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Seismostatistical Characterization of Earthquakes from Geothermal Reservoirs

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ABSTRACT

The occurrence of induced seismicity in the form of felt earthquakes has been recognized as one of the critical environmental burdens associated with recent geothermal development. For this reason, research into enabling technologies for risk assessment of larger magnitude induced events has taken on an increased priority. In this study, we have applied a seismostatistical modeling method to microseismic data collected at two geothermal fields and have investigated its feasibility for risk assessment. Here we have applied the Epidemic Type Aftershock Sequence (ETAS) model (Ogata, 1988), which has been widely used in the area of natural seismology, as a first step in this geothermal earthquake risk assessment study. The microseismicity observed at Yanaizu-Nishiyama, one of the largest hydrothermal geothermal fields in Japan, has been successfully modeled with ETAS. Induced seismicity at the Basel EGS site in Switzerland was also modeled with ETAS, in this case using short moving time windows since modeling for the whole seismically active period was unsuccessful. Our study suggests that one of the parameters in the ETAS model, which has previously been interpreted to represent the occurrence rate of events triggered by external forcing (Hainzl and Ogata, 2005), can in both our cases be correlated with the treatment/stimulation injection rate into each reservoir. Our preliminary results demonstrate the feasibility of seismostatistical modeling in assessing the risks of felt earthquakes associated with various human operations in geothermal reservoirs, although further investigation and modeling of behavior of induced seismicity is required.

1. INTRODUCTION

Occurrences of felt earthquakes from geothermal reservoirs (Evans et al., 2012; Häring et al., 2008) have been recognized as one of the critical environmental burdens associated with geothermal development, and number of studies have sought to address this problem (e.g. Eisner et al., 2010; Majer et al., 2007) and work is ongoing. Studies furthering seismological/geomechanical understanding of the mechanisms behind these felt earthquakes through precise/detailed analysis of collected data have been carried out (Evans et al., 2012; Mukuhira et al., 2013). However, current results suggest that it is unlikely that a single common physical model for all geothermally-related felt earthquakes can be established that might be applied to geothermal operations so as to minimize the risks of felt earthquakes. This is because of the high complexity, uncertainty and site-dependent nature of the earthquakes (Asanuma et al., 2011; Mukuhira et al., 2010). We have therefore considered an alternative approach, i.e. seismostatistical modeling of a series of earthquakes. Seismostatistical methods can provide information for risk assessment of the felt earthquakes in geothermal fields currently under operation because it requires relatively straightforward inputs, such as hypocentral location, amplitude and origin time rather than detailed analysis of individual seismic events by experienced seismologists. Universality of the model can be also realized by applying an automated tuning algorithm to the parameters in the model using prior seismicity from each site.

The effectiveness of such seismostatistical modeling has previously been demonstrated with natural earthquake data (Ogata, 2001), where estimations of the largest likely magnitude of aftershocks and identification of the silent period prior to large earthquakes have been realized (Ogata, 1992; Zhuang et al., 2002). In this paper we investigate the feasibility of such seismostatistical modeling to the geothermal problem by applying one of the common seismostatistical models in seismology to geothermally-induced seismic data. The results here are only preliminary however because it is to be expected that the statistical nature of induced seismicity from geothermal fields will differ from naturally occurring seismicity. Subsequent investigations of alternative seismostatistical models for induced seismicity are necessary.

2. THE ETAS SEISMOSTATISTICAL MODEL

The Epidemic Type Aftershock Sequence (ETAS) model is one of the family of point process models (Ogata, 1988). Seismologists have been using the ETAS model as one of the standard seismostatistical models of natural seismic activity, because its capability to forecast seismic activity in short time range has been demonstrated through analysis of various field data (Ogata, 1992; Zhuang et al., 2002).

The ETAS model is an extended version of the modified Omori formula (Utsu, 1961), which fits well with aftershock sequences and swarms. The occurrence rate of the earthquake $\lambda_0(t \mid \mu, K, c, \alpha, p)$ at a present time t is represented as:

$$\lambda_0(t \mid \mu, K, c, \alpha, p) = \mu + \sum_{t_i < t} \frac{K e^{\alpha(M_i - M_z)}}{(t - t_i + c)^p} \tag{1}$$

Here, the vector $\boldsymbol{\theta}$ which is a function of the parameters μ, K, c, α, p in the ETAS model is defined to be constant for all the earthquakes in a given area and period in most of its applications (Ogata, 1988). The summation on right side of the Equation (1) is taken for all the past earthquakes with an origin time t_i $(t_i < t)$. M_z is a lower cut-off threshold. Events with smaller magnitudes than this threshold are not used in the modeling.

