Characterizing Fractures in The Geysers Geothermal Field Using Soft Computing

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ABSTRACT

Developing improved methods to better characterize fractures in Enhanced Geothermal System (EGS), new methodologies to characterize geothermal reservoir northwest part of The Geysers, and gain better knowledge of their porosity, permeability, fracture size, fracture spacing and reservoir discontinuities (faults and shear zones) is the main objective of this article. In addition, soft computing is used for processing and analyzing the microseimic events.

Some of these fracture systems are created by injecting water, and stimulating fracture development in hot wet rocks, and hot dry rocks. The fractures thus created enhance the permeability of the hot rock formations, enabling better circulation of water for the purpose of producing the geothermal resource. Better understanding of the mechanisms for fracture stimulation leads to a better exploitation of geothermal resources. Our initial test bed for the newly developed methods will be The Geysers field located in Sonoma County, California to be followed by application to other fields with similar sub-surface characteristics.

Careful analysis of the MEQ data in The Geysers field by unleashing the power of neuro-fuzzy approach for the processing of the MEQ data can provide us with a mathematical framework to develop a more practical velocity field. Further, we demonstrate that utilizing various neural-network-based approaches also leads to a better understanding of the fracturing system. This will be accomplished by adapting some of the attributes of the conventional seismic data used in the oil and gas exploration and production to E&P in geothermal fields. Some of such seismic attributes we would like to examine include similarity (coherency), eccentricity, and curvature to carry out fracture modeling analysis and interpretation.

Micro-earthquake (MEQ) data analysis both for compressional waves and shear waves, with the aid of soft computing and fractal techniques, demonstrate the versatility and flexibility of the methods. This enables us to analyze and interpret subtle micro-seismic data effectively. We also show the use of Neuro-fuzzy approach for a hybrid MEQ event picking.

Finally, hybrid neural network and fuzzy logic approach is used to create a more reliable reservoir map. This approach extended to examine and analyze the microseismic data acquired in this article and develop an accurate fracture map for the area. Handpicked events in selected seed points are used as the training set for the neuro-fuzzy auto-picker. Our hybrid approach becomes superior in both ability to pick the subtle events and the efficiency of the process.

Introduction

Soft computing (including neural networks, fuzzy logic, and genetic algorithms) has been used extensively in geosciences and energy-related applications. Some of such applications have been highlighted by (Aminzadeh & de Groot, 2006). Yet, practically no such applications have been for exploration and exploitation of geothermal resources. An exception is the work by (Akin, 2008) who demonstrated how neural networks could be used to create volumetric pressure and enthalpy response in a geothermal field in Turkey (Ghomshei, Meech, Fraser, & R, 2001) used fuzzy logic to design an optimum heat pump in a geothermal field.

The seismic refraction technique has been used for exploration and production from geothermal fields, mainly as a reconnaissance tool for mapping velocity distributions. The focus has been primarily in the top few kilometers of the crust, from which faults, fracture zones, intrusions, rock types and other structural features are inferred.

Investigation of microearthquakes (magnitude range: 1–3), in EGS systems are often characterized by a high level of microearthquake activities which are induced by water injection. Monitoring these events help us to optimize the EGS systems. (Majer & Peterson, 2007)

Large numbers of MEQs take place beneath injection wells, and high resolution MEQ locations should locate the flow paths from these injection wells. This correlation is predictable, implying that intelligent injection procedures helped Calpine to control the increase in seismicity, and permeability. (Majer & Peterson, 2007)

The sudden loss of shear-wave energy is correlated with the sudden loss of high frequencies in the seismic signals from pressurized zones. This was based on an experiment at The Geysers field, at 2635 m depth, wherein the pressurized signals probably demonstrated the top of a zone of large fractures which are normally closed, but have potential to open under pressure, with a corresponding increase of reservoir permeability. In addition, self-propped fractures are characterized by a second loss of high frequencies, correlated with a sudden loss of signal amplitude in the unpressurized spectral power log. (Fehler & Pearson, 1984)

