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Relation between Induced Seismicity and Geothermal Systems: A Case Study from The Gediz Graben, Western Anatolia, Turkey

Hüseyin Uytun[1], Hasan Sözbilir[2], Alper Baba[3], Kemal Yıldızdağ[4] and Murat Karaş[5]

[1] Dokuz Eylül University Applied Geology, Kaynaklar Yerleşkesi, Buca İzmir Turkey

[2] Dokuz Eylül University, Department of Geological Engineering, Kaynaklar Yerleşkesi, Buca İzmir Turkey

[3] İzmir Institute of Technology, Geothermal Energy Research and Application Center, Urla İzmir Turkey

[4] Freiberg Technical University, Department of Geomechanics, rock mechanics/rock engineering Germany

MSC Eng. Geotechnical Drilling Industry Co., Karşıyaka İzmir Turkey

huytun@gmail.com, hasan.sozbilir@deu.edu.tr, alperbaba@iyte.edu.tr,

kemal.yildizdag@ifgt.tu-freiberg.de, muratkaras@gmail.com

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ABSTRACT

It is well known that induced seismicity associated with geothermal systems occurs when the fluid pressure in a fault or fracture reaches a critical value. This study has been focused on induced seismicity associated with operating geothermal systems since 2015 in the Gediz Graben. Geothermal fluid in Gediz Graben originates from structural zones of low angle Gediz detachment fault of Quaternary age and high angle normal faults of Holocene age. For the geothermal application, many wells with the function of production and reinjection have been drilled with a depth range from 1000 to 3500 m in the Graben.

In this study, the seismic data of Kandilli Observatory - Earthquake Research Institute, Prime Ministry Disaster - Emergency Management Authority and the geothermal well data of Manisa Investment, Monitoring - Coordination Directorates were used. Production - reinjection and seismic data were evaluated together with the tectonics and geology of the region by using Geographic Information System-based program Quantum GIS (QGIS). In that analysis, seismicity was observed especially around geothermal wells drilled for reinjection. It is concluded that earthquakes with magnitude 1-3 can be related to the geothermal activity. However, no direct correlation was found between the pressure, flow rate and the earthquake magnitude of the injected fluids. No correlation was observed between the high pressures or flow reinjection induced seismicity. In addition to the reinjection process, micro-earthquakes were observed during the hydraulic fracturing process which may occur due to reactivation of pre-existing faults. To examine that incident in more detail, the seismometers should be deployed near to the power plants and following that, the change of injection flow and pressure varying with time together with lithology should be determined. A method called "traffic light system" has been using especially in countries where enhanced geothermal system applications were used, to trace production and reinjection activities. In worst-case situations, these activities in power plants can be halted using that method. Concerning geothermal power plants in Western Anatolia, detailed studies should be conducted to estimate the relationship between geothermal production-reinjection activities with seismicity subsequent to fulfillment of infrastructure requirements.

1. INTRODUCTION

Induced seismicity refers to seismic events that are a result of human activity. Human activity can cause induced seismicity in many different ways. These human activities include geothermal operations, the reservoir behind dams, wastewater injections, and oil/gas operations such as hydraulic fracturing and mining. It is well known that induced seismicity associated with geothermal systems occurs when the fluid pressure in a fault or fracture reaches a critical value above which the friction preventing fault slip exceeds. According to Doglioni (2018), at least four different types of settings can be recognized in which anthropogenic activities may generate seismicity: "(I) fluid removal from a stratigraphic reservoir in the underground can trigger the compaction of the voids and the collapse of the overlying volume i.e., graviquakes; the deeper the reservoir the bigger the volume and the earthquake magnitude; (II) wastewater or gas reinjection provides the reduction of friction in volumes and along fault planes, allowing creep or sudden activation of tectonic discontinuities, i.e., reinjection quakes; (III) fluid injection at supra-lithostatic pressure generates hydrofracturing and micro-seismicity, i.e., hydrofracturing quakes; (IV) fluid extraction or fluid injection, filling or discharging of artificial lakes modifies the lithostatic load, which is the maximum principal stress in extensional tectonic settings, the minimum principal stress in contractional tectonic settings, and the intermediate principal stress in strike-slip settings, i.e., loadquakes; over given pressure values, the increase of the lithostatic load may favour the activation of normal faults, whereas its decrease may favour thrust faults (Doglioni,2018)".

Some researchers distinguish between "induced" and "triggered" seismicity according to whether all or only part of the strain energy released was anthropogenic, using the term "induced" when most of the energy was anthropogenic, and "triggered" when it was predominantly of natural origin. Determining the proportion of anthropogenic to naturally stored energy is very difficult, although in the case of larger earthquakes it is clear much of the energy is of natural tectonic origin. The term "induced" is used for both cases, which is in keeping with the convention of the Committee on Induced Seismicity Potential (Hitzman, 2013, Induced Seismicity Potential of Energy Technologies). In this study all anthropogenic seismicity is considered as induced seismicity.

