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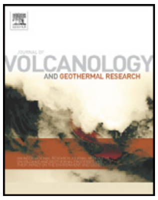

Spatial data analysis for exploration of regional scale geothermal resources

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ABSTRACT

Defining a comprehensive conceptual model of the resources sought is one of the most important steps in geothermal potential mapping. In this study, Fry analysis as a spatial distribution method and 5% well existence, distance distribution, weights of evidence (WofE), and evidential belief function (EBFs) methods as spatial association methods were applied comparatively to known geothermal occurrences, and to publicly-available regional-scale geoscience data in Akita and Iwate provinces within the Tohoku volcanic arc, in northern Japan. Fry analysis and rose diagrams revealed similar directional patterns of geothermal wells and volcanoes, NNW-, NNE-, NE-trending faults, hotsprings and fumaroles. Among the spatial association methods, WofE defined a conceptual model correspondent with the real world situations, approved with the aid of expert opinion. The results of the spatial association analyses quantitatively indicated that the known geothermal occurrences are strongly spatially-associated with geological features such as volcanoes, craters, NNW-, NNE-, NE-direction faults and geochemical features such as hotsprings, hydrothermal alteration zones and fumaroles. Geophysical data contains temperature gradients over 100 °C/km and heat flow over 100 mW/m^2. In general, geochemical and geophysical data were better evidence layers than geological data for exploring geothermal resources. The spatial analyses of the case study area suggested that quantitative knowledge from hydrothermal geothermal resources was significantly useful for further exploration and for geothermal potential mapping in the case study region. The results can also be extended to the regions with nearly similar characteristics.

1. Introduction

The exploration and exploitation of renewable energy, such as wind, solar, hydro, geothermal, and biomass, are clean and environment friendly; therefore, they are nowadays considered as the substitutes for the fossil energy (Calvin et al., 2005; Arianpoo, 2009; Jennejohn, 2009). Exploration of these energy resources can be economical in localities with high heat flow and near surface fluid coincident with fractures (Calvin et al., 2005; Arianpoo, 2009).

Geothermal energy is economically cost-effective. One percent of the confined geothermal energy in the topmost crust would comparable to about 500 times the oil and gas energy (F.I.G., 2010). Moreover, the geothermal energy is independent of weather condition and is always available as opposed to the other types of renewable energy (Qiang Yan et al., 2010).

Geothermal resources are found in a wide variety of geological regimes from limestone to shale, volcanic rock, and granite. Nevertheless, most usages of geothermal resources have been found in volcanic rocks, though the substantial issue is that the existence of tectonic elements and high heat flow is more important than rock type (Manzella, 2007; Huenges, 2010).

2. Literature review

Exploration is among the preliminary steps in the geothermal energy development, and it aims in finding areas with the most possible locations of wells for energy production with the minimum risk of drilling a dry well. Exploration in a geothermal development project costs about 42% of the project costs (Entingh, 2000; Jennejohn, 2009). The exploration program is usually performed as a step-by-step procedure consisting of reconnaissance, pre-feasibility and feasibility studies. These steps are identical with regional to local scale stages of exploration. The most favorable areas are investigated within each step (Berkovski, 1995; Dickson, 2004; Noorollahi et al., 2008; Carranza, 2009a).

The geological, geophysical and geochemical characteristics of areas constitute the prediction evidential layers in every scale of exploration. These layers need to be processed and integrated for further investigation by predictive modeling (Manzella, 1973; Noorollahi et al., 2007; Carranza, 2009a). Predictive modeling involves manipulation of spatial

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data resulting in so-called GIS-based resource prediction models, and performing multi-criteria decision-making. The models can be either knowledge-driven or data-driven (Prol-Ledesma, 2000; Porwal et al., 2003; Carranza et al., 2008; Abedi and Norouzi, 2012; Yousefi et al., 2012).

Defining of a comprehensive conceptual model of the resource sought is the first and the most essential step of defining a predictive model. A conceptual model includes the characteristics of evidential map layers, such as optimum cutoff distance, weights and scores of classes in multi-class evidential maps which are called 'Prospectivity Recognition Criteria (PRC)' hereafter. In addition, the conceptual model explains the interrelationships between evidential map layers and targets for defining the most appropriate predictive model (Carranza et al., 1999; Carranza, 2009a,b; Lisitsin and Rawling, 2011).

Although the conceptual model criteria are not wholly reflective of the story behind the resource sought, defining a conceptual model for discovered resources in well-explored areas can provide intuition and knowledge of spatial association for the exploration of undiscovered resources in those areas. The knowledge can be useful for exploration in green fields (Carranza and Hale, 2001; Carranza, 2010), or in poorly explored areas with similar geological settings to those of well-explored areas (Wibowo, 2006; Carranza et al., 2008; Carranza, 2009a; Carranza, 2009b).