Furthermore, the production and injection zones boundary, the density, and the orientation of the aligned fractures can be estimated by the shear-wave polarization analysis, and by the relative delay of acoustic emission events. (Sato, Matsumoto, & Niitsuma, 1991)

Stark (2003) presented a model to explain an unusual spatial distribution of seismicity observed in the NW Geysers. This model is based on the hypothesis that reservoir hot rock and injected cold water triggers earthquakes by their contact. This model indicated that great amounts of injected water descend into depths within the high temperature zone. Much of this water has been boiled and produced in accordance of the EGS concept. (Stark, 2003)

Rutqvist et al. (2007) concluded that the most probable mechanism of induced seismicity at The Geysers is shear slip along existing fractures. They also indicated that thermal-elastic cooling shrinkage is the main cause of stress changes near injection and production wells due to injection-induced seismicity. Both thermal-elastic cooling shrinkage and increased fluid pressure reduce the effective stress of deep injection-induced seismicity at greater depth below the injection and production wells. In the shallow parts of the system and in the cap rock, Stress redistribution from injection-induced cooling shrinkage within underlying reservoir leading to injection-induced seismicity. (Rutqvist & Oldenburg, 2007.)

Estimating the properties of EGS systems such as porosity, permeability, fracture size, fracture spacing and reservoir discontinuities (faults and shear zones) is the key parameter for developing these systems throughout the world. We used ample amount of microseismic events at The Geysers geothermal field provided by LBNL. Both P- and S- waves are used to create a 3-D seismic velocity model of the field. In addition, soft computing is used for both processing and analyzing the passive data.

We used Neuro-fuzzy approach to develop the hybrid MEQ event picking. Our focus in this part is to carefully analyze the microseismic data in The Geysers field. We used the power of neuro-fuzzy approach in the processing of the MEQ data and in developing a mathematical framework for the velocity fields to develop a more practical velocity field. We used the neuro-fuzzy approach as described in (Aminzadeh & Brouwer, 2006) to help with the automation process and its improvement of picking MEQ seismic events.

Fuzzy clustering of the microseismic events in both discrete time windows and locations leads into accurate fracture map for the area. Careful review of the time windows of each specific location also demonstrates the fracture network propagation direction.

Neural Network to Estimate the Properties of EGS Systems

Among the first use of neural networks for the analysis of MEQ data is the work of Aminzadeh et al (1994) where several attributes of earthquakes precursor data were used as input to a neural network in order to test the predictive power of such attributes in a real data case.

Neural networks provide an accurate estimation of parameters that describe the EGS systems properties. Specially, neural networks accurately obtain functional relationships between subsurface rock properties (e.g., porosity, permeability, fracture size, fracture spacing and reservoir discontinuities) and seismic response information.

According to large volumes of seismic data, analyzing and processing step is time consuming. This is the key step in finding the properties of the EGS system. Using the Neural networks improved the efficiency of the data processing. Characterization of EGS system can be obtained by training the Neural Networks with known data.

The input data to the characterization problem are usually processed and interpreted seismic data and a set of attributes derived from the original data set. (Aminzadeh, Barhen, Glover, & Toomarian, 2000). Neural networks developed for this purpose, establish a relationship between the raw data and physical properties of the EGS system.

The first step of using the neural network is finding appropriate seismic attributes for its input. For this purpose, different seismic attributes should be generated. Creation of these attributes is based on the seismic amplitudes, frequencies, similarity (coherency), eccentricity, curvature and etc. Each of these basic attributes may be cross plotted with different properties of EGS systems which are already known. Correlation of these properties with basic attributes leads to creation of new attributes. Equation (1) demonstrates the relationship between input seismic attributes and predicted properties of EGS system in the simple neural network. Where "z" is estimated property, "x" is seismic attribute, "ω" is connection weight coefficient and "θ" is the node threshold. Figure 1 also demonstrates the schematic view of this kind of neural network.