The parameter μ, in the ETAS model represents the occurrence rate of earthquakes which do not follow the modified Omori formula. Events for which the occurrence rate is defined by μ are referred to as "primary fluid signals" and are interpreted to be triggered by external forcing such as by water injection in the area of seismic monitoring during subsurface development (Hainzl and Ogata, 2005).

The estimate of the occurrence time of i th earthquake can be obtained by Equation (2) which represents the cumulative number of earthquakes that have occurred prior to a present time t. In this study, the magnitude of the i th earthquake in the identified model is defined to be equal to the i th observed earthquake, when we model and evaluate past seismic activity. Meanwhile, in the modeling of future earthquake activity, the magnitude of i th earthquake is obtained from a random array of numbers which follows the Gutenberg-Richter distribution (Gutenberg and Richter, 1941) from the past data.

$$\Lambda_{\boldsymbol{\theta}}(t) = \int_0^t \lambda_{\boldsymbol{\theta}}(s \mid \mu, K, c, \alpha, p)\,ds \tag{2}$$

3. DATA DESCRIPTION

In this study, we analyzed microseismic data from two geothermal fields. The first data set was collected at Yanaizu-Nishiyama, one of the largest hydrothermal fields in Japan (Adachi et al., 2010). The reservoir is steam dominant and most of the geothermal fluid left after power generation has historically been injected into a reinjection zone which has very low seismic activity. However after 2002 for reservoir treatment, some amounts of the fluid have been injected into a well which penetrates into the production zone (Adachi, 2010 et al.; Asanuma, 2011 et al.). Natural seismic activity around this site has been observed since the exploration phase and it has been monitored by a local monitoring network. Local magnitudes of the events from this field are estimated by Watanabe's formula (Watanabe, 1971). Four felt earthquakes with local magnitude M_L larger than 3.0 occurred after starting operation of the power plant in 1996 (Japan Meteorological Agency, 2009). The largest event with 4.3 occurred in October, 2009 and caused some degree of damage to the power plant and residents around the site (Asanuma et al., 2011). However, it has been reported that no significant correlation is observed between some of the features of the felt earthquakes and the operation to the reservoir (Asanuma et al., 2011). The input data for Yanaizu-Nishiyama consists of a total of 11,402 microseismic events that occurred in the period from April 3rd, 1996 to January 25th, 2012 with local magnitudes larger than -1.3.

The second data set for this study was collected at the Basel EGS site in Switzerland, a region characterized by natural seismicity over several hundred years (Häring et al., 2008). This dataset comprises 2924 induced events including a number of felt earthquakes. Seismic activity followed fluid injection on December 2nd, 2006, and six days later the first felt earthquake occurred. Although the injection was stopped and pressure bleeding-off operations were started, further felt earthquakes occurred. Indeed, three felt earthquakes occurred several months after the pressure bleed-off (Häring et al., 2008). We used a total of 2,924 microseismic events that occurred between December 3rd, 2006 and June 7th, 2007 with moment magnitudes M_W larger than 0.0.

4. RESULTS AND DISCUSSION

4.1 Yanaizu-Nishiyama

Figure 1 shows a comparison of the observed data with the identified ETAS results for the data. Both the cumulative curves (Fig. 1a) and the time series plots of observed and modeled magnitudes (Fig. 1b and 1c) are reasonably consistent over the whole monitoring period.

Correlation between the occurrence rate of the interpreted primary fluid signals μ and the actual fluid treatment injection rate using short moving windows each of which includes 100 microseismic events has been investigated. The change of μ with time is shown in Figure 2(g). The value μ rose at the end of 2002, when the treatment injection has started, and remained higher until the occurrence of the largest felt earthquake in October 2009.

