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GM-GRE: AN INTEGRATION METHOD FOR GEOTHERMAL POTENTIAL SITE SELECTION

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ABSTRACT

A toolbox using a Geographic Information System (GIS) was developed and introduced as a decision-making tool to locate potential geothermal areas. The study aims to introduce step-by-step guidelines and develop a user friendly computer program that can determine promising geothermal areas. Six data layers characterizing the geothermal area are employed in the site selection process.

ArcMap was used as a base program to develop the GIS Model for Geothermal Resource Exploration (GM-GRE), which consists of geoprocessing tools and a model builder. Criteria for defining promising areas based on each layer are defined using spatial relationship analysis of currently producing geothermal wells in Akita and Iwate prefectures in northern Japan as proven geothermal resources and evidence layers. Areas with geothermal potential were defined and prioritized using input data layers.

1. INTRODUCTION

Identification of a geothermal prospect area is one of the goals of a geothermal exploration programme. In the early stage of geothermal development, the recognition of promising areas for further exploration is one of the most important tasks. There is no particular step-by-step guideline to direct scientists and engineers on how to collect and manage data and information for identifying promising areas. This paper introduces GIS tools for collecting and interpreting the required data.

Active geothermal areas have various natural manifestations at the ground surface. Hot springs, fumaroles, mud pots, and hydrothermal alteration, particularly in areas of high thermal activity, are natural indicators of geothermal activity, providing a visible indication of the transport of heat and mass through the Earth's crust. Geothermal exploration programmes and also the Geographic Information System (GIS) Model for Geothermal Resource Exploration (GM-GRE) toolbox can make use of such manifestations and measurements with other investigation techniques to identify the location of prospective geothermal resources.

A geothermal exploration programme is usually developed on a step-by-step basis, comprising reconnaissance, feasibility, and assessment. During each stage of the process, the less prospective areas are gradually eliminated from consideration and remaining efforts are concentrated on the most promising areas (Dickson and Fanelli, 2004).

Geothermal exploration management combines the results of a number of exploration methods such as geological, geochemical, and geophysical surveys to locate prospective areas for further development. The basic function of exploration management is to identify the location and extent of areas that warrant further detailed investigation. Identifying areas of high geothermal potential can be a daunting task for exploration project managers; however, the decision-making process can be made less cumbersome if it is broken down into general steps (Noorollahi et al., 2007):

- Collection of required existing data and information;
- Assessment and characterization of the study area;
- Development of site selection criteria and defining of promising areas based on all data sets;
- Development of layer integration model;
- Defining of most promising potential areas;
- Prioritization of selected potential sites.

The decision-making process for locating prospective areas involves combining the results of a number of different surveys and studies; human error is unavoidable during this complex procedure. To provide high reliability for the selected area and to minimize human error, we used a GIS to develop an easy to use toolbox to identify prospective areas by precisely combining various digital data layers.

GIS is an important tool for the integral interpretation of geoscientific data using a computerized approach, especially in exploration work. This approach has been used to determine spatial associations among diverse evidence layers in the area of interest (Noorollahi, 2005; Noorollahi et al, 2007, Noorollahi, et al., in press; Coolbaugh et al., 2002, 2005a, 2005b; Prol-Ledesma, 2000;). GIS models have also been successfully used in regional exploration for mineral resources (Agterberg, 1989; Bonham-Carter, 1991; Katz, 1991; Chung et al., 1992; Bonham-Carter, 1994). The evidence layers can be selected by technical experts such as engineers and scientists to make decisions on further works (Campbell et al., 1982; McCammon, 1993). Geothermal exploration could potentially use such a GIS-based technique at several of the exploration stages (Noorollahi et al., 2007; Noorollahi, 2005). Geothermal exploration requires the analysis of data by combining various sets of geoscientific information, including surface geology, the location of geothermal manifestations, geomagnetic and gravity measurements, thermal data (temperature gradient and heat flow), the geochemistry of surface manifestations, and remote sensing data. The data are analyzed by experts who then determine the location and extent of the most promising geothermal prospect area. GIS-based decision-making systems have been applied in suitability analyses for geothermal resource exploration in northern Japan (Noorollahi et al., 2007), Iran (Yousefi et al., 2007), Iceland (Noorollahi, 2005) and the USA (Coolbaugh et al., 2002, 2005a, 2005b). The results of these studies show that the location and extent of geothermal promising areas defined by the GIS method correlates closely with those defined by conventional methods.

The GM-GRE tool is developed to facilitate the recognition of a geothermal promising area in the early stage of a geothermal exploration programme (Figure 1). The criteria, which are the spatial relationship between producing geothermal wells (proven geothermal resources) and evidence layers in this study, are defined using information from geothermal fields from Akita and Iwate prefectures in northern Japan. The spatial relationship analysis for defining the criteria is described in Section 3. These criteria are applied to the GM-GRE tools as defaults but they can be changed by the user according to the condition of a given study area.