$$z = x_1\omega_1 + x_2\omega_2 + ... + x_N\omega_N + \theta \quad (1)$$

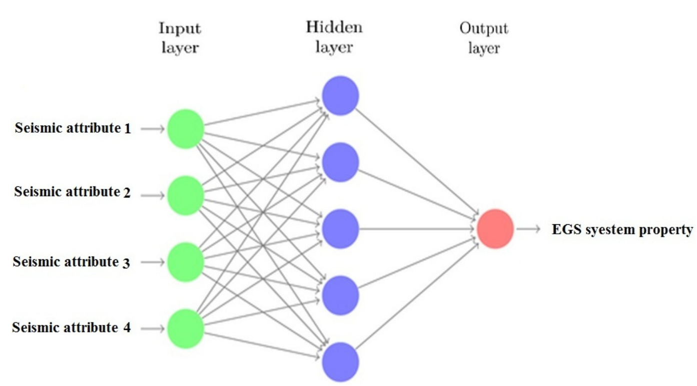

Figure 1. Schematic view of neural network to estimate the EGS system Properties.

Hybrid Neural Network and Fuzzy Logic Approach

For characterizing fractures in EGS system, shear wave splitting analysis is required. For creating the accurate fracture map of The Geysers, it is required to consider the fuzzy compressional and shear wave relationship into the problem. Figure 2 shows the impact of fuzziness in P-wave and S-wave velocities in the separation of different rock types. This fuzziness can be adequately modeled based on the EGS parameters obtained from the Neural Network.

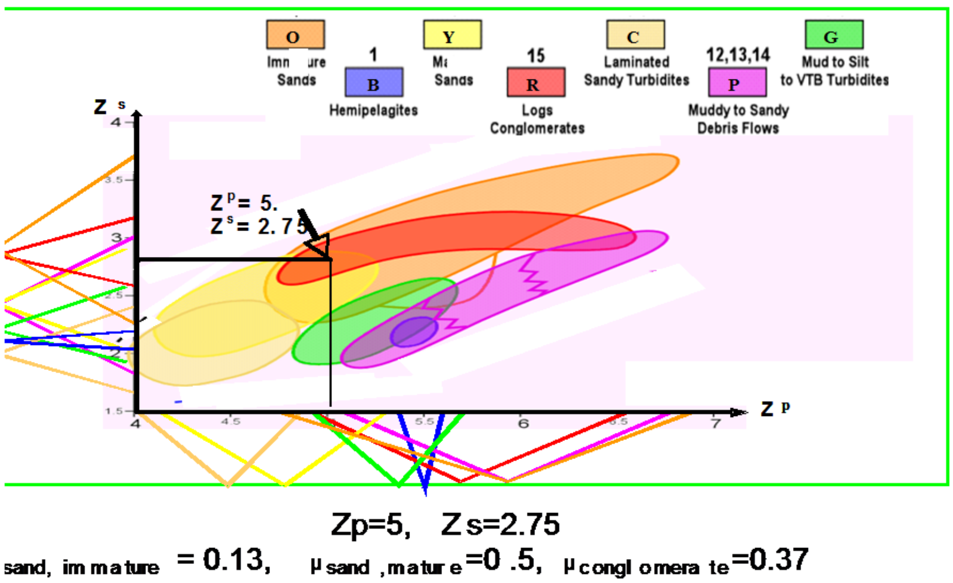

Figure 2. Impact of fuzziness in P-wave and S-wave velocities in the separation of different rock types.

