Cover Page - Example

GM-GRE; A GIS Based Program for Site Selection of Regional Scale Geothermal Potential

Y. NOOROLLAHI[1]
Department of Earth Resources Eng., Kyushu University, Fukuoka, JAPAN

R. ITOI[2]
Department of Earth Resources Eng., Kyushu University, Fukuoka, JAPAN.

Total No of pages (Excluding Cover Page) = 8 (maximum)

Full addresses/phone/fax

[1]No#418, West Building 2, 744, Motooka, Nishi-ku, 819-0395, Fukuoka, JAPAN.
Ph. +81(80) 3964-7181 Fax +81(92) 802-3345

[2]No#420, West Building 2, 744, Motooka, Nishi-ku, 819-0395, Fukuoka, JAPAN.
Ph. +81(92) 802-3346 Fax +81(92) 802-3345

GM-GRE; A GIS BASED PROGRAM FOR SITE SELECTION OF REGIONAL SCALE GEOTHERMAL POTENTIAL

YOUNES NOOROLLAHI, RYUICHI ITOI

Energy Resources Engineering Lab., Department of Earth Resources Engineering,
Kyushu University, Fukuoka, JAPAN

SUMMARY – A Toolsbox using Geographic Information System (GIS) was developed and introduced as a decision-making tool to locate potential regional- scale geothermal resources. The study aims to introduce a step by step guide line and develop user friendly computer program that can determine the promising geothermal potential areas in regional scale. Data layers consist of Quaternary volcanic rocks, calderas and craters, faults, hot springs, fumaroles, hydrothermal alteration zones and temperature gradient that are employed in site selection process. ArcMap was used as a base program to develop a GIS Model for Geothermal Resource Exploration (GM-GRE) consisting of Geoprocessing tools and Modelbuilder. Areas with geothermal potential were defined and prioritized by input data layers. The GM-GRE Toolbox was examined and validated using data from Akita and Iwate prefectures, northern Japan. The results showed that 97% of 430 currently productive geothermal wells in Akita and Iwate prefectures are located within the first priority zone selected by the GM-GER.

1. INTRODUCTION

Identification of the geothermal prospecting area is the goal of the geothermal exploration program. In developing countries and the states that are in the early stage of geothermal development the recognition of the promising areas for further detailed exploration is one of the most important task. There is no particular step by step guideline to direct scientists and engineers to collect and manage the data and information for identifying the geothermal promising areas. This paper is going to introduce a GIS tools for collecting and interpreting the required data. Step by step guideline for map generating and interpretation methods is presented in program user manual.

The 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 programs and also GM-GRE toolbox make use of such manifestations and other investigation techniques and measurements to identify prospective geothermal resources.

A geothermal exploration program 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 the following 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 a layer-combination model
- Defining 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 errors are unavoidable during this complex procedure. To provide reliability to the selected area and to minimize the human errors, in the present study we use a GIS to develop an easy to use Toolsbox to identify prospective areas by 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 the spatial associations among diverse evidence layers in the area of interest (Coolbaugh et al. 2002, 2005a, 2005b; Prol-Ledesma, 2000).

GIS models have also been successfully used in regional exploration for mineral resources (Bonham-Carter et al., 1988; 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 in order to make decisions on further work (Campbell et al., 1982; McCammon, 1993). The application of GIS in the

field of mineral exploration is based on the fact that the fundamental principles involved in the formation of ore deposits are too complex to be approximated using analytical mathematical models (Bonham-Carter, 1991).
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 signatures, geomagnetic and gravity measurements, thermal data (temperature gradient and heat flow), the geochemistry of surface manifestations, and remote sensing data. Analysis of the data is conducted by experts who then decide upon the location and extent of the most promising geothermal prospect area.
A GIS-based decision-making system has been applied in a suitability analysis for geothermal resource exploration in northern Japan (Noorollahi et al, 2007), Iran (Yousefi et al, 2006), Iceland (Noorollahi, 2005) and USA (Coolbaugh et al., 2002, 2005a, 2005b). The results of these studies show that the location and extent of geothermal well sites defined by the GIS method correlates closely with the area defined by conventional methods.
This GR-GRE (GIS Model for Geothermal Resources Exploration) tool is developed to facilitate the recognition of geothermal promising area in early stage of the geothermal exploration program in regional scale. Figure flowdiagram of the GM-GRE which presents the employed layers, tools, operators and derived final suitability layers.