2. EVIDENCE LAYERS (THEMATIC MAPS)

2.1 Geological data layers

Geological studies play an important role in all stages of geothermal exploration. The geological formations that host a hydrothermal system require suitable rock formations that allow water to

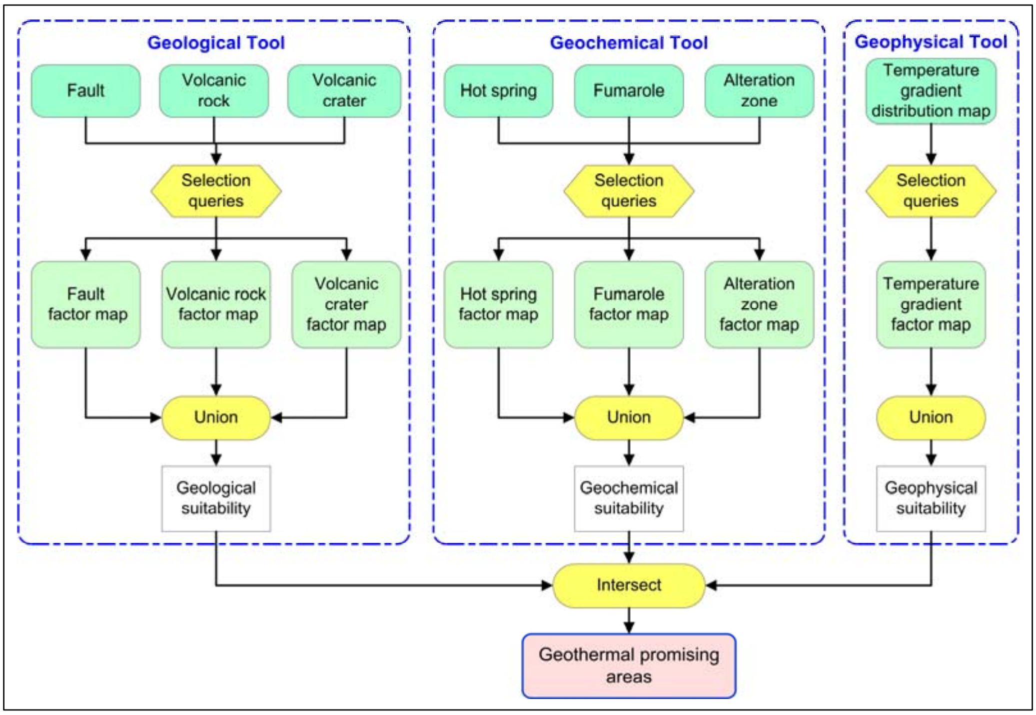


FIGURE 1: Flow diagram of the GM-GRE which presents the employed layers, tools, operators and derived final suitability layers

circulate to deep levels, a source of heat, an adequate availability of water, sufficient time and surface area of heat exchange to enable the water to be heated and a return path toward the surface. The aim of geological studies in the early stage of geothermal exploration is to evaluate the possibility of the presence of a heat source, geological formations to host geothermal fluid, a downward pathway for infiltration of meteoric water to recharge the system and an upward pathway for geothermal fluid.

Geothermal systems occur in a variety of geological situations. They are more often related to areas of andesitic, dacitic, and rhyolitic rocks than to basaltic eruption centres (McNitt, 1964; Case and Wilde, 1976). Many geothermal fields have structures produced by tectonic activity, such as block faulting, graben formation, or rift valleys. Locations are particularly favourable at the intersection of faults bordering major structural blocks. For example, the majority of geothermal fields in New Zealand are situated in major graben structures, as are the fields in the Salton Sea, California, and Cerro Prieto, Mexico. Several fields are associated with volcanic caldera structures (e.g., Matsukawa, Pauzhetsk, Valles Caldera, and Ahuachapan) whereas others are related to specific volcanoes (e.g., Momotombo, Nicaragua and Kawah Kamojang, Indonesia).

Waters are derived from local meteoric waters, which may descend to considerable depths through fault-fissure systems, then they are heated and flow upward by convective forces. Major upflow routes are commonly located through faults and fissure zones with high permeability. The heating of water at depth is usually attributed to conductive heat originating from the magma body. Geological evidence layers in a geothermal potential site selection process include required conditions that are necessary for the development of a geothermal system.

The presence and distribution of volcanic rocks, active volcanoes, craters and calderas, and faults are the main data used as geological evidences for geothermal resource prospecting.

2.1.1 Volcanic rocks

Most geothermal potentials occur along Quaternary volcanic zones; consequently, their heat sources can be considered to be linked to volcanoes. The presence of Quaternary volcanic rocks is one of the evidence layers used for identifying geothermal prospects because they produce heat sources in the form of intrusive dikes. Large, igneous-related geothermal systems that have high temperatures are associated with Quaternary volcanic fields, and geothermal potential declines rapidly as age increases. Most high-grade recoverable geothermal energy is likely to be associated with silicic volcanic systems that have been active in the past 1 million years (Sherrod and Smith, 2000). Lower grade (lower temperature) geothermal resources may be associated with somewhat older rocks; however, volcanic rocks emplaced more than 2 million years ago are unlikely geothermal targets (Smith and Shaw, 1975).

A young (Quaternary, almost 1-2 Ma) volcanic rock map of the study area is required to make an ArcMap polygon layer that denotes the surface signature of the geothermal potential at depth and is used as an input data layer.

2.1.2 Volcanic craters, and calderas

Volcanoes are an obvious indicator of underground heat sources. Volcanic craters can constitute one of the elements in geological exploration for geothermal resources, as the presence of craters leads geologists to assume the area hosts or hosted a great deal of volcanic activity. The location of craters is one line of evidence for deciding where to concentrate additional exploration work in the area to locate a potential prospect.