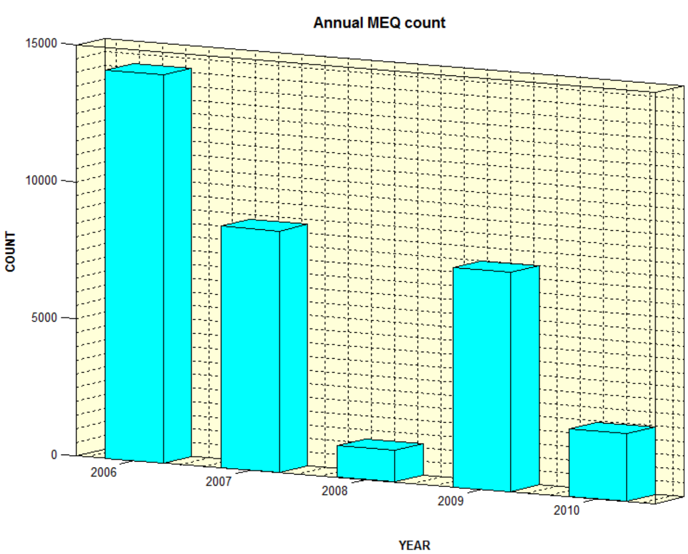

Figure 3. Number of microseimic events in each year.

The Geysers' MEQ Data

The MEQ data collected from 3/1/2006 to 3/31/2010 is catalogued at 44568 locations. Figure 3 shows the histogram for the number of microseismic events in the catalogues. The available location data is used to visualize the MEQ's. We do preliminary spatial and temporal analysis to understand the distribution.

Some statistical analyses are accomplished on the dataset for a better perceptive. Figure 4 demonstrates the spatial distribution of the data set in different views. The distribution clearly identifies statistically significant zones leading us to a better understanding of the regions to look into for further analysis. While the depth range is found to be statistically significant only up to 6 km below the MSL, spatial distribution is limited to certain specific regions over the field. It is noteworthy that there is significant variation in the spatial distribution when time windows are considered which may indicate start or end of injection activities.

Velocity Field of The Geysers

Access to preliminary velocity models of a section of the field allowed us to look at spatial distribution of MEQ's and to compare it with the velocity distribution. This provides us with some interesting zonal distributions which indicate the strong linkage between the velocity and MEQ's as expected. Further analysis in this regard is contingent upon the availability of more comprehensive velocity models. Figure 5 presents an example of the velocity model at The Geysers for the cross section at latitude of 38.843.

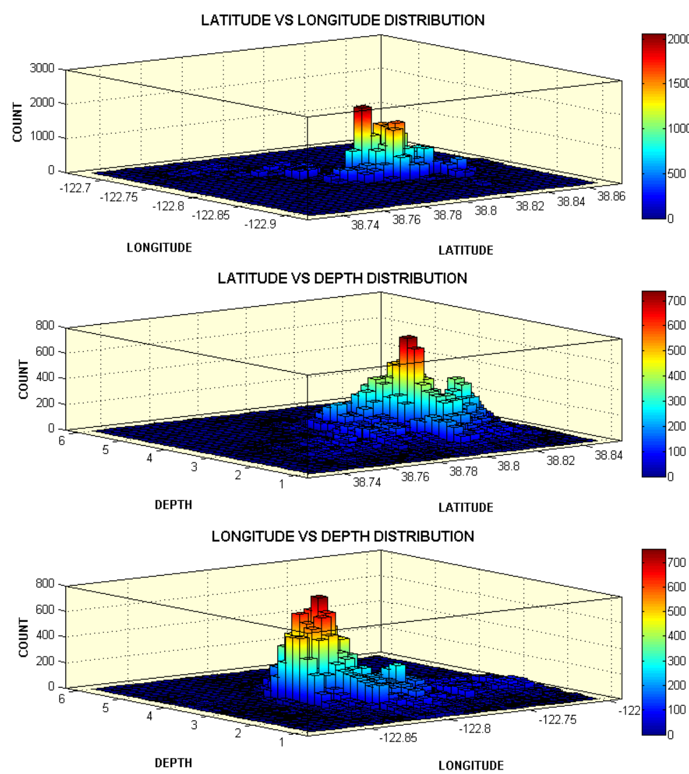

Figure 4. Spatial distribution of the data.