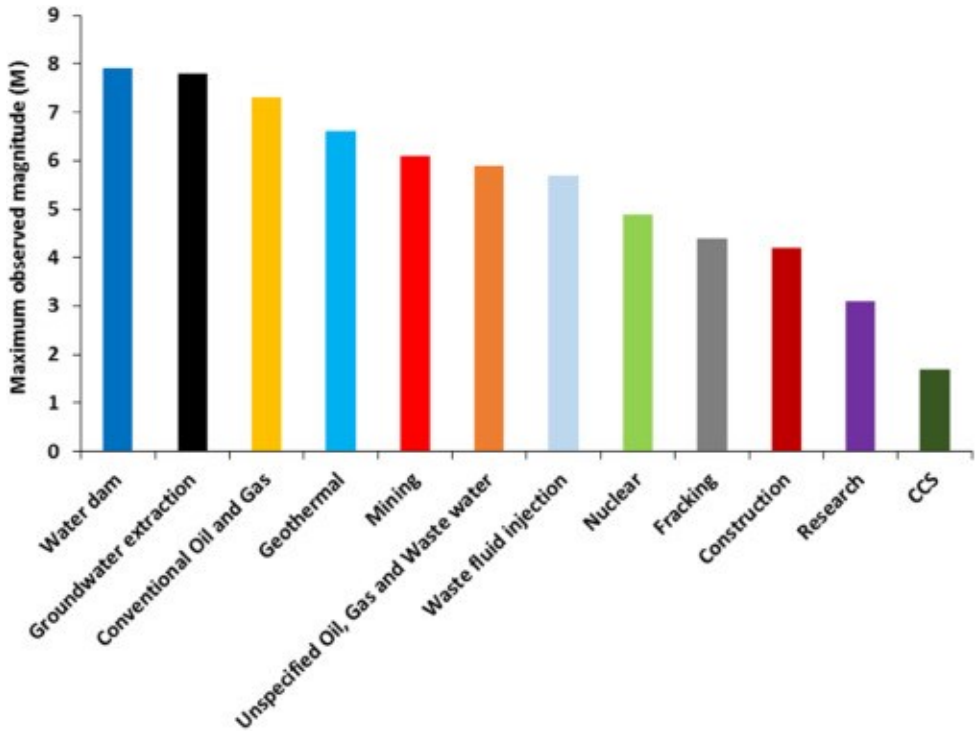

Figure 1: The maximum observed induced seismicity magnitudes and human activities (CCS : Carbon Capture and storage). (Inducedearthquakes.org Last accessed June 2019)

The number of triggered earthquake events observed to date and reported to the literature is about 1000 at all around the world. As the above chart suggests, large earthquakes can occur with human intervention. The biggest triggered earthquakes are caused by dams. Fracking was recently recorded as the most triggered seismicity producing activity by inducedearthquakes.org. The use of geothermal energy is one of the important factors causing triggered seismicity.

Considering active tectonic settings high levels of natural seismicity are common, faults may be pre-stressed and seismicity may be triggered by induced stress changes. Magnitude and number of seismicity depend on natural factors (the local stress, friction, fault orientations, locations). Factors affecting seismicity are: displacement stresses from volumetric contraction caused by fluid extraction (HM Coupling); thermal stress created by injection of cool fluids into hot rock (TM Coupling); and chemical stresses associated with injection of brines or acid fluids (CM Coupling, see figure 2), causing mechanical degradation of rock or stress relief. On the other hand, there are controllable factors such as injection pressure-temperature and volume of injected fluid (Bromley, 2012).

McClure and Horne (2012) point out that "induced seismicity occurs when stress is changed on preexisting fractures so that their shear traction exceeds their frictional resistance to slip according to the Coulomb failure criterion":

$$\tau = \mu(\sigma_n - P) + S \quad (1)$$

Where τ is shear traction on a fracture [Pa], σ_n is normal stress [Pa], P is fluid pressure [Pa], S is the fracture cohesion, and m is the coefficient of the friction [-]. When the failure criterion is exceeded on a fracture, slip occurs to relieve shear stress (McClure and Horne, 2012 and Jaeger *et al.* 2007)". According to the equation, seismicity is triggered by shear stress, normal stress, or fluid pressure change. Triggered seismicity is directly related to the properties of the rock matrix, the properties of the fracture-crack system, temperature and stress changes. Kaiser effect phenomenon is that when rock cores are loaded in uniaxial compression, acoustic emission occurs when the stress reaches a level greater than that which the rock has previously experienced (Lehtonen and Cosgrove, 2012). According to Zang *et al.* (2014) "stress magnitudes are important in multiple stimulations of wells where little or no seismicity is observed until the previous maximum stress level is exceeded (Kaiser Effect).

Hydraulic fracturing or fracturing operations have been applied to enhance the permeability of reservoir rocks by injection of water with high pressures. Due to that injection, new cracks and fractures in reservoir can be generated via altering of effective stress distribution and this may trigger seismicity with magnitudes approximately 2 -3. According to Matsugana *et al.* (1993) hydraulic fracturing is the most common method used to create an artificial fracture for extracting heat from a Hot Dry Rock (HDR) geothermal reservoir.