The locations of craters and calderas in a given study area can be extracted from geological or any other available maps and standardize to the ArcMap environment as a polyline data type.

2.1.3 Faults and fractures

A key to targeting a region of geothermal potential is to understand the role of faults and fractures in controlling subsurface fluid flow. Fractures and faults can play an important role in geothermal fields, as fluid mostly flows through fractures in the source rocks. The importance of faults and fractures in geothermal development is well recognized; Hanano (2000) pointed out that faults influence the character of natural convection in geothermal systems. Blewitt et al. (2003) indicated that at a regional scale, the locations of existing geothermal power plants in Great Basin, USA, and the spatial pattern of geothermal wells are strongly correlated with measured rates of tectonic transtensional strain. This indicates that geothermal systems in some regions might be controlled by fault planes that act as conduits for fluid flow and are continuously being extended by tectonic activity.

The study of geothermal fields in the Black Rock Desert, Pyramid Lake, and Carson Sink regions shows that many systems occupy discrete steps in fault zones or lie in belts of intersecting, overlapping, and/or terminating faults. In addition, most fields are associated with steeply dipping faults and, in many cases, with Quaternary faults (Faulds et al., 2006).

Faults and fractures contribute to the occurrence of natural convection in the observed geothermal systems. Accordingly, faults can be used as an evidence layer in the selection of potential geothermal sites. Faults within the study area can be determined from a geological or structural map and defined as a polyline feature class in the GIS environment.

2.2 Geochemical data layers

Geochemical studies such as those on the occurrence and spatial distribution of hot springs, fumaroles and acidic alteration zones play important roles in the investigation of geothermal resource prospect areas. Geochemical methods are widely used in both preliminary prospecting and at every stage of geothermal exploration and development. Geochemical evidence layers used for geothermal resource prospecting include the distributions of hydrothermal alteration zones, hot springs with temperatures in excess of 25°C, and fumaroles, which are described in this paper.

2.2.1 Hydrothermal alteration zones

Hydrothermal alteration involves mineralogical changes resulting from the interaction between hydrothermal fluids and rocks. The formation of secondary minerals in geothermal systems is controlled by the chemical/physical conditions of the system. For example, the presence, abundance, and stability of hydrothermal alteration minerals depend on the temperature, pressure, lithology, permeability, and fluid composition of the system (Browne, 1978; Harvey and Browne, 1991). Thus, analysis of the hydrothermal alteration provides information on the occurrence of geothermal resources, the location of geothermally prospective areas, and the chemical characteristics of deep water within the system. For site selection, the location and surface distribution of acidic hydrothermal alteration zones are applicable. Knowledge of the distribution of surface alteration zones can lead to the identification of prospective geothermal areas.

The locations of the acidic hydrothermal alteration zones in study areas can be extracted from geological or any other available maps and standardize to the ArcMap environment as a polygon data type.

2.2.2 Fumaroles

Fumaroles emit mixtures of steam and other gases to the atmosphere, and are one of the mostly commonly occurring geothermal features within active volcanic areas. The existence of fumaroles in an area lets geothermal researchers assume the probability of there being geothermal resources at depth is much higher than in other areas.

A location map of fumaroles can be extracted from different source maps such as geological and hydrological maps and digitized as a point feature class data layer in the ArcMap environment.

2.2.3 Hot Springs

Hot springs have always provided irrefutable proof of a subsurface heat source. It is assumed that the probability of the occurrence of a geothermal resource is higher in an area with geothermal surface signatures such as hot springs and steaming ground than that in the surrounding area. Based on this assumption, the area of high probability of a geothermal resource can be selected.

A hot spring data layer is prepared by making a point data layer in the ArcMap environment. Hot springs with temperatures higher than 25°C are used in this data layer.

2.3 Geophysical data layers

Geophysical exploration methods have been applied successfully to locate the heat sources of a geothermal system and characterize the probability of the potential reservoir. Gravimetric, aeromagnetic, seismic and thermal methods (thermal gradient and heat flow) can be used in geothermal resource prospecting in large scale investigations. However, the temperature gradient is the most common data and can be accessed from oil drilling, mining and ground water wells.

2.3.1 Temperature gradient

Subsurface temperature data are used to determine the temperature gradient and thermal anomalies in many areas around the world for geothermal resource prospecting (Flovenz et al., 2000; Coolbaugh et. al., 2007; Lihe et al., 2005; Chopra and Holgate, 2005; Rasteniene and Puronas, 2005). Temperature gradient data can be collected from different sources such as petroleum, ground water, mining and geothermal wells. The gradient can be obtained from measurements of subsurface temperature in wells at specified depths. The geothermal gradient represents the rate of change in temperature (ΔT)

with depth (ΔZ) in the subsurface. High geothermal gradients are commonly found in areas around hot springs and volcanoes.

The distribution model of the geothermal gradient in the study area can be developed using the Natural Neighbor method housed in ArcMap-3DAnalyst. The study area is classified into two different classes, and the area with lower geothermal gradient is discarded from further analysis. An area with a temperature gradient higher than the average temperature gradient (30°C/km), for example 50°C/km, can be selected as a promising area. The map of this selected area is converted to a feature class vector data layer in polygon format.

