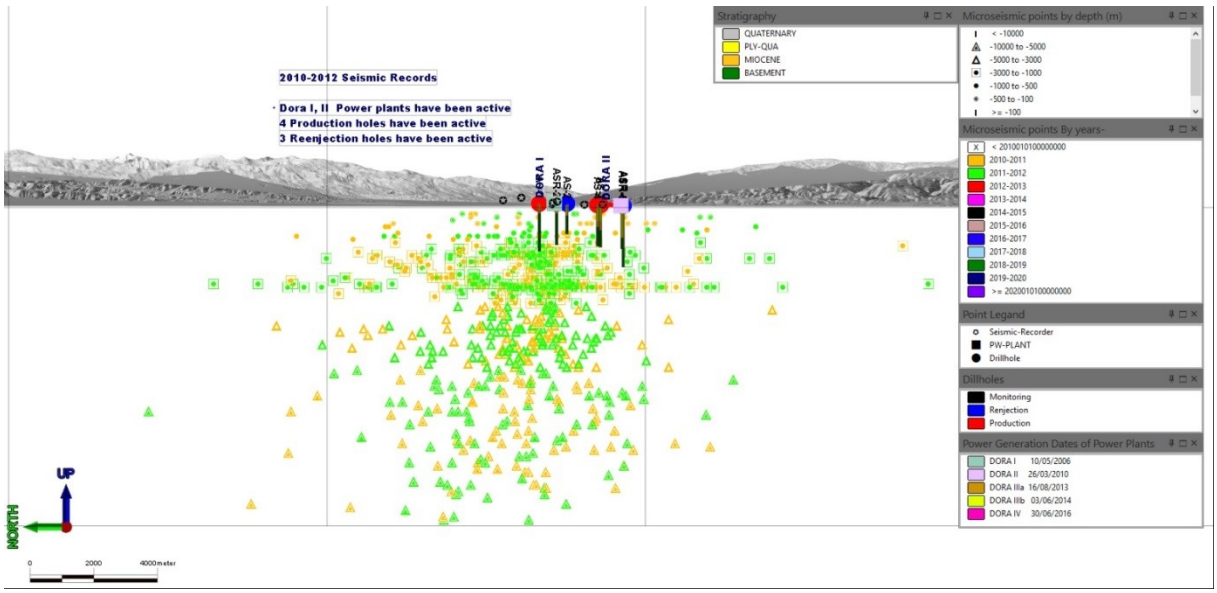

Figure 3: 2010-2012 period seismic activities on N-S cross section

Fig 3 indicates recordings of a 2 year period in which four production and three reinjection wells were operating. There is a clear N-S (over and under 2000 m depth) trend of microseismic activities extending especially to the north. Reinjection was started 6 years ago in 2006. Overlapping activities during 2010-2012 periods indicate continues reinjection effect.