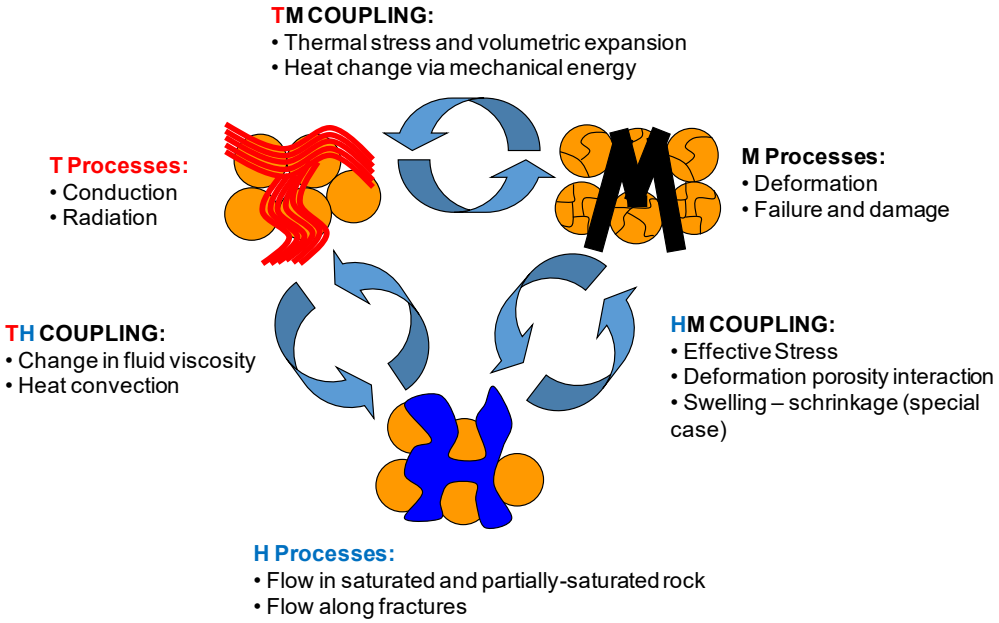

Figure 2: General illustration of Thermo-Hydro-Mechanical (THM) coupling processes in a rock excluding chemical coupling after Konietzky & Yildizdag (2018)

2. TECTONİC SETTİNG AND GEOTHERMAL POTENTİAL

Turkey lies on a significant region on the western segment of the Alpine-Himalayan orogenic belt. Hellenides and Carpathians branches of Alpine system cross Turkey in the form of complex Tauride and Pontide blocks and connect with Bitlis-Zagros zone to the east. Compressional, strike-slip and local extensional deformations are observable throughout the entire Alpine-Himalayan belt driven by complicated convergence of Africa and Eurasia (Şengör & Yılmaz, 1981).

The Aegean Region has been suffering from the active N-S extensional tectonics, under the control of two main motions. One of them is the westward escape of the Anatolian Plate, bounded by the North Anatolian Fault and the East Anatolian fault, intersecting at the Karlıova depression of the East Anatolia. Rate of this motion is about 20-25 mm/year (Şengör & Yılmaz, 1981). The westward motion changes the direction in West Anatolia with a rather abrupt anticlockwise rotation, toward Southwest over the Hellenic trench. The other motion is the North-South extension of the Western Anatolia and the Aegean with a rate of about 3-6 cm/year (Yılmaz 2000). As a consequence of these motions, a group of approximately east-west trending grabens has been developing (Yılmaz, 2000). Gediz Graben is one of the best-developed grabens in Western Turkey. Almost the entire section of the graben fill is exposed along its southern margin, revealing many aspects of the depositional system and the extensional deformation (Çiftçi & Bozkurt, 2009).

As Seyitoğlu & Işık (2015) has noted the Aegean region (including Western Anatolia, Aegean Sea, and Greece) is one of the areas of the earth under the effect of extensional tectonics and the extensional area includes the typical features of core complexes in this type of region. The Menderes Massif in Western Anatolia was exhumed initially as an asymmetric core complex in the Early Miocene due to extension beginning in the Oligocene and then the central Menderes Massif was further exhumed as asymmetric core complex.

2.1 Geology of Gediz Graben

Gediz Graben is located in Manisa which belongs to the West Anatolia (Figure-3). At the regional scale, the Gediz Graben comprises the main depression of the surface drainage system of the Gediz Basin. The Alaşehir section of the Gediz Graben, which possesses the largest alluvial area in the Gediz Basin, is 140 km long and 5 to 15 km wide. The Graben extends in the NW-SE direction between Sarigol and Alasehir in the west and it is divided into two main branches as from the town of Salihli towards the west. The Southernmost branch extending in E-W direction is divided into two branches, namely the Kemalpasa Basin and the Manisa Basin as from the Town of Turgutlu. The branch extending in the NW-SE direction from the Town of Salihli is known as the Golmarmara Basin. The Miocene period units of these sub-basins include the same Quaternary Alluvial unit and the basin fill sequences offer differences in the horizontal and vertical directions. According to the Turkish Petroleum Corporation's deep seismic cross-sections (Çiftçi & Bozkurt, 2009), it has been found out that there are three different Neogene sub-basins divided from one another by transfer faults under alluvium in the vicinity of Alasehir, Salihli, and Turgutlu. The seismic data showed that the easternmost basin starts in the east of Sarigol and extends as far as Derekoy towards the northwest. The basin deepening again towards Salihli pasts a transfer fault extending in the NE-SW direction closes around Sardis. Here, the Turgutlu-Ahmetli sub-basin starts through a second transfer zone. According to these data, three depressions are remaining from the Neogene period under the Alasehir (Gediz) Graben which observed as a single alluvial basin along the Sarigol-Alasehir-Salihli-Turgutlu line (Sözbilir, 2015 unpublished report). A great number of studies have been carried out on the stratigraphy of the section of the (Gediz) Graben between Alasehir and Sarigol. In such studies, the formations belonging to these made by Yazman *et al.* (1991) has reached the present day with a little change.



Figure 3: Study area and geothermal wells.