3. SPATIAL RELATIONSHIP ANALYSIS OF GEOTHERMAL SIGNATURES AND EVIDENCE LAYERS

To determine the spatial distribution relationship of known geothermal resources and GM-GRE evidence layers, a distance relationship analysis was conducted in the Tohoku district of Japan. The GM-GRE evidence layers comprised data layers provided by different exploration surveys, and were used in a GIS model of geothermal resource exploration. Distance relationship analysis was conducted using ArcMap to determine the dominant distance association of the production wells as approved geothermal resources to data in the GM-GRE evidence layers. In the Tohoku area, there are 430 productive geothermal wells in many geothermal fields such as Matsukawa, Sumikawa, Ohnuma, Kakkonda, and Uenotai (Geological Survey of Japan, 2002). These wells were used for the distance relationship analysis. Distances were calculated between the locations of geothermal wells and volcanic rocks, volcanic calderas and craters, active faults, hot springs, fumaroles and hydrothermal alteration zones.

For polygon layers such as those that contain data on Quaternary volcanic rocks and hydrothermal alteration zones, distance was calculated from the geothermal well to the edge of the nearest polygon unit. The distance was defined as a “zero” metre for wells drilled within polygons. For layers that contain point data (hot springs and fumaroles), distance was defined from the wellhead to the hot spring or fumarole. For layers that contain line data such as volcanic calderas and craters and active faults, distance was calculated from the wellhead to the nearest portion of the line.

The calculated dominant distance data for each layer was then plotted as a histogram with a 1000 m bin size; each bin contains information on the start and end values of the bin range. We performed a relative frequency analysis of calculated distance by specifying a dominant distance for the distribution of wells within each evidence layer. Relative frequency analysis of measured distance was plotted on the vertical axis, and 5% relative frequency was selected for identifying a dominant relative distance for all data layers. In other words, the area within each evidence layer was classified into 1000 m distance classes; if the numbers of wells located within a class is equal or more than 5% of all wells, the associated distance is marked up as a selection distance. In GM-GRE tools, this defined distance was used to define promising areas based on the data in each layer. The results of the calculation and defined distances for each of the evidence layers are summarized in Table 1. As an example of the analysis, Figure 2 shows a histogram and distribution analysis of the relative distances from geothermal wells to the locations of hydrothermal alteration zones.

TABLE 1: Result of calculations and defined distances for evidence layers

Evidence layer	**Layer type**	**Number of class Incl. > 5% of wells**	**Wells inside select. area (%)**	**Def. distance for further analysis (m)**
Quaternary volcanic rocks	polygon	2	84	2000
Volcanic craters	polyline	6	94	6000
Active faults	polyline	6	76	6000
Hot springs	point	4	97	4000
Fumaroles	point	4	88	4000
Hydrothermal alteration	polygon	3	91	3000

4. GM-GRE TOOLS AND SUITABILITY SITE SELECTION

4.1 Geological suitability method and tool

Geological suitability can be determined by integrating the defined areas based on volcanic rocks, volcanic craters, and active faults. These three layers can be overlain and the selected areas are combined (union) to identify geologically suitable areas. The Union Tool in ArcMap creates a new coverage by overlaying two or more polygon coverages. The output coverage contains the combined polygons and the attributes of both coverages. In using this method, those areas selected as suitable areas by any one of the evidence layers are combined to prevent the loss of any prospective areas defined by a single evidence layer.

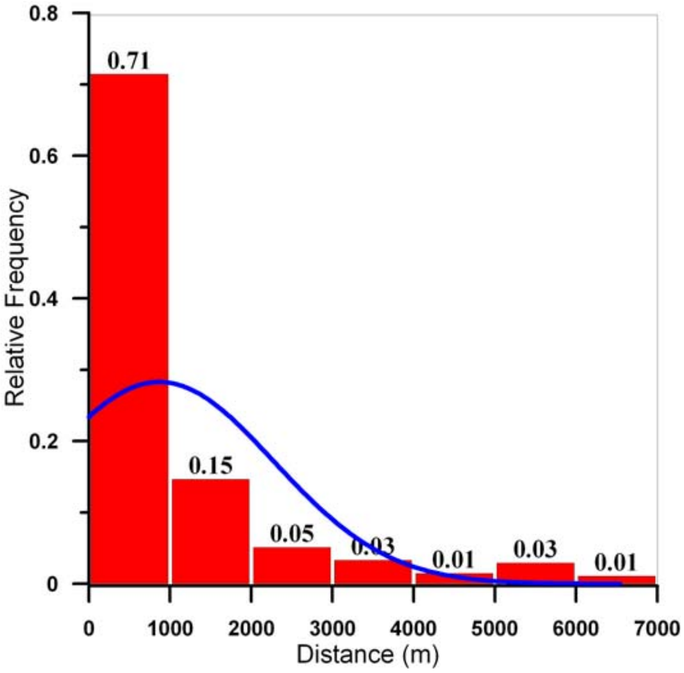


FIGURE 2: Histogram and distribution analysis of the relative distances from geothermal wells to the locations of hydrothermal alteration zones

A GM-GRE geological tool is developed in the ArcMap environment using Geoprossesing tools as an ArcToolbox. The input layers are Quaternary volcanic rocks, faults and fractures, and volcanic craters and calderas. A selection query of the tool is the buffer size for generating factor maps of each data layer, and default distances are given in Table 1 although the distances can be changed by the user according to the conditions of the study area. When the factor maps are generated from input data layers they are combined to identify geological suitability using:

$$Geological\ suitibility = (FA \cup VC \cup VR)$$

where *FA*, *VC* and *VR* denote the fault, volcanic crater and Quaternary volcanic rock factor maps and U is the "OR" (UONION) Boolean operator.