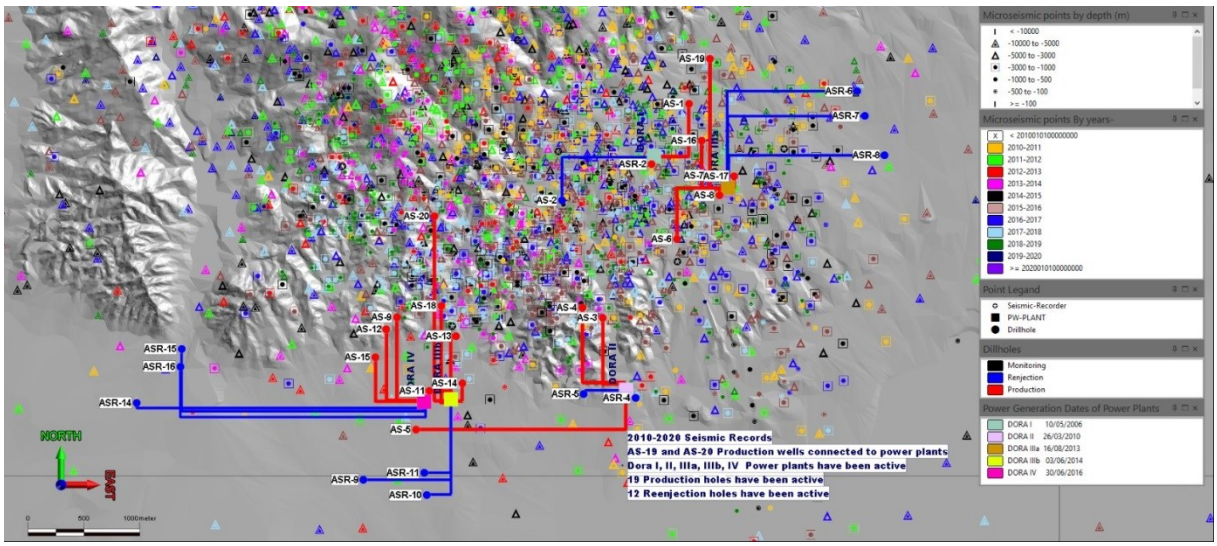

Figure 4: 2010-2020 period production and reinjection wells power plants and seismic activities shown on topography.

During the progress of field development, three power plants (in years 2013, 2014 and 2016) along with 19 production and 12 reinjection wells have been placed into operation. If we look at the reinjection operation's induced seismic activities closely, no appreciable activities are seen for Dora 2, Dora 3b and Dora 4 power plant related reinjection (Fig. 4). On the other hand, for Dora 3a operations to the east, started in 2013, there seems some developing seismic activity over time.

Because reinjection wells for Dora 2, Dora 3b and Dora 4 power plants reinjection operations were located in the southern margin of the reservoir where reservoir pressures are relatively low with respect to the reservoir center, the reinjection operations might not induce seismic activities. Moreover, in this zone, production and reinjection wells are located perpendicular to the main faulting trend and there might be no direct communication paths, and therefore, small or no activities are induced. On the other hand, Dora 1 and Dora 3a power plant production and reinjection wells that are located in the north and east, respectively are found on the graben faulting which would facilitate hydraulic communication between reinjection and production wells on the same trend.

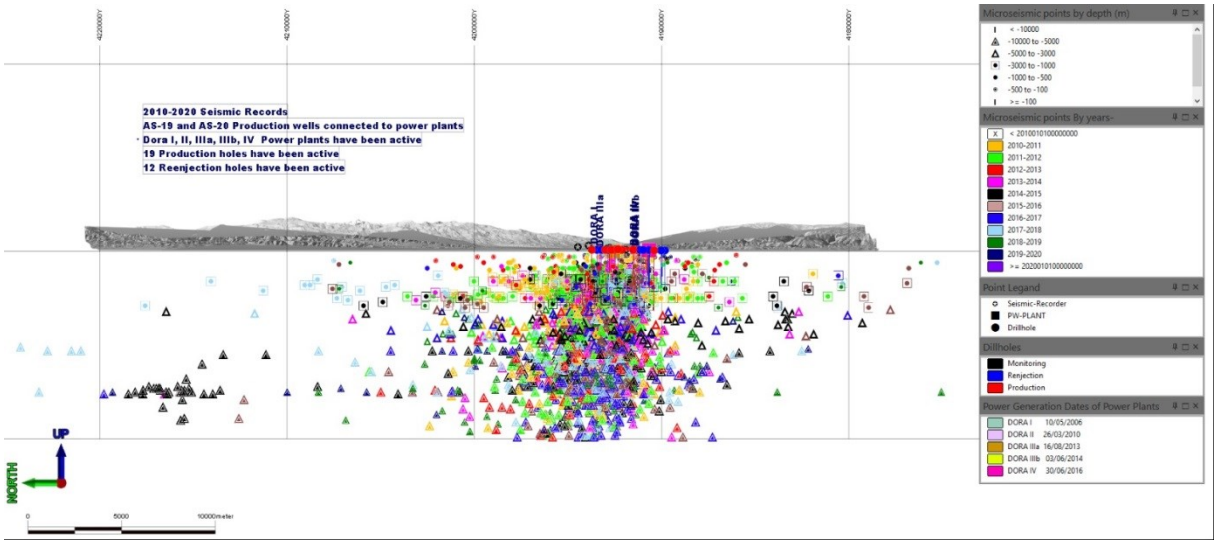

Figure 5: 2010-2020 period seismic activities on N-S cross section.