2. GEOLOGICAL DATA LAYERS

Geological studies play an important role in all stages of geothermal exploration. The aim of geological evaluation at an early stage of geothermal exploration is to evaluate the possibility of the presence of heat source and pathway for fluid. Geological studies also provide background information for interpreting the data obtained by other exploration methods. The duration and cost of exploration can be minimized by adopting a well-designed exploration program and efficiently coordinating research. The presence and distribution of young volcanic rocks, active volcanoes, craters and calderas, and active faults are the main data which are used in geological evidence layers.

2.1 Young volcanic rocks

Most geothermal potentials occur along Quaternary volcanic zones; consequently, their heat sources can be considered to be linked to the young volcanoes themselves. The presence of Quaternary volcanic rocks is one of the evidence layers used for identifying geothermal prospects because recent volcanic activity produces heat sources in the form of intrusive dikes.
A Quaternary volcanic rock map of the study area is required to make as ArcMap polygon layer and all other rock type polygon are deleted. All Quaternary volcanic rocks can be surface signature of geothermal potential.
An analysis of the distance from existing geothermal wells to Quaternary volcanic rocks in Tohoku, Japan (Noorollahi et al, 2007) shows that most of the wells are located within 2000 m of Quaternary rocks. Thus, by using Buffer tool the covered area by quaternary volcanic rocks with 2000 m surrounded area can be selected using this criterion and assumed to be an area of geothermal potential based on rock types. This criterion is applied to the GM-GRE as a default but can be changed by user

2.2 Volcanic craters, and calderas

Volcanoes are obvious indicators 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 that the area hosts or hosted a great deal of volcanic activity. The location of craters is one line of evidence for deciding upon where to concentrate additional exploration work in the area to locate a potential prospect.
Noorollahi et al (2007) proposed that, on the basis of the distance calculation from 430 productive geothermal wells to volcanic craters and calderas in northern Japan, a distance of 5000 m was found to select promising areas within this data layer. Thus this criterion is applied in GM-GRE for selection of promising area as default but can be changed by user when running model to any other area.
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. To identify suitable areas based on the presence of volcanic features, a buffer with 5000 m in distance by default assigned to conduct by program and the selected areas is labeled as volcanic crater suitability map.

2.3 Active faults

One of the keys to targeting a region of geothermal potential is to understand the role of faults 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 is strongly correlated with GPS-measured rates of tectonic transtensional strain. This indicates that in some regions geothermal systems might be controlled by Quaternary fault planes that act as conduits that are continuously being extended by tectonic activity.
Active faults contribute to the occurrence of natural convection in the observed geothermal systems. Accordingly, active faults can be used as an evidence layer in the selection of potential geothermal sites. Active faults within the study area can be determined from geological or structural map and defines as a polyline feature class in the GIS environment.
Distance relationship analysis was conducted to determine the distance from geothermal wells to the faults show that most of the wells (95% of the wells) are located in 6000 m to the faults. For this calculation the map in the scale of 1:250,000 by Noorollahi et aI (2007) in northern Japan were used. This distance seems too far to have permeability and fluid circulation. However, in the scale of 1:250.000 only major fault zones are presented and there should be several smaller and associated faults in detailed scales which are not presented in this scale and not accounted in distance relationship calculation. If more detailed map is available in any other study area this distance (6000 m) can be altered.
The proposed model employed ArcMap Buffer tool and a 6000 m selection query to select the geothermal promising area based on faults. The 600 m buffer size is applied to the GM-GRE tool as a default but can be changed by user.

2.4 GM-GRE geological tool

Geological suitability can be determined by integrating the selected areas based on Quaternary 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 Arcinfo 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 area defined by just a single evidence layer.

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

where FA, VC and QVR denote faults, volcanic craters and Quaternary volcanic rocks factor maps and U is the “OR” (UONION) Boolean operator.
GM-GRE geological tool is developed in ArcMap environment using Geoprossesing tools as an ArcToolbox script. The input layers are Quaternary volcanic rocks, faults and fractures, and volcanic craters and calderas. A selection query of Buffer with particular distances is needed to assign to each layer by user. The default value which is proposed based on Noorollahi et al, (2007) or can be entered by user. The output layers are proposed to store in specific folder in personal computer as an intermediate data type and combined by using Union tool of the ArcToolbox. The generated combined output layers include several polygons which are merged using Dissolved tool. Figure 2 shows the input window of the Geological Toolbox.