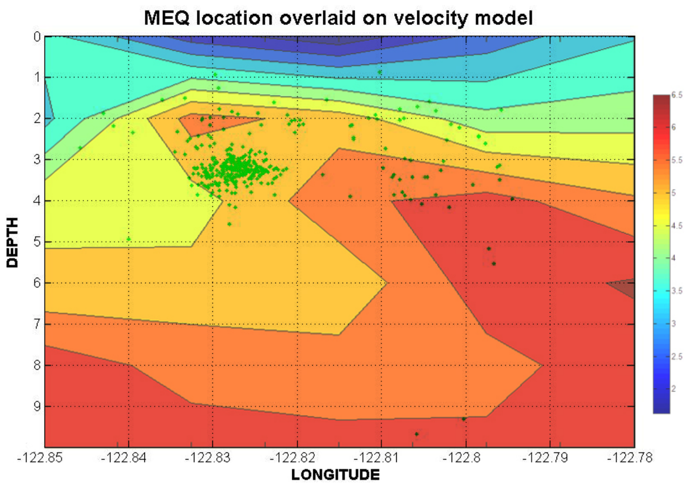

Figure 5. MEQs events overlaid on the velocity model at The Geysers for the section with latitude 38.843.

Fuzzy Clustering

Figure 6 demonstrates 3D distribution of microseismic events at The Geysers for the years 2006 to 2009. Given the extent of overlap between different regions, a fuzzy logic approach could prove advantageous (Aminzadeh & de Groot, 2006). This along with our observation of actual microseismic event locations indicates that using fuzzy clustering may improve our understanding of said events.

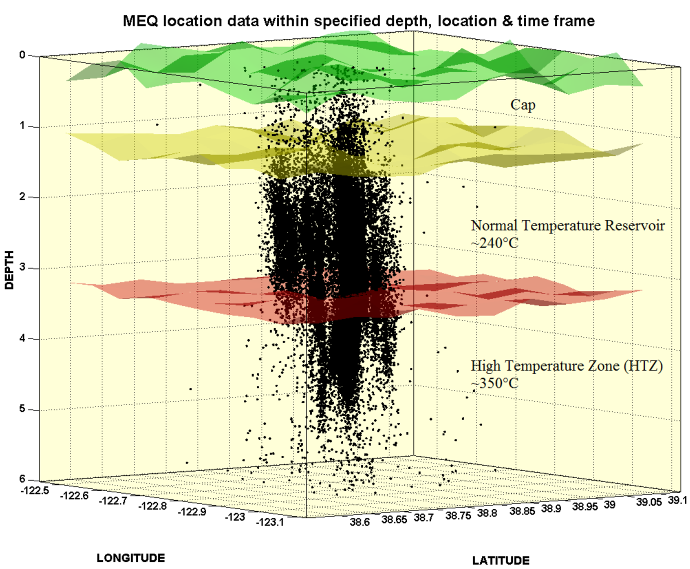

Figure 6. 3D Distribution of microseismic events at The Geysers for the years 2006 to 2009.

We are only interested in the high temperature zone (HTZ) for EGS system. Thus, α-cut of 3.2 km in depth is used for limiting the top of the desired locations and α-cut of 6 km in depth is used for limiting the bottom of the desired location for EGS reservoir. This α-cut representation is extracted from the geologic map of The Geysers. This subset of microseismic events is used for further analyzing and processing.

For implementing fuzzy clustering technique, the set of seismic events is divided into five different zones. These zones are demonstrated in Figure 7 along with the production well locations. They are chosen based on the locations of production wells and also the locations showing aggregation of seismic events. In each zone three clusters were considered. Furthermore, annual time windows are used to analyze the MEQ events in this article. Figure 8 depicts cluster centers for all the years at the HTZ zone. Figure 9 to 13, shows these cluster centers in each zones separately. These cluster center locations and their movement through time may result in finding a new methodology to locate the appropriate locations of future EGS wells at The Geysers. The theory and methodology are described in the next section of this article.