We spatially clustered the microseismic events at Yanaizu-Nishiyama using a sphere with a center at the treatment injection point and a radius of 600 meters. The changes in μ for events inside and outside of the sphere are shown in Figure 2(h) and (i). The notable difference between these two plots is the rapid rise in near field μ from near-zero values following the commencement of injection in late 2002. In contrast, the far field μ shows no obvious change at this time.

The change in μ with distance from the treatment injection point is seen more clearly in Figure 3. Here we plot the ETAS modeled μ values for 100 events clustered around the injection point against distance. In spite of some scatter in the results, a clear decrease in μ associated with distance can be seen in the figure.

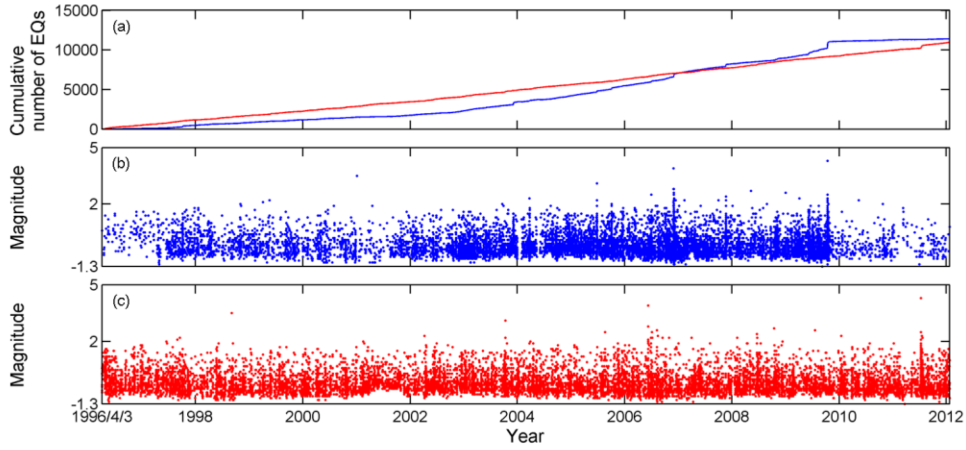

Figure 1: Data comparison between observation and identified ETAS model at Yanaizu-Nishiyama. (a) Cumulative number of microearthquakes (blue: observation, red: identified ETAS model). (b) Magnitudes of the events (observation). (c) Magnitudes of the events (identified ETAS model).