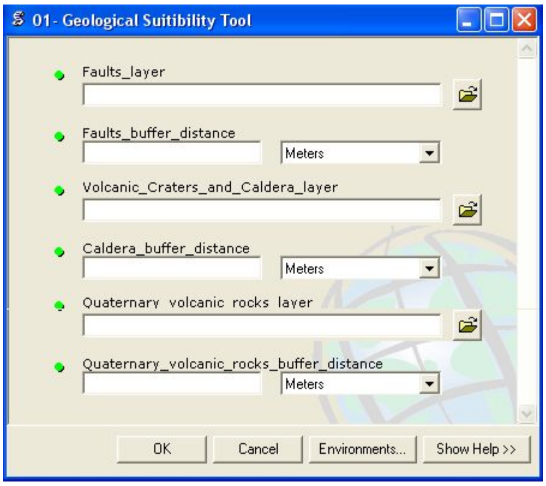

Figure 2 Input window of the GM-GRE Geological Toolbox

3. GEOCHEMICAL DATA LAYERS

Geochemistry plays an important role in any investigation of geothermal resources. 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.
Geochemical suitability can be identified by integrating factor maps on the base of 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 using;

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

where HS, FU and AZ are hot springs, fumaroles and acidic alteration zones factor maps respectively.

3.1 Hydrothermal alteration zones

Hydrothermal alteration involves mineralogical changes resulting from the interaction of hydrothermal fluids and iocks. 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, location of geothermally prospective areas, and the chemical characteristics of deep water within the system. For site selection purpose the location and surface distribution of hydrothermal alteration zones are applicable.
The location and distribution of surface alteration zones can help to identify prospective geothermal areas. In other words, it is more likely that geothermal resources occur within and around hydrothermal alteration zones than in unaltered areas.
The statistical analysis presented by Noorollahi et al (2007) shows that more than 90% of existing geothermal wells in north Japan are located within or in 3000 m distance from edges of alteration zones.
The acidic alteration zones of the given study area can be extracted from geological or other source maps. This information need to be digitized and converted to ArcMap data layer in polygon format. This layer is used in GM-GRE geochemical toolbox as input layer. A 3000 meter buffer size selection query using the ArcMap Buffer tool applied to the GM-GRE geochemical tool by the default but it is possible to change by user to any desired value.

3.2 Fumaroles

Fumaroles emit mixtures of steam and other gases to the atmosphere, and are the one of the geothermal features that can mostly occur within active volcanic areas. The existence of the fumaroles aid geothermal researchers to assume that the probability of the geothermal resources occurrence in such areas is much higher than others.
The statistical analysis of the distance of existing geothermal wells from fumaroles in Tohoku northern Japan shows that 88% of the wells in the known geothermal fields are located within 4000 m of fumaroles (Noorollahi et al, 2007). Thus, this distance can be used for selecting promising areas based on fumarole locations.
The location map of the fumaroles from different source maps such as geological map, hydrological map and can be extracted and digitized as a point feature class data layer in ArcMap environment. A selection query is programmed in Geochemical Toolbox using the ArcMap Buffer tool. The 4000 m buffer size from fumaroles is assigned as a default in program but it can be changed to any value by user.

3.3 Hot Springs

Hot springs have always provided irrefutable proof of a subsurface heat source. Those locations where the hot water and steam discharges to the surface are termed geothermally active areas. It is assumed that the probability of occurrence of a geothermal resource is higher in a geothermally active area than that in the surrounding area. Based on this assumption the area of high probability of the geothermal resources areas have to be selected.
The hot spring data layer is prepared by making a point data layer in ArcMap environment. The spring with temperature of exceed 25CC are used in this data layer.
Analysis of the spatial distribution of hot springs and geothermal wells in Japan shows that 97% of geothermal wells are located within 4000 m of hot springs (Noorollahi et al, 2007). Thus, this distance is applicable as an evidence distance to select promising geothermal areas based on the location of hot springs in Geochemical Toolbox of the GM-GRE program. This distance is selected based on study in Japan and it can be changed by user. Hopefully more accurate distance numbers can be found by conducting same works and data analysis in other geothermal leading countries such as Iceland, USA, New Zealand, Italy, Philippine and ect.