Analyzing the spatial distribution of the occurrences of resource sought (Vearncombe and Vearncombe, 1999) and analyzing their spatial associations with certain geoscience data (Bonham-Carter, 1985) are helpful to define a conceptual model of mineral prospectivity (Carranza and Hale, 2002b; Carranza, 2009a). These methods provide qualitative and quantitative aspects of spatial characteristics of prospective areas with respect to geoscience data (Carranza and Hale, 2002b). The literature is poor in the studies that quantitatively indicate the PRC of geothermal resources with respect to geoscience spatial data. Blewitt et al. (2002) has visually done spatial distribution analysis among geothermal resources and geodetic strain and geological structures. Coolbaugh et al. (2003, 2002) used weights of evidence (WofE) method to quantify spatial associations between geothermal occurrences and geoscience data. Noorollahi et al. (2007) calculated cutoff proximity distances from some geoscience data. They used a 5% well existence as a condition to select proximity cutoff distances. Carranza et al. (2008) defined a conceptual model among geothermal occurrences and some geological and geophysical features with Fry analysis, distance distribution, and evidential belief function methods. Kimball (2010) used the optimum cutoff distance criteria of Carranza et al. (2008) and Noorollahi et al. (2007) to estimate the optimum cutoff distance criteria. They calculated evidential map weights based on expert knowledge, weighted summation, and AHP methods.

3. Aims and motivation

According to the literature, several methods have been used to estimate the conceptual model criteria for predictive models. The objective of this research is to calculate all Prospectivity Recognition Criteria (PRC) for hydrothermal geothermal resources of existing geoscience spatial data and geothermal wells in the Japan Akita and Iwate provinces. These criteria are calculated in regional-scale of the area. This study aims at presenting quantitative insight extracted from hydrothermal geothermal characteristics of the areas that have previously been explored by use of field method comprehensively. Moreover, it is extremely useful for regions that have similar characteristics, which can also reveal the target pattern to provide a reliable prospective map for further exploration in the case study region. The study has been concluded based on a) review of literatures for geoscience spatial data characteristics of the known geothermal occurrences in the study area; b) spatial distribution analysis of the known geothermal wells and geoscience spatial data; c) spatial association analysis between known geothermal wells and geoscience spatial data. This study compares known spatial association methods and proceeds to select the best one according to experts' knowledge.

4. Proposed method

Qualitative and quantitative analyses of known geothermal resources and geoscience evidential features are one of the most important steps in geothermal exploration which are useful in defining a conceptual model of geothermal prospectivity (Carranza and Hale, 2002a,b; Wibowo, 2006; Carranza, 2009a). Fry analysis in conjunction with rose diagram is applied to analyze the spatial distribution of point and line type features. In addition, spatial association analysis methods including 5% well existence, distance distribution analysis, weights of evidence and evidential belief functions (EBFs) methods are compared. PRC is estimated through these spatial association methods to define conceptual model parameters of the Akita and Iwate Provinces geothermal resource area. Indeed, spatial association analysis completes spatial distribution analysis due to quantitative nature of the results (Carranza and Hale, 2002a,b). The results of these analyses represent conceptual model of the Japan Akita and Iwate provinces' geothermal resources by introducing optimum cutoff distances, weight of each geoscience layers and the score of internal classes of individual layer. Finally, geothermal and geologist experts compared and analyzed the results and they introduced the final conceptual model criteria close to real world situation. The schema of proposed method can be seen in Fig. 1.

4.1. Spatial distribution analysis

4.1.1. Fry analysis and rose diagram

Fry analysis is a point distribution analysis which uses a geometrical method of spatial autocorrelation to indicate point pattern distribution. The method plots all points by putting each point at the center position and looking at other points from its prospective. This process continues until all points have been used as centers. The resultant graph displays relative position of each point to all other points, it is an enhanced distribution of points in the area named "all object separation" plot which is commonly known as "Fry plot". The rose diagram is used as a complementary tool in visual analysis of the trend of features controlling the resource sought (Wibowo, 2006).

4.2. Spatial association analysis

4.2.1. 5% well existence method

In this method, the distance data provided from evidence layers are classified with 0.5-percentile interval method. The classified data are used to calculate proximity cutoff distance from geothermal wells. Among all distance classes, the first class which has less than 5% of all wells is selected, and its distance is to be the cutoff distance where all inside areas will be considered as the optimum exploration region related to each specific feature (Noorollahi et al., 2007).

4.2.2. Distance distribution method

In this method, the null hypothesis: "the set of resource sought points and the set of geoscience features are spatially independent" is considered. For testing the hypothesis in buffer analysis, the observed and expected cumulative frequency distribution curves are compared. The expected curve is constructed of cumulative distance buffer of features versus the relative cumulative frequency ($\hat{E}(X)$) of all pixels within buffer zones and the observed curve is constructed of cumulative distance buffer of features versus the relative cumulative frequency of resource sought points ($\hat{O}(X)$) within buffer zones. Then, the Kolmogorov-Smirnov statistic: $D = \hat{O}(X) - - \hat{E}(X)$ is computed. If $D \approx 0$, the null hypothesis is considered true, that is, the creation of the resource sought is independent of geoscience features. $D > 0$, meaning that the observed curve is above the expected curve. This further suggests that within buffer distance area, there is higher chance of finding resource sought than random pixels, or there is a positive spatial association between them. $D < 0$. That is, the observed curve is below the expected curve, which in turn means that within buffer distance area and there is lower chance