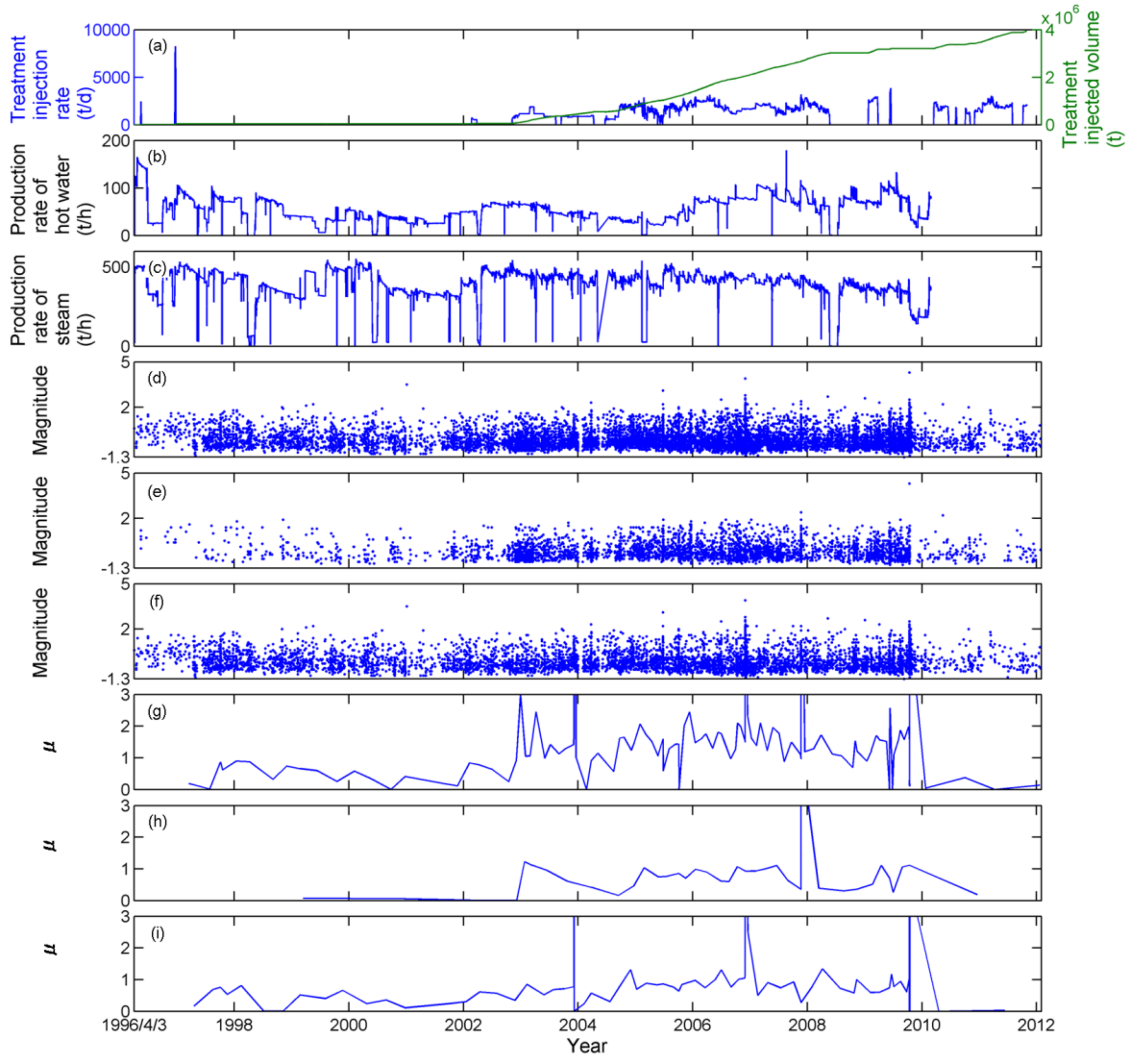

Figure 2: Relationships between production/treatment injection rate, seismic activity, and the occurrence rate of primary fluid signals for the data at Yanaizu-Nishiyama. (a) Treatment injection rate of water (blue) and cumulative injected volume (green). (b) Production rate of hot water. (c) Production rate of steam. (d) Magnitude of the events (all events). (e) Magnitude of the events (near field). (f) Magnitude of the events (far field). (g) Occurrence rate of primary fluid signals (all events). (h) Occurrence rate of primary fluid signals (near field). (i) Occurrence rate of primary fluid signals (far field).

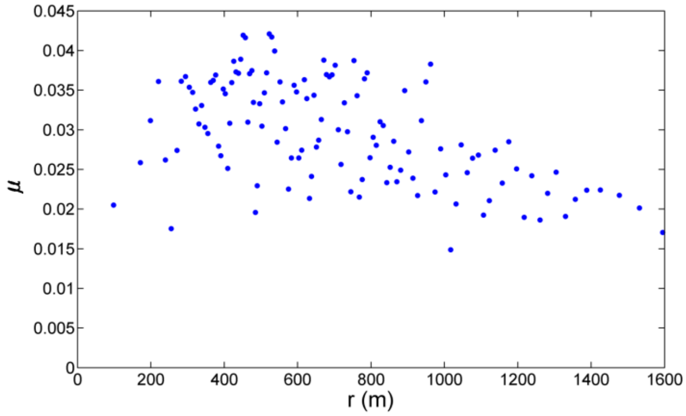

Figure 3: The occurrence rate of the interpreted primary fluid signals as a function of distance from the treatment injection point (Yanaizu-Nishiyama).

4.2 Basel

We found that both the ETAS modeled events are inconsistent with the overall set of observations. We therefore tried to model the data at Basel using short moving windows each of which includes 100 microseismic events. The results of this analysis are shown in Figure 4. Here the cumulative event curve and the magnitude time series calculated by the identified ETAS model can be seen to be reasonably consistent with the observed data. Similar correlations are seen for each short period window.

The time changes of occurrence rate of the primary fluid signals have been also estimated as shown in Figures 5. In Figure 5(f) the value can be seen to have increased in the period from December 6th to December 8th, 2006 and then decreased, generally showing good correlation with the pumping history (Figure 5(a)).