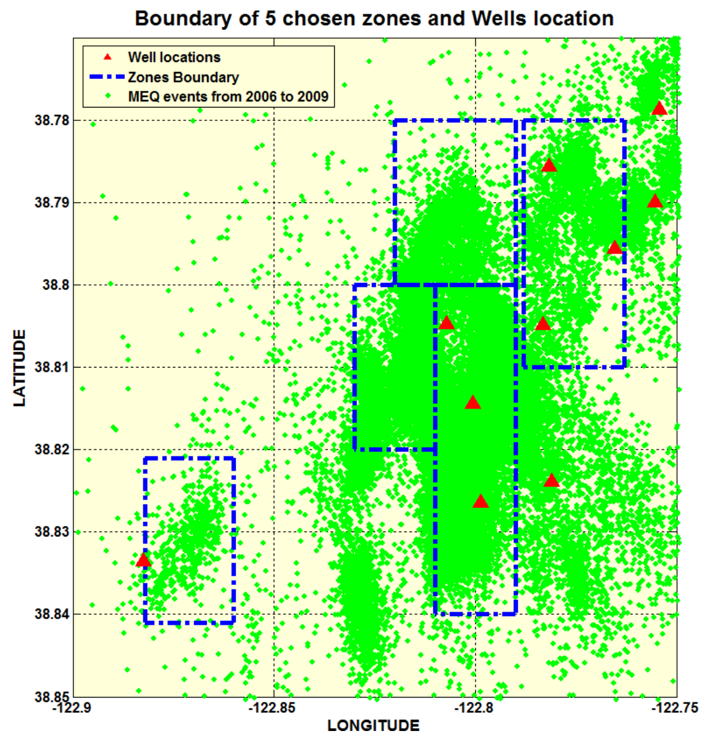

Figure 7. Zones boundary for applying the fuzzy clustering technique and the production wells locations.

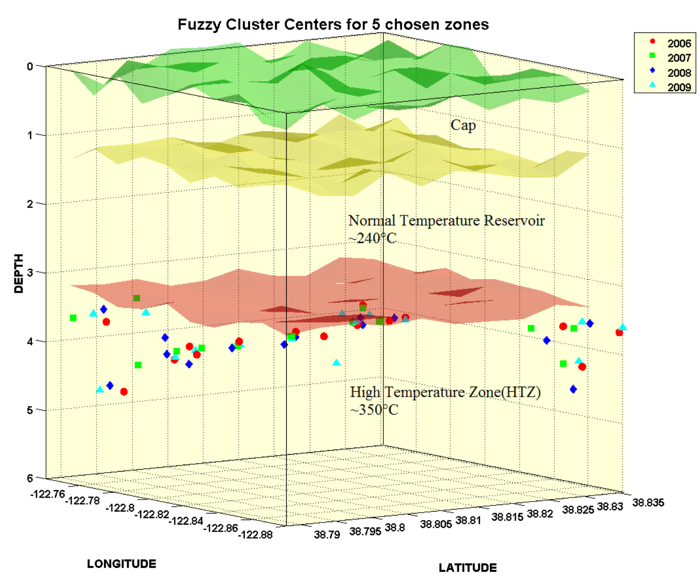

Figure 8. Fuzzy cluster centers for all the years at the HTZ zone.

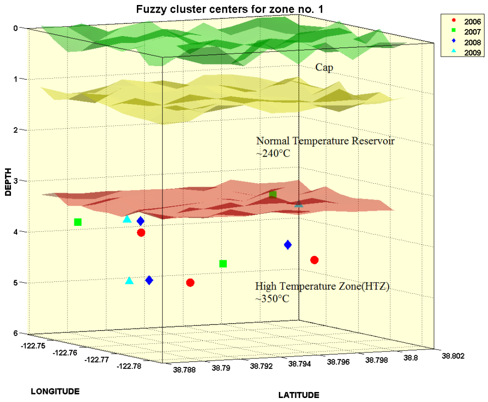

Figure 9. Fuzzy cluster centers for all the years at the zone one.