3.4 GM-GRE geochemical tool

The Geoprossesing tools are used to develop GM-GRE Geochemical Toolbox in ArcMap environment for selection of geothermally suitable localities based on geochemical data. Acidic alteration zones, fumaroles and hot springs are the input layers for this toolbox. A selection query of Buffer with particular distances is needed to assign to each layer by user. The user can use default value which is proposed based on Noorollahi et al, (2007) or can be entered by user. The output layers are proposed to store in specific folder in personal computer as an intermediate data type and combined by using Union tool of the ArcToolbox. The generated combined output layer includes several polygons which are merged using Dissolved tool. Figure 3 shows the input window of the Geochemical Toolbox. A description of each data layer that is proposed to input into the toolbox is described in “Help Menu” of the input window.

4. GEOPHYSICAL DATA LAYERS

Geophysical exploration techniques have been used successfully to locate the heat sources of geothermal system and characterized the permeability of the potential reservoir. For geothermal resources siting several geophysical methods can be used in national scale but the availability of geophysical data in wide scale is limited. Gravimetry, Aeromagnetic, Seismic and Thermal methods (thermal gradient and heat flow) which are some of the methods can be used in geothermal resources prospecting in large scale investigations. But the temperature gradient is the most common data which can be accessible from many of the sources than others and is used in this program.

4.1 Temperature gradient

Temperature data are used to determine the temperature distribution and thermal anomalies in many areas around the world for geothermal resources prospecting. The temperature gradient data can be collected from different sources. Petroleum, ground water, mining and geothermal wells can be the main sources of temperature gradient data. Temperature gradient survey involves the measurement of subsurface temperature in wells at specified depths. The geothermal gradient represents the rate of change in temperature (ΔT) with depth (ΔZ) in subsurface. Geothermal gradients are commonly found along faults and in areas around hot springs and volcanoes.
The distribution model of the geothermal gradient in the study area can be calculated using the Natural Neighbor method that is housed in ArcMap-3DAnalyst. Study area can be classified into two different classes, and the area with a geothermal gradient of less than 50°C/km is discarded from further analysis. The area with temperature gradient more than, for example, 50 °C/km can be selected and converted to the feature class vector map in polygon format. Thus, the map includes a polygon which indicates the area of temperature gradient higher than 50 °C/km and was defined as a temperature gradient factor map.

4.2 GM-GRE geophysical tool

In a geophysical tool the temperature gradient distribution map used as input file and the area with the temperature gradient more than 50C/krn is generated as an output file. Figure 4 shows the input window of the geophysical tool.

5. DATA INTEGRATION AND GEOTHERMAL POTENTIAL SITE SELECTION

Favorable and unfavorable terrains in a study area in terms of geothermal potential can be defined using three suitability digital layers (geological suitability, geochemical suitability, and temperature gradient suitability) and Boolean integration methods.
Boolean integration methods are applicable for logical combination of binary maps. Two conditional operators of 'OR" (Union) and "AND" (Intersect) are applied for data integration.