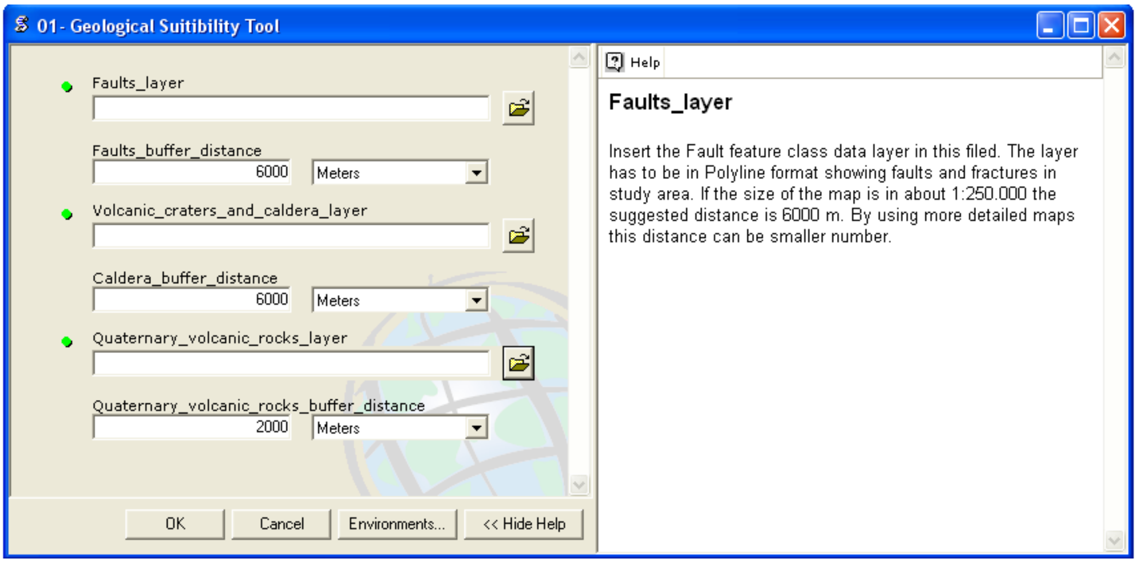
The output layers are stored in a specific folder on a personal computer as an intermediate data type and combined using the Union tool of ArcToolbox. The generated combined output layers include several polygons that are merged using the Dissolved tool. The defined area is a prospecting area based on only geological data. Figure 3 shows the input window of the Geological tool.

4.2 Geochemical suitability method and tool

Geoprossesing tools are used to develop the GM-GRE Geochemical Toolbox in the ArcMap environment for selection of geothermally suitable localities based on geochemical data. Geochemical suitability can be identified by integrating factor maps based on hot springs, fumaroles, and alteration zones. These three layers can be overlain and the selected areas need to be combined (union) to identify the geochemically suitable area:

$$Geochemical\ suitibility = (HS \cup FU \cup AZ)$$

where *HS*, *FU* and *AZ* are the hot spring, fumarole and acidic alteration zone factor maps respectively.



01- Geological Suitibility Tool

Faults_layer

Faults_buffer_distance: 6000 Meters

Volcanic_craters_and_caldera_layer

Caldera_buffer_distance: 6000 Meters

Quaternary_volcanic_rocks_layer

Quaternary_volcanic_rocks_buffer_distance: 2000 Meters

Faults_layer

Insert the Fault feature class data layer in this filed. The layer has to be in Polyline format showing faults and fractures in study area. If the size of the map is in about 1:250.000 the suggested distance is 6000 m. By using more detailed maps this distance can be smaller number.

FIGURE 3: Input window of the GM-GRE Geological Toolbox

The distances in Table 1 are used for the selection query of buffer sizes in defining the promising locations; however, the distances can be changed by the user according to the conditions of the study area.

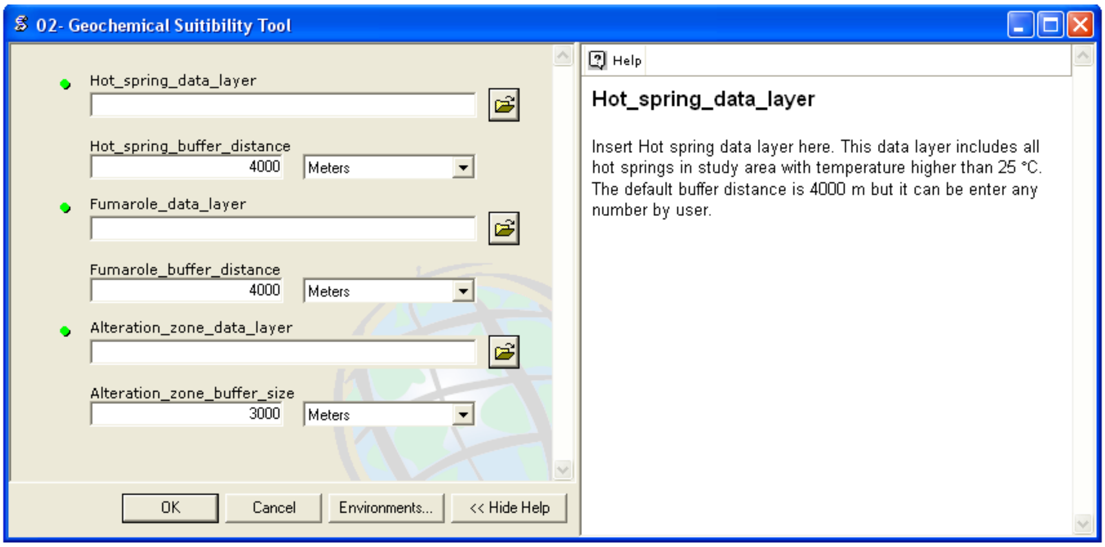
The output of this tool denotes a promising area based on only geochemical data layers. Figure 4 shows the input window of the Geochemical Toolbox. A brief description of each input data layer is described in the “Help Menu” of the input window of the program.