The sequence set according to this study has been combined with the seismic surveys carried out for petroleum extraction purposes in the basin and the basin pattern has been thus revealed. Accordingly, the pre-Miocene base rocks are comprised of the metamorphic rocks of the Menderes Massif and the ophiolitic rocks of the Izmir-Ankara Zone in the basin. The Miocene-Quaternary sedimentary fill of the basin is the Alasehir formation, Çaltılık formation, Gediz formation, Kaletepe formation, Bintepeler formation, and alluviums from the bottom to the top (Figure 5). The oldest sedimentary unit is Alaşehir Formation which cropping out on the southern margin of the Gediz Graben. The Alaşehir formation is characterized by a clastic facies consisted of alluvial fan deposits on the basement. This facies is defined as Haciveliler member in Yazman et al. (1991) and as Evrenli Formation in Yilmaz et al. (2000). This facies switches to sand-rich and shale-marl-rich facies in the horizontal and vertical directions. Yazman et al. (1991) combined both facies at the member level and identified them as the Evrenli member in the Alasehir Formation. The Evrenli member was studied at formation level as Kurttepe and Zeytincay, respectively and these two formations were gathered under the designation of the Alasehir Group (Yilmaz et al. 2000). The last survey carried out in the region (Ciftci, 2009) designates the coarse-grained facies of the Alasehir formation as the Evrenli member and the fine-grained facies as the Zeytincay member (Sözbilir et al. in Prep. 2019). The Çaltılık Formation overlies the Alasehir Formation with a transitional contact characterized by sandstones and pebble stones with limestone lenses. The Çaltılık Formation was first identified at the Çaltılık Village by Yilmaz et al. (2000). Seyitoglu et al. (2000) considered the Çaltılık Formation within the Kursunlu Formation. The Çaltılık Formation may be correlated with Unit II in the study of Cohen et al. (1995) and the muddy-sandy alluvial fan facies in the study of Purvis & Robertson (2005). According to magnetostratigraphic data obtained from the transitional contact of the Caltılık and Alasehir Formations, the age is 15.5 million years (Seyitoglu *et al.2015*).

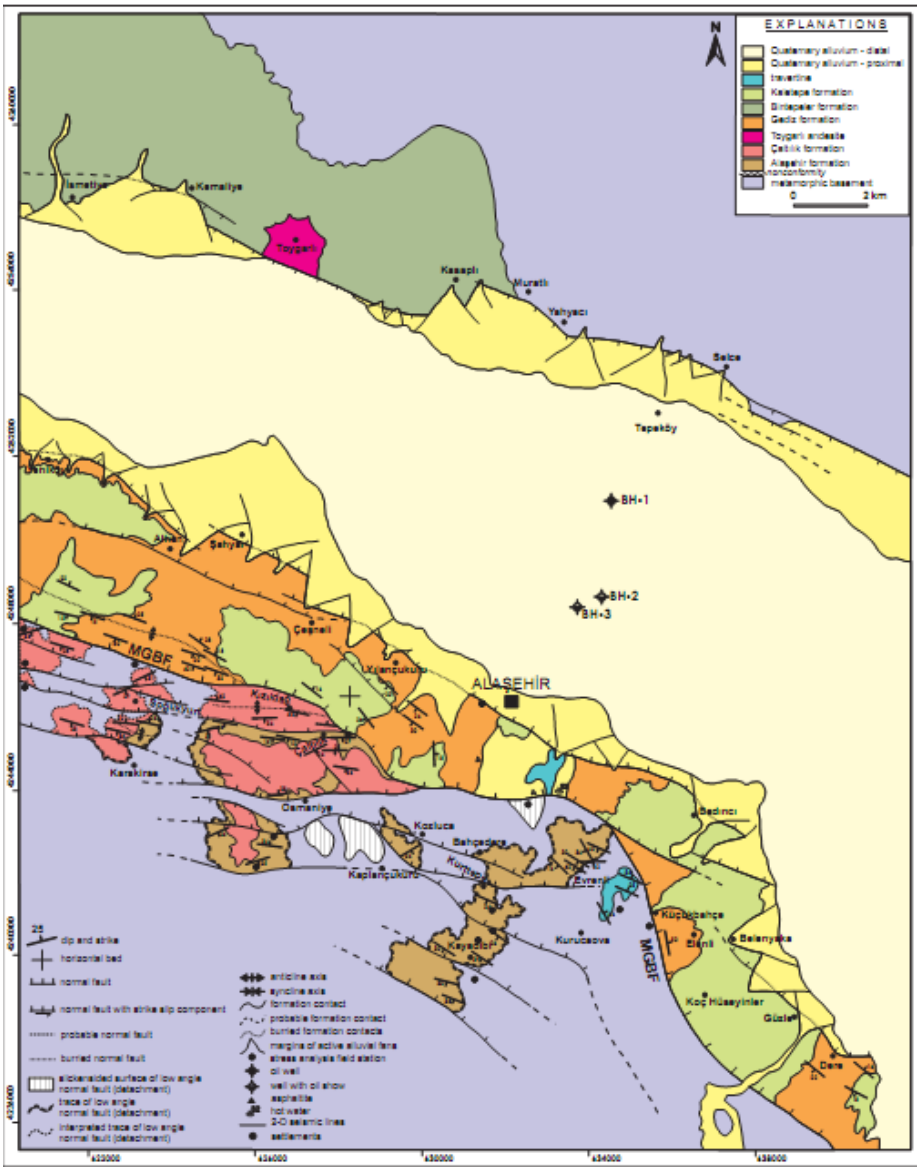

Figure 4: Geological map of the study area (Çiftçi & Bozkurt, 2009)

The Gediz Formation extends along the southern margin of the graben along a line limited by NW-SE oriented and north-trending normal faults. The Gediz Formation was first identified as the Gediz group by Yazman *et al.* (1991). According to the authors, the Gediz group is comprised of the Hamamdere and Salihli formations. These two formations consist of conglomeratic alluvial fan system and sandy fluvial system respectively. Yilmaz et al. (2000) use the designation of Kizildag group for this lithology. On the other hand, Kocyigit et al. (1999) studied the same group under the designation of Saglikdere, Kartalucan, Acidere and Gobekli formations. According to Seyitoglu et al. (2002), the Kursunlu formation contains both the Caltılık and the Gediz formations.