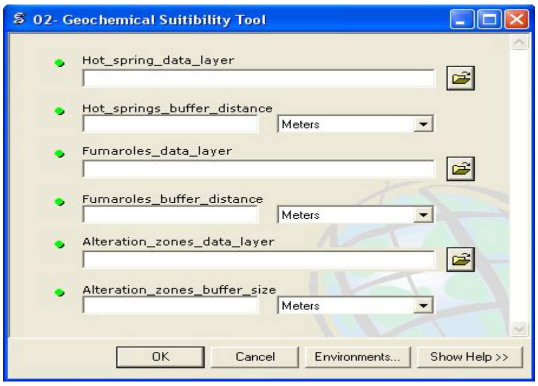

Figure 3 Input window of the GM-GRE Geochemical Toolbox

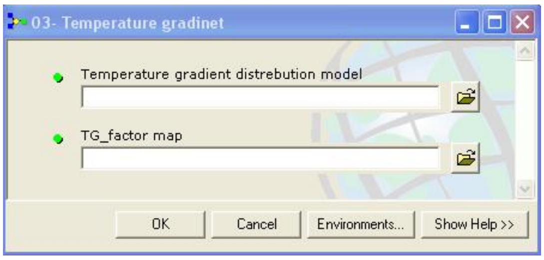

Figure 4 Input window of the GM-GRE Geophysical Toolbox

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., elevated temperature gradients, surface mapped alteration, etc.). Features that are common to all input data layers are selected using this method (Bonham-Carter, 1994). This implies that the selected area is suitable for the purpose of a study based on all input data layers, and the selected area receives the highest suitability ranking. Those areas that are common to some but not all data layers are selected and ranked in the next priority levels.
For performing 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 where there is geothermal resources and 0 for the area without geothermal resources. The defined areas in three suitability data layers (geological, geochemical and geophysical suitability maps) were received the value of one and other parts of the study area in each data layer received the value of 0.
The final sites were selected by running the GM-GRE Geothermal potential area toolbox. This toolbox combines three input data layers including Geological suitability, geochemical suitability and Temperature gradient suitability data layers. The Boolean AND (Intersect) operator was used on overlying this layers and the areas which are common for all three layers are selected as the best suitable areas. To integrate data layers for selection of the geothermal promising area this Equation was applied;

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

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

The input window of the program is presented in Figure 5. User is asked to input the requested three mentioned data layers, and the program then calculates and selects the potential locations.

By integrating different number of data layers prospected areas are defined and ranked. Priorities of selected areas depend on the number of data layers employed. The area which is common to all three dada layers (geological, geochemical and geophysical layers) is the best area and defined as the first priority. The second priority area is common for geophysical and geochemical layers and the third priority area defined by employing geophysical and geological layers. Integration of geological and geochemical layers defines the fourth priority area. Table 1 summarizes the employed layers and their ranks of the defined geothermal potential areas.

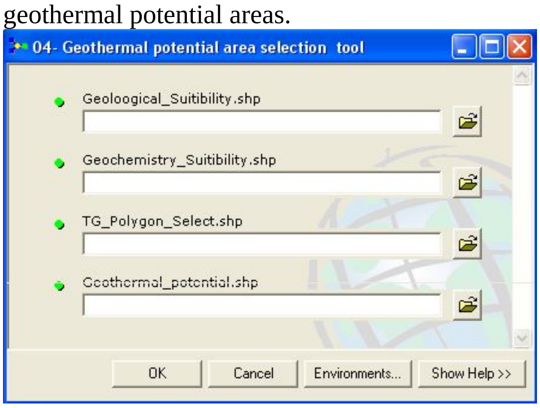

Figure 5 Input window of the geothermal potential area tool

Table 1 Employed layers and ranking of the defined geothermal prospected areas

Rank	Geological suitability	Geochemical suitability	Geophysical suitability
1st priority	o	o	o
2end priority	×	o	o
3red priority	o	×	o
4th priority	o	o	×

6. CASE STUDY - AKITA AND IWATE PREFECTURES IN NORTHERN JAPAN

A case study is carried out by this model to validate the program in two prefectures Akita and Iwate in northern Japan where a large amount of data and information on geothermal potential are available.

The goal of the this part of the work is to define the geothermal potential areas using a GIS Model for Geothermal Resource Exploration (GM-GER) toolboxes and to validate the results on the basis of the locations of known geothermal fields.

Geothermal areas in Japan with high-enthalpy resources can be found mainly along two volcanic fronts: one that trends north-south through eastern Japan (from Hokkaido via eastern Honshu Island to the Izu Islands), and another that trends from Kyushu Island to the Southwestern Islands (Kawazoe and Shirakura, 2005). Hot springs and fumarolic fields around Quaternary volcanoes are derived from andesitic or dacitic volcanism. Most dacitic and andesitic lava domes or volcanic spines act as a heat source, and natural hydrothermal systems that occur in the vicinity of the intrusive rocks produce fumaroles and/or hot springs at the surface. Geothermal fields in Japan are associated with Quaternary andesitic and dacitic volcanism and Tertiary acidic intrusive (Ishikawa, 1970).

Akita and Iwate prefectures are located in the Tohoku volcanic arc, northern Japan. The Tohoku volcanic arc on Honshu and southwestern Hokkaido is generated by subduction of the oceanic Pacific Plate beneath the continental North American Plate and Okhotsk Microplate. The arc generates significant volcanic and geothermal activity (Tamanyu et al., 2000).