4.3 Geophysical tool

In the Geophysical tool, the temperature gradient distribution map is used as an input file and the area with a temperature gradient greater than 50°C/km is generated as an output file. Figure 5 shows the input window of the Geophysical tool.

4.4 Geothermal potential site selection and GPA tool

Favourable and unfavourable terrains in a study area in terms of geothermal potential can be defined using three suitability digital layers, namely the geological, geochemical, and temperature gradient



02- Geochemical Suitibility Tool

Hot_spring_data_layer

Hot_spring_buffer_distance: 4000 Meters

Fumarole_data_layer

Fumarole_buffer_distance: 4000 Meters

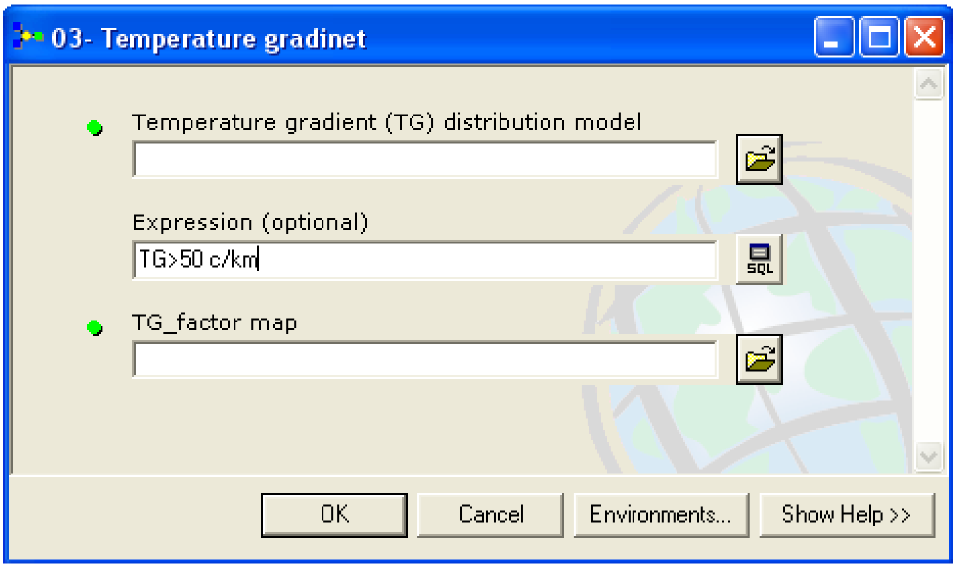
Alteration_zone_data_layer

Alteration_zone_buffer_size: 3000 Meters

Hot_spring_data_layer

Insert Hot spring data layer here. This data layer includes all hot springs in study area with temperature higher than 25 °C. The default buffer distance is 4000 m but it can be enter any number by user.

FIGURE 4: Input window of the GM-GRE Geochemical Toolbox



Expression (optional): TG>50 c/km

FIGURE 5: Input window of the GM-GRE Geophysical Toolbox

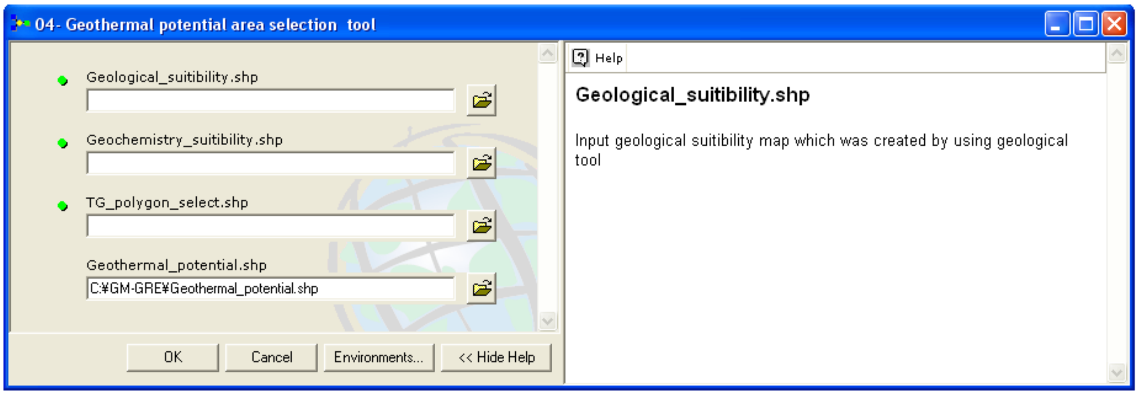
suitability layers, and Boolean integration methods. Boolean integration methods are applicable for logical combination of binary maps. Two conditional operators, ‘OR” (Union) and “AND” (Intersect), are applied for data integration. The Intersect (AND) Tool in ArcMap calculates the geometric intersection of any number of feature classes and data layers that are indicative of geothermal activity (e.g. high-temperature gradients and mapped surface alterations). Features that are common to all input data layers are selected using this method (Bonham-Carter, 1994). This implies the selected area is suitable for a study based on all input data layers, and the selected area receives the highest suitability rank. Those areas that are common to some but not all data layers are selected and ranked in the next priority levels.