The Bintepeler Formation crops out on the northern margin of the Gediz graben. The formation was first mapped and designated by Yazman *et al.* (1991). The Bintepeler formation unconformably overlies the rocks of the Menderes Massif starts with coarse-grained conglomerate on the basement and limestone prevails with the finning grain size towards the top.

The Kaletepe Formation extends in the form of a strip along the southern margin of the Gediz graben. The Kaletepe Formation was first identified by Yazman et al. (1991) and then the same formation was studied under the designation of the Sart group in Yilmaz et al. (2000), Sart Formation in Seyitoglu et al. (2002) and Asartepe Formation in Emre (1996) and Kocyigit et al. (1999). The Kaletepe Formation is characterized by a less-consolidated conglomerate with multi-exemplary components and interlayers of sandstone and mudstone at small percentages. The unit overlies the Gediz Formation with angular unconformity.

The alluviums comprising the current fill of the Gediz Graben may be studied under two main facies as a lateral alluvial fan and axial fluvial sediments. Lateral alluvial fans are observed along the southern and northern margins of the Gediz Graben. The fans are made up of clastic materials deriving from the host rising along the margin of the graben. These sediments have developed under the control of the Alasehir river to penetrate the axial fluvial sediments in horizontal and vertical directions towards the center of the Graben.

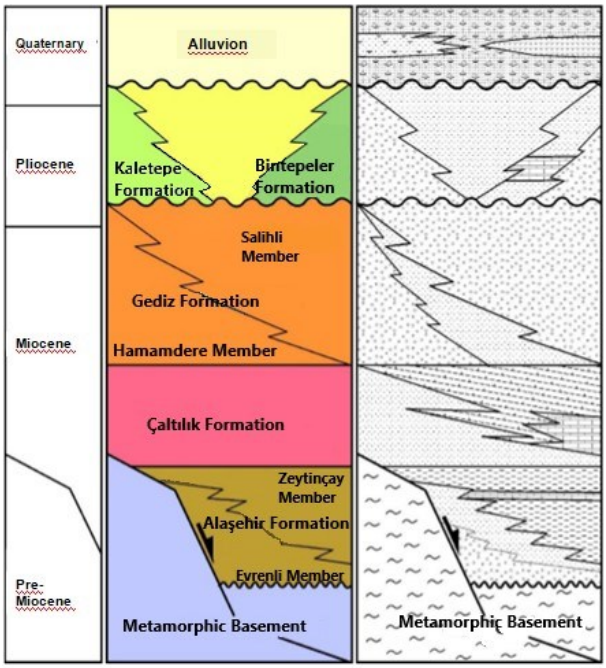

Figure 5: Stratigraphic column of the study area (Çiftçi and Bozkurt, 2009)

2.2. Geothermal Potential of the Gediz Graben

In the Gediz Graben, geothermal systems were determined on a metamorphic basis. The geological units such as Alaşehir, Çaltılık, Gediz and Kaletepe Formations on the metamorphic basement act as a cap rock. Menderes massif composed of schists, quartzites, phyllites, and carbonates. Particularly, marble, schist, and mica schists are commonly observed in the reservoir. Beside marble and schists, calc-schist, dolomite gneiss and quartzite are observed as well. Menderes Massif rocks are highly fractured due to faults so that they are crucial considering geothermal operations. Geothermal fluid in Gediz Graben originates from structural zones of low angle Gediz detachment fault of Quaternary age and high angle normal faults of Holocene age. For the geothermal application, many wells with the function of production and reinjection have been drilled with a depth range from 1000 to 3500 m in the Graben. There are medium-high enthalpy fields in the study area. Reservoir thickness and temperature data are evaluated from drilling reports.



Figure 6: Active faults with geothermal production and reinjection wells in the study area (revised from MTA Active fault map 2012)