4.3 Discussion

Natural microseismic activity has been recorded in the Yanaizu-Nishiyama geothermal field since before geothermal developments began there. This long term microseismic activity at the Yanaizu-Nishiyama geothermal field has been successfully modeled by the ETAS. Meanwhile, we found that the long-term seismicity induced by the hydraulic stimulation at Basel was poorly modeled by the ETAS. The reason for this difference in modeling behavior is uncertain but it may point to the possibly different nature of the induced seismicity at Basel when compared with Yanaizu-Nishiyama and with naturally occurring seismicity where ETAS has been used successfully in the past by others.

The most significant finding from our study is that there is a clear correlation between μ and treatment/stimulation injection rate into the reservoirs in both cases. It has been also found that the value of μ decreased with distance from the treatment injection point in the case of Yanaizu-Nishiyama. From a seismostatistical point of view, and given that models such as ETAS have been used successfully in the past to model natural seismicity, the current results suggest that the seismicity at Yanaizu-Nishiyama is suitable for ETAS modeling. Events located for which the hypocenters are located within approximately 300-700m of the treatment injection point may have a more induced nature. It is also seen that the value of μ generally showed reasonable correlation with the stimulation injection rate in the case of the Basel dataset. The decrease in μ in the middle/final stages of the stimulation on December 7, 2006 might in turn suggest that the seismic events started to acquire a more natural character, i.e. sequences of events with similar nature to aftershocks started to occur in this period.

We consider that our results, while preliminary, demonstrate the feasibility of seismostatistically-derived risk assessment of felt earthquakes associated with various human operations in geothermal reservoirs. While the model introduced in this study has been developed for natural seismicity, our results suggest that models such as these may be extended into studies of induced seismicity. The authors have previously reported that some of the characteristics of the seismicity from geothermal reservoirs, such as extension of the hypocentral cloud, initiation of microseismic multiplets, and magnitudes of the events, show correlations with human operations on the reservoirs (Asanuma et al., 2011, Shapiro et al., 2010). Hence, we expect that the derivation of the seismostatistical representations of such operation-related behavior of the seismicity from the geothermal reservoirs would enable us to establish risk assessment technique of induced felt earthquakes, and further studies will be conducted focusing on this issue.

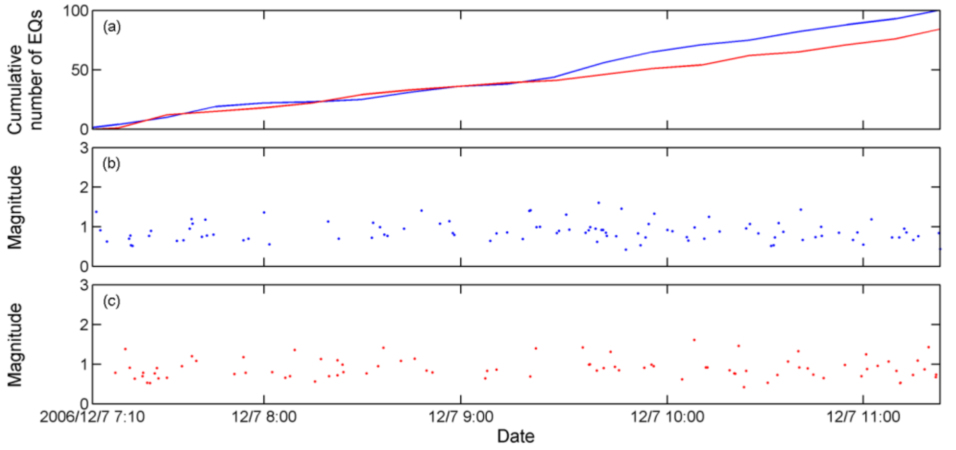

Figure 4: An example of data comparison of observation and identified ETAS model at Basel using short moving time windows (December 7th, 2006). (a) Cumulative number of microearthquakes (blue: observation, red: identified ETAS model). (b) Magnitudes of the events (observation). (c) Magnitudes of the events (identified ETAS model).