As seen in Fig. 3 microseismic activities developed under the reinjection well in depth and north and west during 2010-2012 periods. Fig 5 indicates that previously horizontally developed seismic activities around 2000m started to extend further northward in 2017-2018. Furthermore, another deeper trend (extension to the north) developed earlier, and has reached a threshold over 25 km. The depth of this trend has developed over 5000 m. Although relation of these far away activities to the main field zone is difficult to explain geoscientifically, there seems a clear connection in Fig. 5.

On the other hand, apart from the intensive seismic activity right under the field, listric alignments might be associated detachment faults. These alignments on the both sides of intense seismic activities display the graben image.

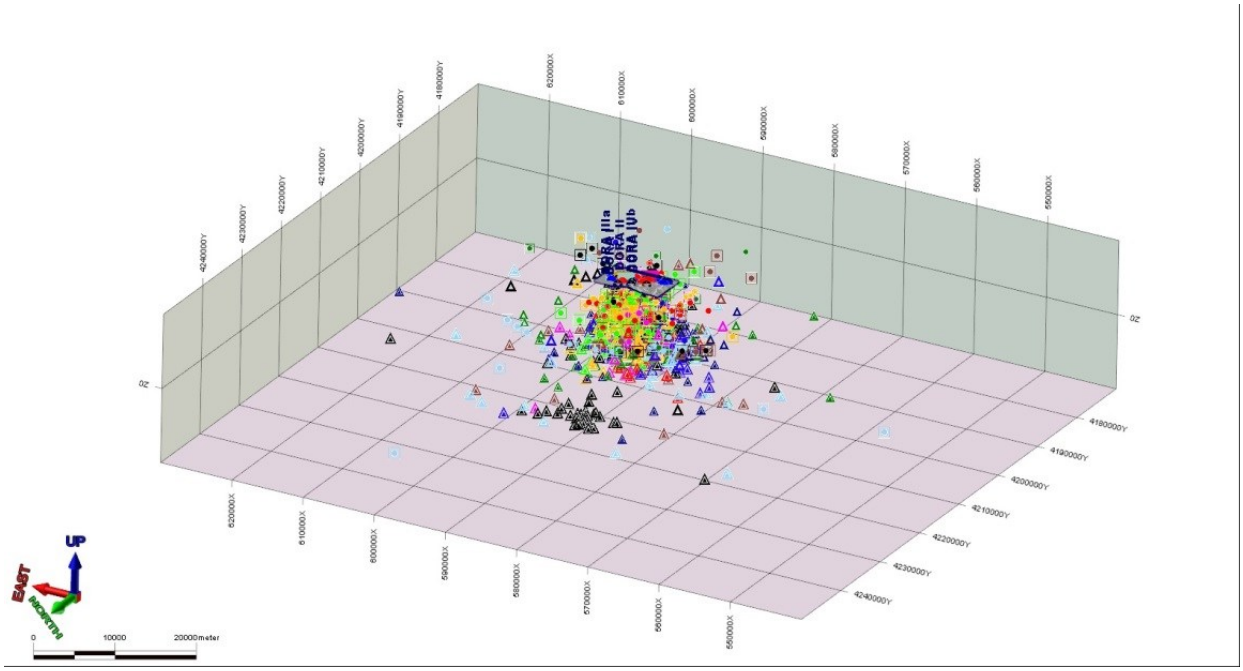

Figure 6: 3D Seismic activities in 2010-2019 periods.

All studies were conducted using a 3D model, and all cross-sections presented above are obtained from this 3D modeling. Fig. 6 shows a 3D illustration of seismic activities during 2010-2019 periods. This figure also shows the expanding nature of activities toward the north.