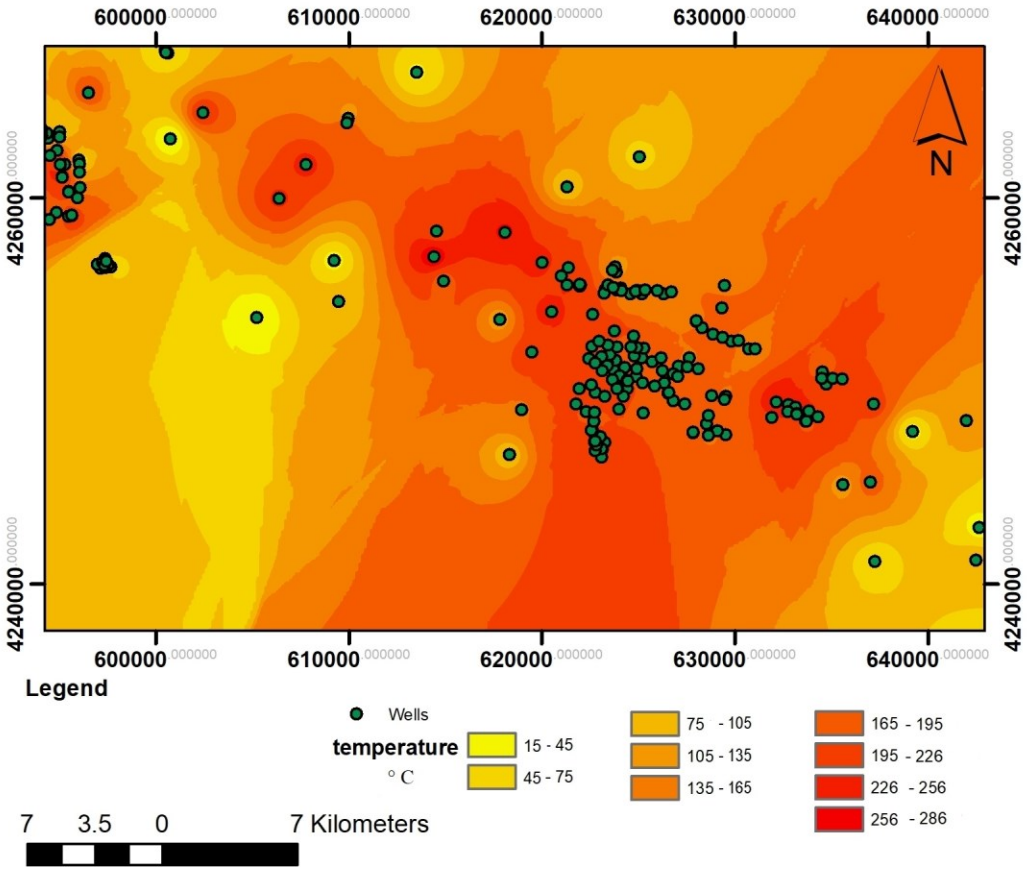

Figure 7: Bottomhole temperatures of the geothermal wells (° C)

Reservoir temperatures from geothermal wells at the southern part of the Graben indicated high temperatures (>250°C). At the eastern part of the Graben, reservoir temperatures are between 110-150°C (Figure 7). The maximum measured temperature is 286°C at the center of Gediz Graben. In the exploration stage reservoir temperatures estimates ranged from 193°C to 217° C based on quartz geothermometer.

There are nine binary and a combined flash-binary power plants with approximately 300 geothermal wells in the study area. The total capacity of these geothermal power plants is over 220 MW. Additional new power plants will be installed before 2020 due to geothermal incentive laws. Further development in geothermal energy industry is expected to accelerate in the next years. In this study, five geothermal fields in the Alaşehir part of Gediz Graben were examined.

3. SEISMICITY AND GEOTHERMICS IN GEDIZ GRABEN

Production - reinjection data and seismic data were evaluated together with the tectonics and geology of the region by using the software QGIS. In that analysis, especially seismicity was observed around geothermal wells drilled for reinjection. It is concluded that earthquakes with magnitude 1-3 can be related to the geothermal activity. However, no direct correlation was found between the pressure, flow rate and the earthquake magnitude of the injected fluids. No correlation was observed between the high pressures or flow reinjection and induced seismicity. In addition to the reinjection process, micro-earthquakes were observed during the hydraulic fracturing process which may occur due to reactivation of preexisting faults. According to the Observatory - Earthquake Research Institute and Prime Ministry Disaster - Emergency Management Authority data, earthquake epicenter depths range between 2-10 km. Most of earthquake epicenter depths are between 2-7 km intersecting Holocene and Quarternary fault zones and reservoir levels. Significant seismic activities observed at some locations are estimated to be related with the Quarternary faults which form the hottest regions (Figures 8 and 9).

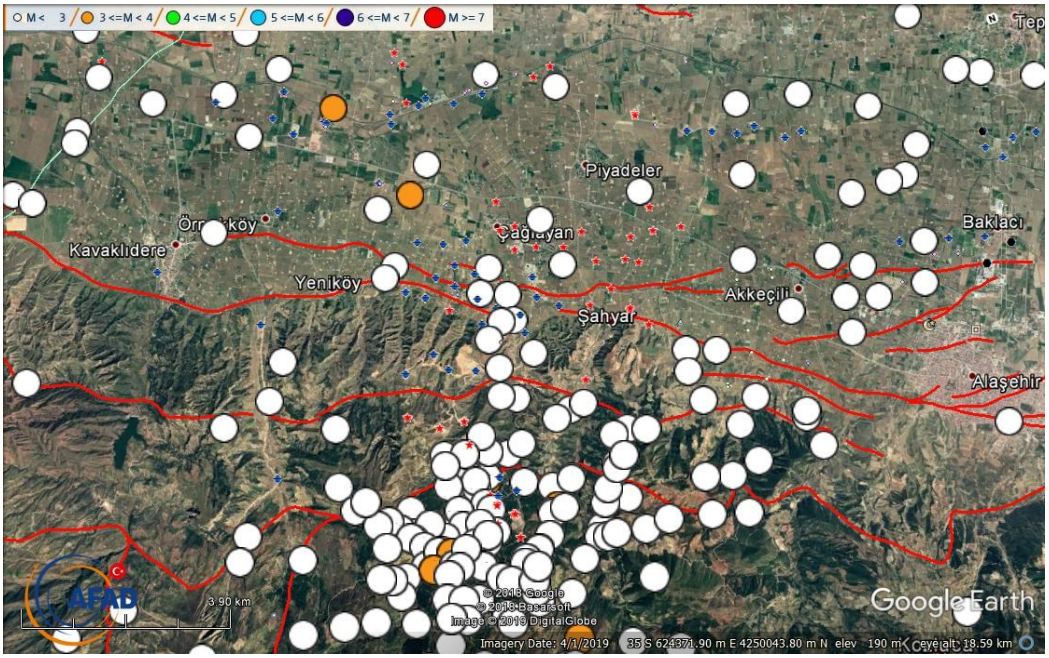

Figure 8: Earthquake epicenters (circles), geothermal wells (stars) and active faults (red curves).