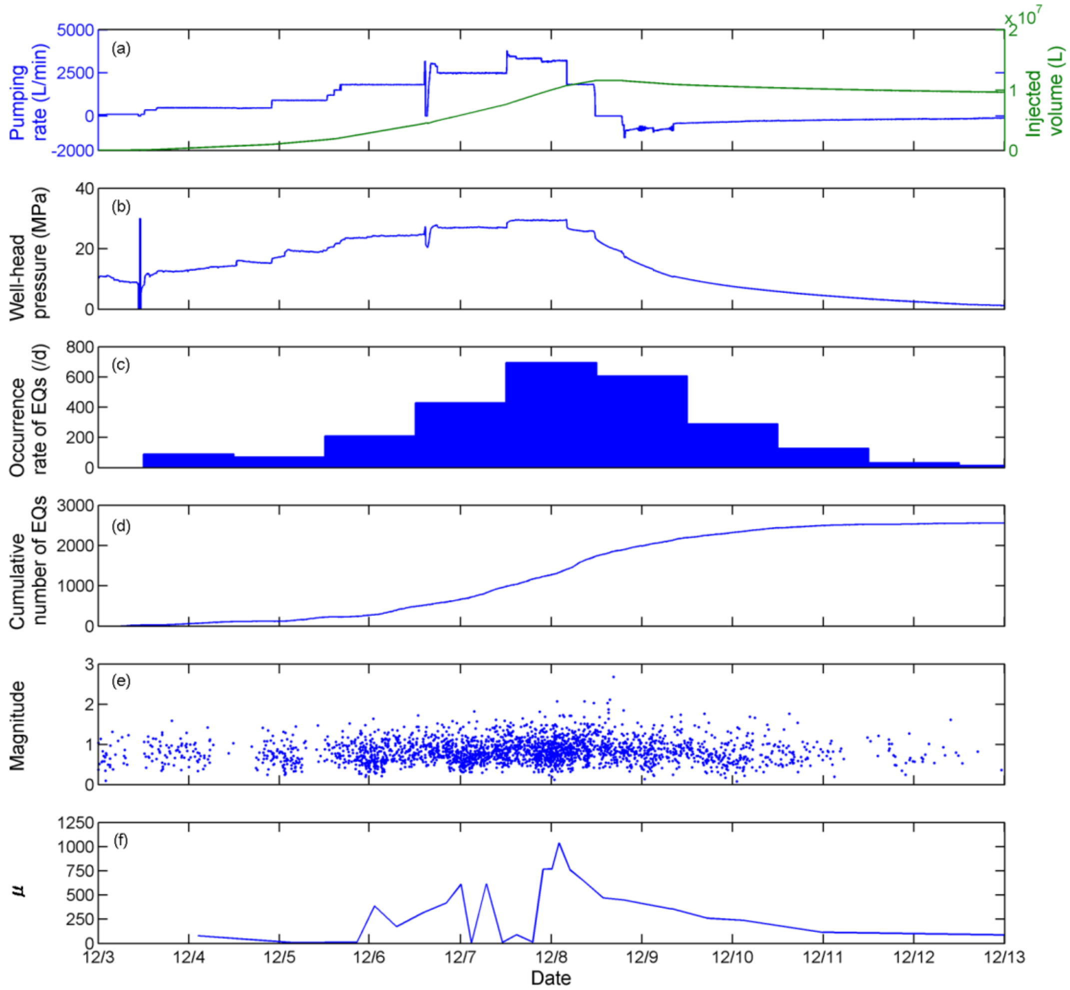

Figure 5: Figure 7: Relationships between pumping rate, well-head pressure, seismic activity, and occurrence rate of primary fluid signals for the data at Basel (December 3rd to 12th, 2006). (a) Pumping rate of water (blue) and cumulative injected volume (green). (b) Well-head pressure. (c) Occurrence rate of microearthquakes. (d) Cumulative number of microearthquakes. (e) Magnitudes of the events. (f) Occurrence rate of primary fluid signals.

5. CONCLUSIONS

A seismostatistical model, which has been used in natural seismology, has been applied to seismic events observed in hydrothermal and EGS sites. The seismic activity from a hydrothermal field with pre-existing background natural microseismicity was successfully modeled. Meanwhile, a large misfit has been found when modeling data from an EGS site. This differing success with the modeling is thought to be due to significant differences between the characteristics of induced and natural seismicity. We, however, found that one of the parameters in the model, which is inferred to represent the occurrence rate of independent events related to human operation, showed clear correlations with the injection history of the reservoirs, suggesting the feasibility of this statistical approach. Studies to establish a seismostatistical model for risk assessment of induced felt earthquakes will be continued by integrating our previous observations on natural/induced seismicity from reservoirs.