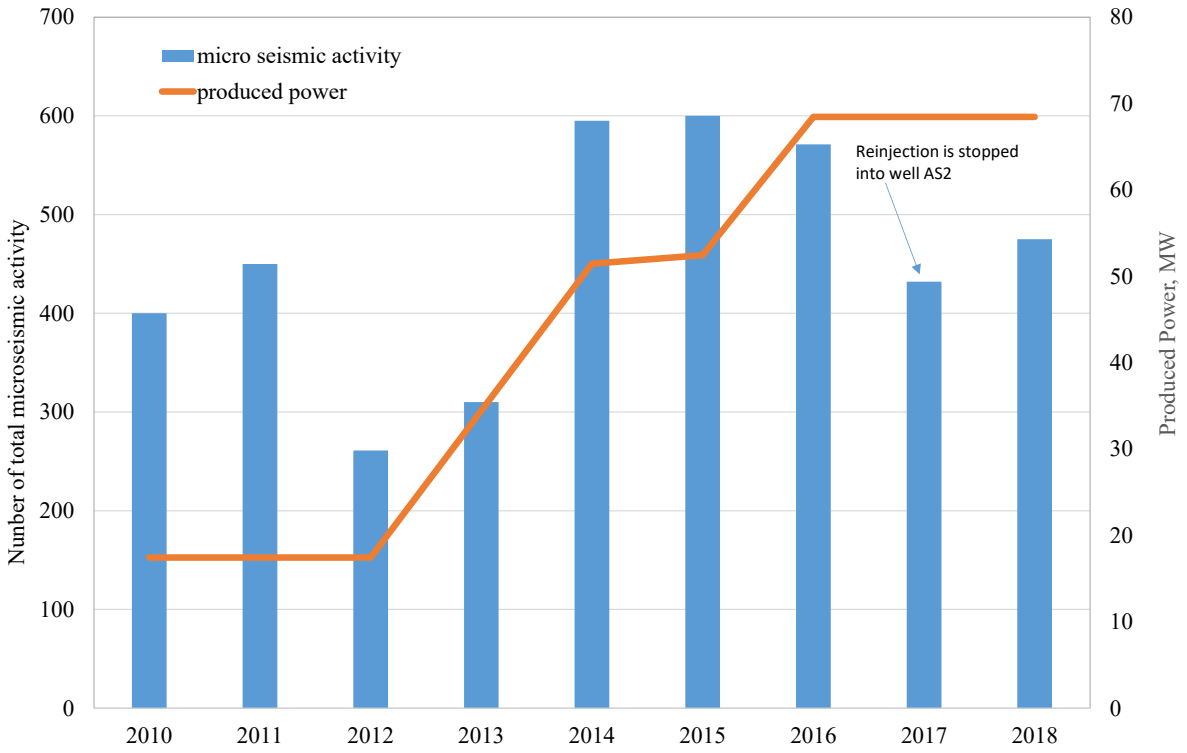

Figure 7: Seismic activity and power generation development over time.

Fig. 7 illustrates changes of seismic activity numbers and power generation in the field over time. This change is important because it might indicate the response of the geothermal resource to geothermal fluid extraction and reinjection. As seen from the figure, seismic activities are clearly increasing with increasing power generation, that is, fluid production and reinjection. But there are periods in which activities change while power generation is constant.

5. CONCLUSIONS

Microseismic data were collected over 9 years during which field development activities were conducted, such as drilling new production and reinjection wells, and connecting them to new power plants. Over this period 3 new bigger capacity plants were placed into line. The response of geothermal field was observed over this period.

- Response to reinjection is clearly followed in northern and eastern operations. No seismic activities attributable to reinjection were detected in the southern and western operations.
- Reinjection in the low reservoir pressure area did not induce seismic response.
- Intensive seismic activities observed just below the field can be attributed to the fluid extraction, that is, production.
- Activities in the northern part of the field could be attributed to both reinjection operation and active detachment faults.

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