For performing a Boolean logic model, the study area based on each evidence layer needs to be classified and assigned different values. Two different values are assigned to the area: 1 for the area with geothermal resources and 0 for the area without geothermal resources. The defined areas in the three suitability data layers were assigned the value 1 and other parts of the study area in each data layer received the value 0. The final sites were selected by running the GM-GRE Geothermal Potential Area (GPA) toolbox that combines the three input data layers. The Boolean AND (Intersect) operator was used for overlying these three layers and the areas that are common for all three layers are selected as the best suitable area. Integrating data layers for the selection of the promising geothermal area is done by:

$$GPA = (GEOL \cup GEOCH \cup TG)$$

where *GPA*, *GEOL*, *GEOCH* and *TG* are the geothermal potential area, geological suitability, geochemical suitability and temperature gradient suitability maps, respectively, and $\cup$ is the “AND” (Intersect) Boolean operator.

The input window of the program is presented in Figure 6. The user is asked to input the three mentioned data layers, and then the program calculates and selects the potential locations. By integrating a different number of data layers, prospective areas are defined and ranked. Priorities of selected areas depend on the number of data layers employed in selecting an area. The area common to all three data layers is given first priority. The second priority area is the area common for geophysical and geochemical layers and the third priority area is the area common for geophysical and geological layers. Integration of geological and geochemical layers gives the fourth priority area. Table 2 summarizes how the layers are employed and the corresponding rankings.



Geological_suitibility.shp

Geochemistry_suitibility.shp

TG_polygon_select.shp

Geothermal_potential.shp
C:¥GM-GRE¥Geothermal_potential.shp

Geological_suitibility.shp

Input geological suitibility map which was created by using geological tool

FIGURE 6: Input window of the geothermal potential area tool

TABLE 2: Employed layers and ranking of the geothermal prospect areas

Rank	Geological suitability	Geochemical suitability	Geophysical suitability
1st priority	o	o	o
2nd priority	×	o	o
3rd priority	o	×	o
4th priority	o	o	×

5. CONCLUSIONS

A GM-GRE Toolbox was developed in a GIS environment for regional scale geothermal potential site selection. The tool was developed to be user friendly and step-by-step guidelines help scientists and engineers define the geothermal prospect locations. Digital data layers and maps can be used in a GIS environment to develop a geothermal favourability map.

Three different data sources, namely geological and geochemistry sources and the geothermal gradient, are applicable to the tool to assess the geothermal potential on a regional scale. The tool's default selection criteria are those proposed by Noorollahi et al. (2007) but the criteria can be changed by the user.

The GM-GRE model was validated using data and information from Akita and lwate prefectures, northern Japan. The results demonstrate the vast majority of production wells currently operating for power generation are located within the first priority area.

6. REFERENCES

Agterberg, F.P., 1989: Computer programs for mineral exploration. *Science 245*, 76-81.

Blewitt, G., Coolbaugh, M., Holt, W., Kreemer, C., Davis, J., Bennett, R., 2003: Targeting potential geothermal resources in the Great Basin from regional to basin scale relationships between geodetic strain and geological structures. *Geothermal Resources Council, Transactions, 27*, pp 3-7.

Bonham-Carter, G.E., 1991: Integration of geoscientific data using GIS, In: Maguire, D.J., Goodchild, M.F., and Rhind, D.W. (eds.), *Geographical information systems: principles and applications.* Longman, Essex, 171-184.

Bonham-Carter, G.E., 1994: *Geographical information systems for geoscientists: modeling with GIS.* Computer Methods in the Geosciences ,13, Pergamon, NY, 398 pp.

Browne, P.R.L., 1978: Hydrothermal alteration in active geothermal fields. *Annual Review of Earth and Planetary Science, 6,* 229-250.

Campbell, A.N., Hollister, V.G., Duda, R.O., 1982: Recognition of a hidden mineral deposit by an artificial intelligence program. *Science 217,* 927-929.

Case, C.W., and Wilde, P., 1976: *Method for geothermal reservoir detection emphasizing submerged environments.* Energy and Environment Division, Lawrence Berkeley Laboratory, University of California, 64 pp.

Chopra, P., and Holgate, F., 2005: A GIS analysis of temperature in the Australian crust. *Proceedings of the World Geothermal Congress 2005, Antalya, Turkey,* CD, 7 pp.

Chung, C.F., Jeoerson, C.W., Singer, D.A., 1992: A quantitative link among mineral deposit modelling, geosciences mapping, and exploration resource assessment. *Economic Geology, 87,* 194-197.

Coolbaugh, M. F., Sladek, C., Faulds, J.E., Zehner, R.E., and Oppliger, G.L., 2007: Use of rapid temperature measurements at a 2-metre depth to augment deeper temperature gradient drilling. *Proceedings of the 32nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California,* CD, 1-8.