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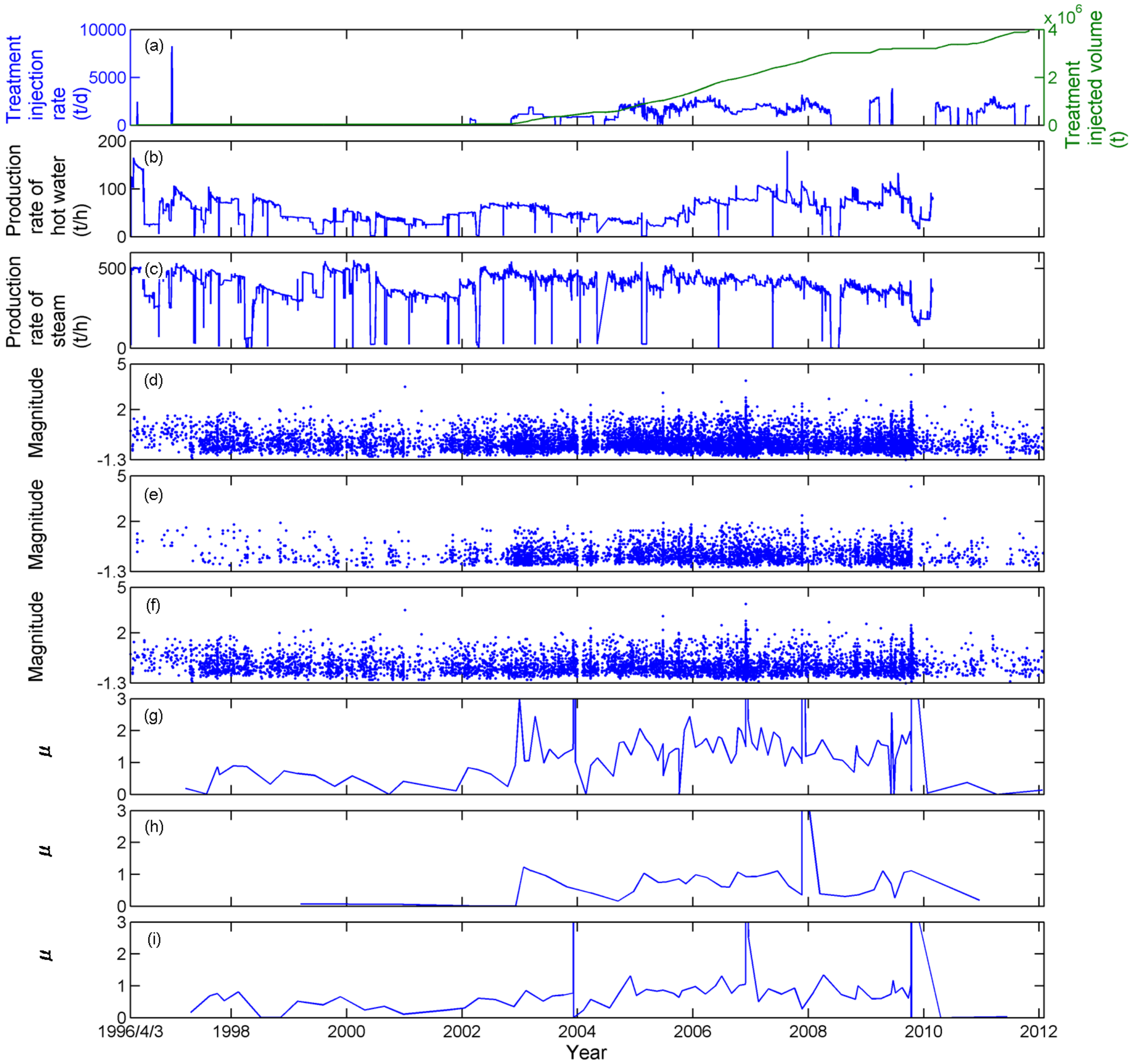

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2.2 Sections of Your Paper

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