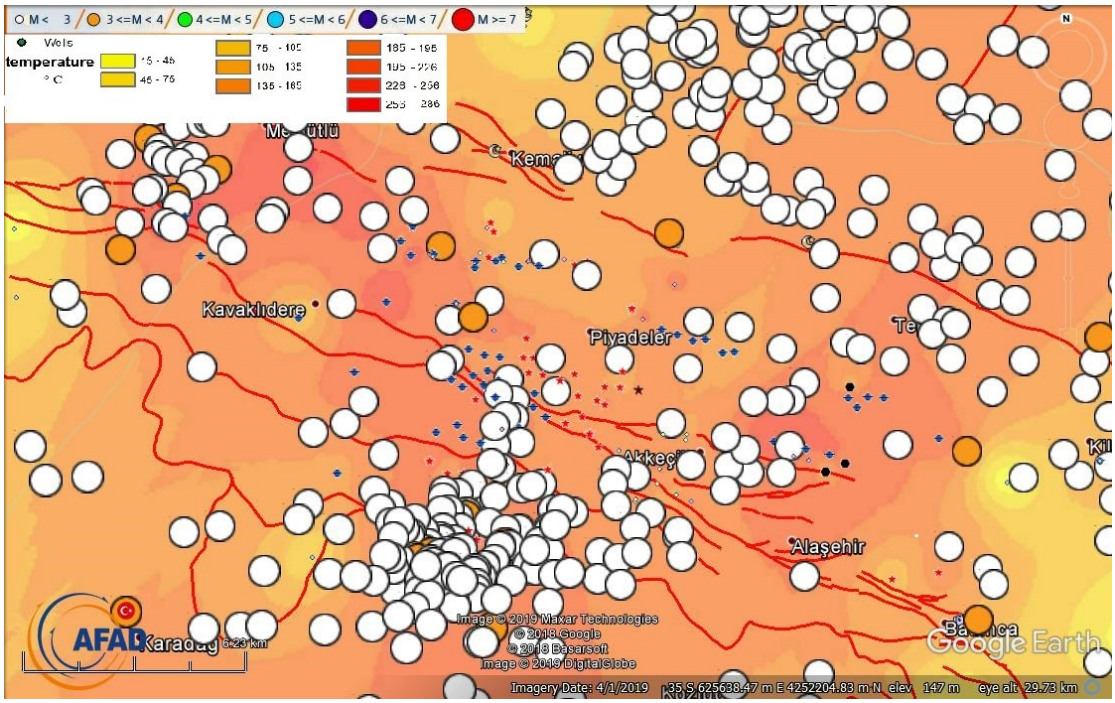

Figure 9: Earthquake epicenters, geothermal wells and bottomhole temperature.

Geothermal fluids have been produced and injected in five different sites. Except Kemaliye Geothermal Site most of them are high-temperature fields. In general high temperature sites are seismically more active. It is anticipated that the high seismicity in high-temperature fields can be caused by active faults in these areas (Figure 9).

Geothermal Site & Power Plant	Capacity (MW)	Date of Operation Starting	Injection Depth [m]	Daily Average Injection (m^3 / day)	Seismicity	Largest Earthquake [ML]	Reinjection Site
Soğukyurt	23,52	2017 March	1500-3700	15000	Large	3,4	Gediz Graben Detachment Fault
Alkan-Piyadeler	48	2015 September - 2016 October	1300-2700	50000	Minor	2,1	Alaşehir Segment
Çeşneli-Şahyar	45	2015 October	1000-1900	45000	Moderate	2,2	Alaşehir Segment
Kemaliye	24,9	2016 May	700 - 3400	35000	Minor	1,4	Northern Graben Fault
Örnekköy	10	2017 June	2000-2500	12000	Minor	1,6	Alaşehir Segment

Table 1: Geothermal sites and maximum observed magnitudes of earthquakes.

Reinjection data is obtained from geothermal operators and Manisa Investment, Monitoring - Coordination Directorates. Although the research area has a background of natural seismicity, geothermal activities are thought to trigger earthquakes. It is determined that 233 of the 500 earthquakes occurred between 2016-2018 in the study area within the time interval of 1990-2018 (Figure 10). Most of the geothermal wells were drilled between 2011-2015 in the Gediz Graben. Fracturing operations and injection tests after drilling wells may have triggered seismicity. Although the seismicity decreases after the commencement dates of the power plants, it continues depending on the original conditions of the site such as proximity the active faults.

Before the geothermal fluid production and injection, reservoir pressure was reached at 5 MPa locally. During the geothermal application, reservoir pressure decreased to levels of 1-2 MPa. This decline affected production and reinjection pressure in recent years. Flow rates and reinjection pressures fell drastically. The decrease in the reservoir pressure due to the change in the partial pressure of carbon dioxide also reduced the reinjection pressure. Since 2017, that decrease in reinjection pressure has caused a decrease in seismicity (Figure 10).