Coolbaugh, M.F., Taranik, J.V., Raines, G.L., Shevenell, L.A., Sawatzky, D.L., Minor, T.B., and Bedell, R., 2002: A geothermal GIS for Nevada: defining regional controls and favourable exploration terrains for extensional geothermal systems. *Geothermal Resources Council, Transactions, 26,* 485-490.

Coolbaugh, M., Zehner, R., Kreemer, C., Blackwell, D., Oppliger, G., Sawatzky, D., Blewitt, G., Pancha, A., Richards, M., Helm-Clark, C., Shevenell, L., Raines, G., Johnson, G., Minor, T., and Boyd, T., 2005a: *Geothermal potential map of the Great Basin, western United States.* Nevada Bureau of Mines and Geology, map 151.

Coolbaugh, M.F., Zehner, R.E., Raines, G.L., Oppliger, G.L., and Kreemer, C., 2005b: Regional prediction of geothermal systems in the Great Basin, USA using weights of evidence and logistic regression in a Geographic Information System (GIS). In: Cheng, Q., and Bonham-Carter, G. (eds.), *GIS and Spatial Analysis.* International Association of Mathematical Geology Annual Conference, Proceedings, Toronto, Canada, 505-510.

Dickson, M.H., Fanelli, M., 2004: *What is geothermal energy.* Instituto di Geoscienze e Georisorse, CNR, Pisa, Italy, 61 pp.

Ellis, A.J, and Mahon, W.A.J., 1977*:* *Chemistry and geothermal systems*. Academic Press, NY, 392 pp.

Faulds J., Coolbaugh M., and Vice, G., 2006: Geologic and geophysical analyses of geothermal fields in the Northwestern Great Basin, western USA: Characterizing structural and tectonic controls. *Enhanced Geothermal Innovative Network for Europe, Workshop 1, defining, exploring, imaging and assessing reservoirs for potential heat exchange, Geoforschungszentrum, Potsdam, Germany,* 29-35.

Flovenz, O.G., Karlsdottir, R., Saemundsson, K., Smarason, O.B., Eysteinsson, H., Bjornsson, G., Olafsson, M., and Bjornsson, T., 2000: Geothermal exploration in Arskogsstrond, N-Iceland. *Proceedings of the World Geothermal Congress 2000, Kyushu - Tohoku, Japan,* 1133-1138.

Geological Survey of Japan (ed.), 2002: *Geothermal resources map of Tohoku and Kyushu, Digital geosciences map GT-1.* Geological Survey of Japan.

Hanano, M., 2000: Two different roles of fractures in geothermal development, *Proceedings of the World Geothermal Congress 2000, Kyushu - Tohoku, Japan,* 2597- 2602.

Harvey, C.C., Browne, P.R.L., 1991: Mixed layer clay geothermometer in the Wairakei geothermal field. *New Zealand, Clays and Clay Minerals, 39,* 614-621

Katz, S.S., 1991. Emulating the prospector expert system with a raster GIS. *Computers & Geosciences, 17,* 1033-1050.

Lihe Y., Guangcai H., and Xiaoyong W., 2005: Geothermal gradient in the Ordos Basin. *Proceedings of the World Geothermal Congress 2005, Antalya, Turkey,* CD, 3 pp.

McCammon, R.B., 1993: Prospector Il-An expert system for mineral deposits models. In: Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., and Duke, J.M. (eds.), *Mineral deposit modelling*. Geological Association of Canada, Special Paper 40, 679-684.

McNitt, J.R., 1964: Geology of the Geysers thermal area*.* *Proceedings of the United Nations Conferences on New Sources Energy, 1961, 2,* 292-301.

Noorollahi, Y., 2005: *Application of GIS and remote sensing in exploration and environmental management of Namafjall geothermal area, N-Iceland.* MSc thesis, University of Iceland, Reykjavik, UNU-GTP, report 1, 114 pp.

Noorollahi, Y., ltoi, R., Fujii, H., Toshiaki, T., 2007: GIS model for geothermal resource exploration in Akita and Iwate prefectures, Northern Japan. *J. Computer & Geosciences, 33- 8,* 1008-1021.

Noorollahi, Y., Itoi, R., Fujii, H., and Toshiaki, T., in press: GIS integration model for geothermal exploration and well siting, *Geothermics, 19,* pp.

Prol-Ledesma, R.M., 2000: Evaluation of the reconnaissance results in geothermal exploration using GIS. *Geothermics, 29,* 83-103.

Rasteniene, V., and Puronas, V., 2005: Geothermal atlas of Lithuania**.** *Proceedings of the World Geothermal Congress 2005, Antalya, Turkey,* CD, 6 pp.

Sherrod, D.R., and Smith, J.G., 2000: *Geologic map of upper Eocene to Holocene volcanic and related rocks of the Cascade Range, Oregon.* Geologic Investigations Series Map I-2569, 2 sheets, scale 1:500,000, U. S. Geological Survey, 17 pp.

Smith, R.L., and Shaw, H.R., 1975: Igneous-related geothermal systems. In: White, D.E., and Williams, D.L., (eds.), *Assessment of geothermal resources of the United States – 1975*. U.S. Geological Survey Circular ,726, 58-83.

Yousefi, H., Ehara, S., and Noorollahi, Y., 2007: Geothermal potential site selection using GIS in Iran. *Proceedings of the 32nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California,* 174-182.