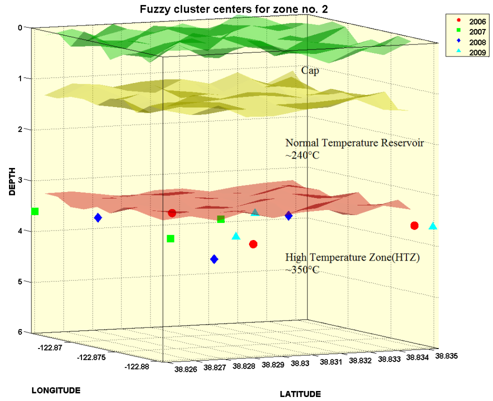

Figure 10. Fuzzy cluster centers for all the years at the zone two.

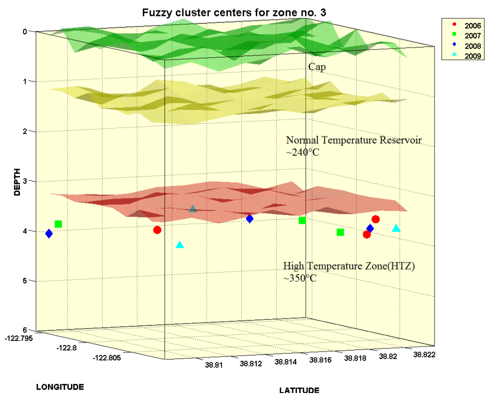

Figure 11. Fuzzy cluster centers for all the years at the zone three.

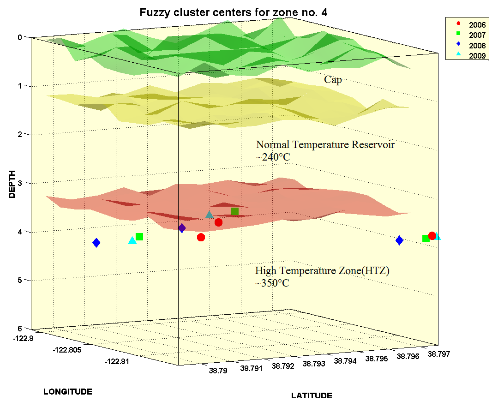

Figure 12. Fuzzy cluster centers for all the years at the zone four.

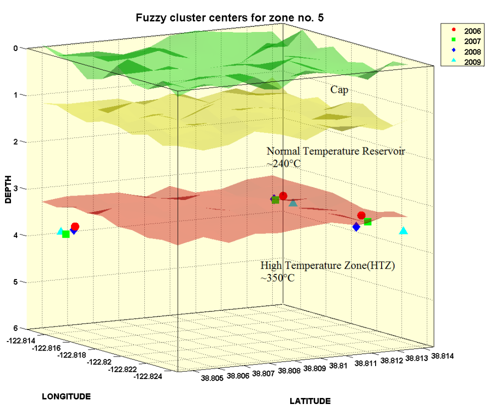

Figure 13. Fuzzy cluster centers for all the years at the zone five.

Fracture Network Characterization

Lawrence Berkeley National Laboratory mentioned four different mechanisms that have been hypothesized to explain the occurrences of these microseimic events in geothermal settings. Pore-pressure increase, temperature changes, volume change due to fluid withdrawal/injection and chemical alteration of fracture surfaces are the mechanisms that may explain the microseismic events at The Geysers or any other geothermal field. (LBNL, 2010)

Pore-Pressure Increase can reduce stresses keeping the faults from failing and thereby facilitate seismic slip in the presence of an unbalanced stress field. Water injection for hydraulic fracturing at EGS systems can locally increase pore pressure and possibly account for high seismicity around injection wells. Cool water injecting into the hot dry rock may create the fractures and seismicity directly related to thermal-elastic cooling shrinkage. (Rutqvist & Oldenburg, 2007.)

