Geothermics 50 (2014) 189–201

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Spatial analysis and multi-criteria decision making for regional-scale geothermal favorability map

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ARTICLE INFO

Article history:
Received 30 January 2013
Accepted 18 September 2013
Available online 2 November 2013

Keywords:
Geothermal prospectivity mapping
Spatial analysis
GIS
Conceptual model
Multi-criteria decision-making
Fuzzy

ABSTRACT

Fry analysis and weights of evidence were employed to study the spatial distribution and spatial association between known occurrences of geothermal resources and publicly available geoscience data sets at regional-scale. These analyses support a regional-scale conceptual model of geological, geochemical and geophysical interaction by calculating the optimum cutoff distance and weight of each evidence feature. Spatial association analysis indicated the geochemical and geophysical data play more important roles than geological data as evidence layers to explore geothermal resources. Integration of spatial evidential data indicates how these layers interacted to form the geothermal resources. Boolean index overlay, Boolean index overlay with OR operation, multi-class index overlay and fuzzy logic prediction models were applied and compared to construct prospective maps. Prediction rate estimator showed the fuzzy logic modeling resulted in the most reliable and accurate prediction with prediction rate about 26 in the high-favorite areas.

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 (Arianpoo, 2009; Calvin et al., 2005; Jennejohn, 2009). Geothermal energy makes use of the interior heat of the earth as an energy resource. Exploration of these energy resources can be economical in localities with high heat flow and near surface fluid coincident with fractures (Arianpoo, 2009; Calvin et al., 2005).

Geothermal energy is economically cost-effective, as 1% of this energy confined in the topmost crust would be comparable to about 500 times of oil and gas energy (F.I.G., 2010). Furthermore, 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 are more important than rock type (Huenges, 2010; Manzella, 2007).

2. Literature review

Exploration is among the preliminary steps in the geothermal energy development. The aim of exploration is finding areas with the most possible location for siting 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 charges (Entingh, 2000; Jennejohn, 2009). The exploration program is usually performed in 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; Carranza, 2009a; Dickson, 2004; Noorollahi et al., 2008). 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 a model usually named predictive modeling (Carranza, 2009a; Manzella, 1973; Noorollahi et al., 2007). This kind of modeling involves manipulation of spatial data resulting in so-called GIS-based resource prediction models and doing multi-criteria decision making. The models can be

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http://dx.doi.org/10.1016/j.geothermics.2013.09.004

either knowledge-driven or data-driven (Abedi and Norouzi, 2012; Carranza et al., 2008; Prol-Ledesma, 2000; 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 is included 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, 2009a,b; Carranza et al., 1999; Lisitsin and Rawling, 2011)

Conceptual model criteria provide quantitative knowledge with some parameters that reveal how the geoscience features participate in formation of the resource sought. In addition, knowledge-driven predictive models represent inter-relationships among individual geoscience map layers and target resource, which may reveal how they interacted with each other to form target resources and therefore where the resources sought are likely to occur. The result of the predictive model is a prospectivity map referring to chance or likelihood that the target can be found in an area where it is being explored. Actually, defining of conceptual model is a process to calculate the conceptual model criteria for individual geoscience map layers and the integration of them according to the proposition that "this location is prospective for hydrothermal geothermal resource sought" (Carranza, 2009a).

Analyzing the spatial distribution of the occurrences of the resource sought (Vearncombe and Vearncombe, 1999) and their spatial associations with certain geoscience data (Bonham-Carter, 1985), are helpful to define a conceptual model of mineral prospectivity (Carranza, 2009a; Carranza and Hale, 2002b). These analyses provide qualitative and quantitative aspects of spatial analysis (Carranza and Hale, 2002b). In addition, there are different knowledge-driven mapping techniques of mineral prospectivity and geothermal resource prospectivity. Prol-Ledesma (2000) defined conceptual model parameters for geothermal exploration based on the expert knowledge and compared Boolean logic, multi-class index overlay and fuzzy hierarchical aggregation models for prospectivity mapping. (Coolbaugh et al., 2002, 2003) used weights of evidence method with studentized contrast parameter to quantify the geothermal occurrences and geoscience data. They applied logistic regression model as a prediction model for undiscovered geothermal resources and high temperature geothermal resources. Noorollahi et al. (2007) calculated cutoff proximity distances from some geoscience data. They used a 5% wells existence as a condition to select proximity distance class and Boolean index overlay as a prediction model. 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 functions methods. They calculated the optimum cutoff distance criteria and applied data-driven evidential belief functions for predictive mapping of regional-scale geothermal potential areas. Kimball (2010) used the optimum cutoff distance criteria of Carranza et al. (2008) and Noorollahi et al. (2007) to estimate evidential map weights based on expert knowledge, weighted summation, and analytical hierarchy process (AHP) methods. They used multi-class index overlay model to integrate evidence map layers. Yousefi et al. (2010) provided a map of potential geothermal resource areas for Iran using Boolean logic model to integrate geological, geochemical and geophysical evidence map layers.

3. Motivation

Analysis of spatial relationship between geoscience data and modeling the inter-relationships between them and geothermal resources must lead to making a reliable decision for accomplishment of drilling. Therefore, at the first, the exploration criteria must be estimated and then the prediction model should be defined so as not to ignore probably prospective area with a strictly decision and not to suggest wide areas that might be un-useful for exploration and therefore increasing exploration issues. The objective of this research is to define a reliable conceptual model for hydrothermal geothermal resources from existing geoscience data and geothermal wells in Japan's Akita and Iwate provinces. At the first, the PRC will be calculated and then, the prediction models mentioned in literatures will be compared with a fuzzy inference model at regional-scale to reach reliable prospective map for the case study. The suggested conceptual model represents quantitative knowledge and characteristics of hydrothermal geothermal from the area that has previously been explored effectively. The conceptual model is extremely useful for regions that have similar characteristics and reveals the target pattern that provides a reliable prospective map for further exploration in the case study region.

4. Proposed method

Qualitative and quantitative analysis of known geothermal resources and geoscience evidential features are applied for defining a conceptual model of geothermal prospectivity. Fry analysis and interpretation of rose diagram are applied to analyze the spatial distribution of point and line features. Weights of evidence method is used for spatial association analysis to calculate the PRC in the Akita and Iwate provinces. Indeed, spatial association analysis completes spatial distribution analysis because its results are quantitative (Carranza, 2009b; Carranza and Hale, 2002b; Carranza et al., 2008). The results of these analyses are combined with some geothermal and geologist experts' opinions to define a conceptual model of the Japanese Akita and Iwate provinces' geothermal resources by introducing optimum cutoff distances, weight of each geoscience evidence map layer and the score of internal classes of individual map layers. The evidential features are transformed to factor maps, which are used as input data for prediction models, using PRC. The factor maps are used as input factors to knowledge driven prediction models to integrate evidential map layers for prospectivity mapping. The prospective map is then classified into importance classes. Furthermore, the prediction-rate of each importance classes are estimated and the model which has higher prediction-rate or contains more geothermal wells in less importance classes area is selected as the best performance model. The Schema of the 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 that uses a geometrical method of spatial auto-correlation 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 perspective. This process continues until all points have been used as centers. The resultant graph displays the relative position of each point to all other points, it is an enhanced distribution of the points in the area that is named "all object separation" plot which is commonly known as "Fry plot". The rose diagram is used as a complementary tool that helps in visual analysis of features controlling the resource sought (Wibowo, 2006).