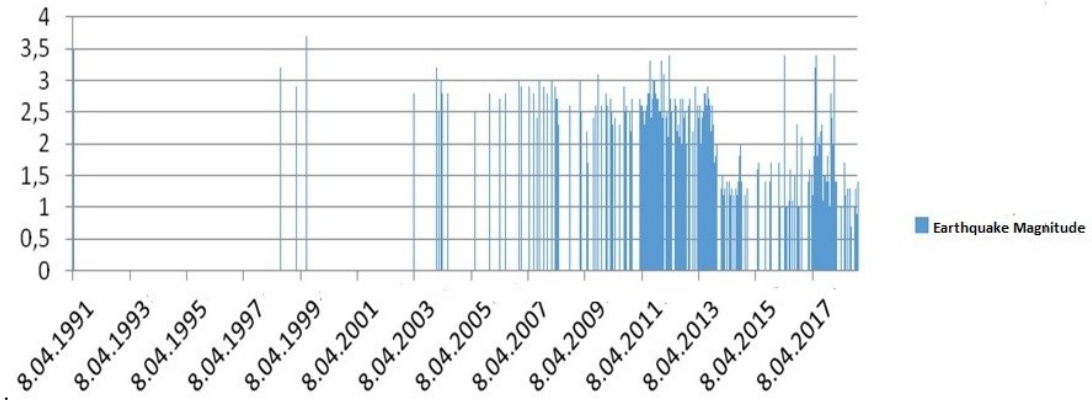

Figure 10: Observed earthquakes magnitudes in the Gediz Graben between 1990-2017.

Although the amount of production and reinjection is low, the most seismically active area is the Soğukyurt site.. The maximum observed earthquake magnitude is 3,4 in the Soğukyurt site (Table 1). Soğukyurt reinjection site is on Gediz Graben Detachment Fault and metamorphic basement cropped out at the surface (Figure 4 and Figure 8). Minor seismicity is observed at the Alkan Piyadeler geothermal site. The maximum observed magnitudes is 2,2 at the Alkan Piyadeler and Şahyar- Çeşneli sites. Şahyar-Çeşneli site is more active than the Alkan-Piyadeler site seismically. Kemaliye and Örnekköy sites has minor seismicity and the magnitudes are below 2. This data set points out that the induced seismicity may be related with the Gediz Graben Detachment Fault. For example, Soğukyurt geothermal field has minor reinjection capacity but also there is high seismicity observed (Table 1).

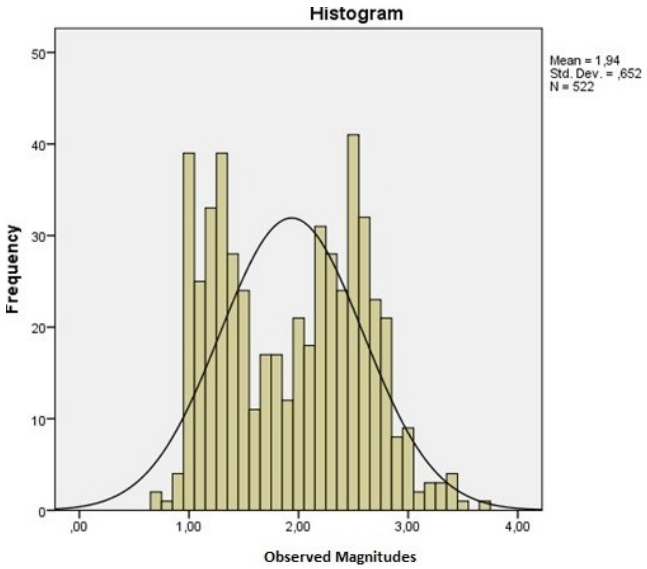

Figure 11: Observed earthquake magnitudes in the Gediz Graben between 1990-2017 (AFAD 2018).

The histogram of the observed earthquake magnitudes in the study area is depicted in Figure 11. Most of the magnitudes are ranging between 1 - 1,5 and 2 - 3. Other earthquakes are not related to geothermal fields, possibly due to different operating dates of the plant and re-injection wells.

4. CONCLUSIONS

It is concluded that earthquakes with magnitude of 1-3 can be related to the geothermal activity. However, no direct correlation was found between the pressure, flow rate and the earthquake magnitude of the injected fluids. No correlation was observed between the high pressures or flow reinjection induced seismicity. In addition to the reinjection process, micro-earthquakes were observed during the hydraulic fracturing operations which may occur due to reactivation of preexisting faults. In order to examine that incident in more detail, the seismometers should be deployed near to the power plants and, following that the change of the injection flow and pressure varying with time together with lithology should be determined. Most of earthquake epicenter depths are between 2-7 km intersecting Holocene - Quarternary fault zones and reservoir levels. Seismically most active locations may have a relation with the Quarternary faults which form the hottest regions.

Progress of geothermal resources has been accelerated with the release of Law on Geothermal Resources and Natural Mineral Waters (No: 5686, Date: June 3, 2007) and its Implementation Regulation (No: 26727, Date: December 2007) in Turkey. Various environmental problems are experienced due to rapid development. Induced seismicity is also one of the neglected factors during that rapid development. Geothermal development is expected to be continued next years in Turkey, especially in the Gediz Graben. Therefore, methods should be developed to monitor the seismic effects of geothermal activities.

A method called “traffic light system” has been using especially in countries where enhanced geothermal system applications were conducted, in order to trace production and reinjection activities. In worst-case situations, these activities in power plants can be halted using that method (Grigoli et al. 2017 and Gaucher 2018). Ensuring such kind of infrastructure concerning geothermal power plants in Western Anatolia is very important. Detailed studies can be then conducted to estimate the relationship between geothermal production-reinjection activities with seismicity.

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