As fluid is produced (or also injected) from a geothermal reservoir, hot rock may compact or be stressed. These volume changes cause a perturbation in local stresses. This situation can lead to seismic slip within or around the reservoir. Injecting non-native fluids into the formation may cause geochemical alteration of fracture surfaces. This geochemical alteration may reduce or increase the coefficient of friction on the surface. In the case of reduced friction, smaller events may occur. And increased friction may result in larger events. (LBNL, 2010)

As discussed above, the area where microseismic events occurred may be a good estimation of fracture network at the geothermal field. In order to have EGS reservoir, large aerial distribution of fracture network is required. Hence, any fuzzy cluster of the microseismic events should represent a connected fracture network at The Geysers. Drilling new EGS wells (both injection and production wells) in these location may ease the creation of EGS reservoir.

For further investigation of this hypothesis, fuzzy cluster centers movement is depicted on Figure 14. As shown in this Figure, these centers have significant movement at the HTZ. Direction of arrows in this Figure demonstrates the direction of movement of microseismic events clusters. Authors believe that

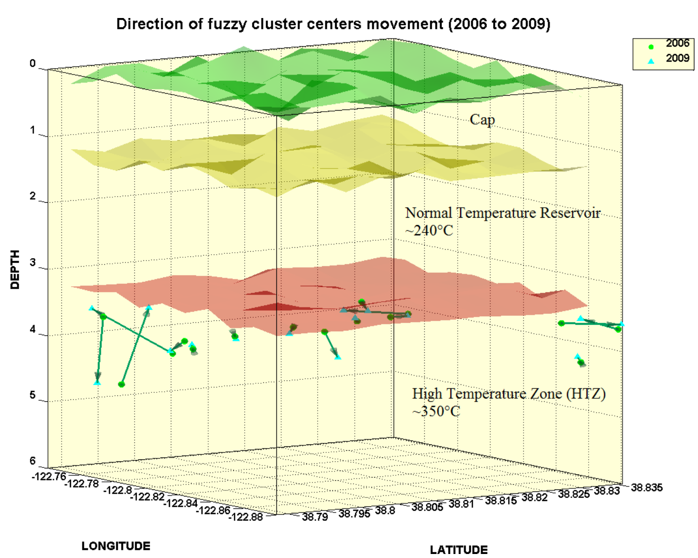

Figure 14. Ffuzzy cluster center movement from 2006 to 2009.

these directions may also represent the fracture network propagation direction (in case of small movements.) Large movements may indicate fault movements or may have other reasons.. The start of arrows indicates the 2006 cluster centers and end of them are 2009 cluster centers. It means that centers of fracture network are at these locations.

Considering the discussion above, to propose the new drilling locations for EGS wells, it is recommended to drill the injection and production well along the arrow within acceptable distance. This distance can be calculated by reservoir simulators. The technique described in this section can be applied to other geothermal fields which have the potential of EGS system.

Conclusion

In this article, some of the applications of soft computing like neural networks and fuzzy logic for characterizing EGS system are described.

Neural networks can be used to accurately estimate the EGS systems properties. Applying neural networks may result in functional relationships between these properties (e.g., porosity, permeability, fracture size, fracture spacing and reservoir discontinuities) and seismic attributes. This kind of application of neural network needs further study of the EGS systems and microseismic events which will be accomplished by authors in the future.

Concept of the fuzziness in the estimation of the EGS system properties especially characterization of fractures is unavoidable. One of the applications of fuzzy logic as described in this article was the use of fuzzy clustering techniques to find the fracture network areas. The cluster centers may represent the locations of drilling new EGS well. These centers probably are the centers of the connected fracture network which is ideal for EGS reservoir creation.

The results in this article are also compatible with Lawrence Berkeley National Laboratory's report about induced seismicity in EGS reservoir and their causes.

Finally, we are confident that such applications of soft computing find their path through the exploration and exploitation of geothermal resources in the future.

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