We analyzed three different data sources—geology, geochemistry, and thermal conditions—using a GIS model to assess geothermal potential in study area. Digital data layers and maps were used in a GIS environment to develop a geothermal favorability map. Relationships in terms of the distances between the locations of producing wells and the boundaries of geothermal features such as Quaternary volcanic rocks were extracted, and the results expressed as favorability maps for the evaluation of geothermal potential.

7. CONCLUSIONS

The GM-GRE model was run for data and information in Akita and Iwate prefectures and the results are illustrated in Figure 6.

The results demonstrate that the vast majority of producing wells that are currently operated for power generation are located within the first priority area. The final favorability map shows that there are numerous other areas that have a high potential for geothermal development.

GM-GRE Tools box was developed in GIS environment for regional scale geothermal potential site selection. The model was developed user friendly and step by step guideline lets scientists and engineers to fallow the instruction to define the geothermal prospected localities. Digital data layers and maps can be used in a GIS environment to develop a geothermal favorability map.

Three different data sources—geology, geochemistry, and thermal conditions—can be applicable to the model to assess geothermal potential in regional scale.

The criteria for selection of promising area based on each data layers are assigned to use proposed buffer size by Noorollahi et al, (2007) as a default, but they can be changed by user to any other criteria.

The model was validated using data and information in Akita and lwate prefectures, northern Japan.

8. REFERENCES

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

Bonham-Carter, G.F., (1991), Integration of geoscientific data using GIS, In: *Geographical Information Systems: Principles and Applications*, Maguire, D.J., Goodchild, M.F., Rhind, D.W. (Eds.), Longman, Essex, pp. 171-184.

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

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, 3-7.

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.

Chung, CF., Jeoerson, C.W., Singer, D.A., (1992), A quantitative link among mineral deposit modeling, geoscience mapping, and exploration-resource assessment. *Economic Geology* 87, 194-197.

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 favorable exploration terrains for extensional geothermal systems. in: Proceedings, Annual Meeting, Reno, NV., Sept. 22-25, 2002, Geothermal Resources Council Transactions, v. 26, p. 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. and BonhamCarter, G., eds., GIS and Spatial Analysis: International Association of Mathematical Geology Annual Conference Proceedings, Toronto, Canada, Aug. 21-26, 2005, p. 505-510.

Dickson. M.H., Fanelli, M., (2004), *What is Geothermal Energy?* Istituto di Geoscienze e Georisorse, CNR, Pisa, Italy,

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

Hanano, M., (2000), Two different roles of fractures in geothermal development, In: Proceedings of World Geothermal Congress 2000, Kyushu-Tohoku, Japan, May 28-June 10, 2000, 2597- 2602.

Katz, S.S., (1991). Emulating the prospector expert system with a raster GIS. *Computers & Geosciences* 17, 1033-1 050

Kawazoe, S., Shirakura, N., (2005). Geothermal power generation and direct use in Japan. In: Proceedings of World Geothermal Congress 2005, Antalya, Turkey, 24—29 April, 2005, 1-7.

Ishikawa, T., (1970), Geothermal fields in Japan considered from the geological and petrological viewpoint. *Geothermics* 2, Part 2, 1205-1211

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

Noorollahi. Y, ltoi. R, Fujii. H and Toshiaki. T., (2007), GIS model for geothermal resource exploration in Akita and Iwate prefectures, Northern Japan, Journal of *Computer & Geosciences*, Vol. 33, No. 8, pp. 1008-1 021

Noorollahi, Y., (2005), *Application of GIS and remote sensing in exploration and environmental management of Namafjall geothermal area, N-Iceland*, M.Sc. Dissertation, University of Iceland, Reykjavik, Iceland, 193 pp

Prol-Ledesma, R.M., (2000), Evaluation of the reconnaissance results in geothermal exploration using GIS. *Geothermics* 29, 83-1 03

Tamanyu, S., Takahashi, M., Murata, Y., Kimbara, K., Kawamura, M., Matsunami, T., Yamaguchi, H., (2000), An updated geothermal resources map of the Tohoku volcanic arc, Japan, In: Proceedings of World Geothermal Congress 2000, Kyushu-Tohoku, Japan, May 28-June 10, 2000, 1817-1 822

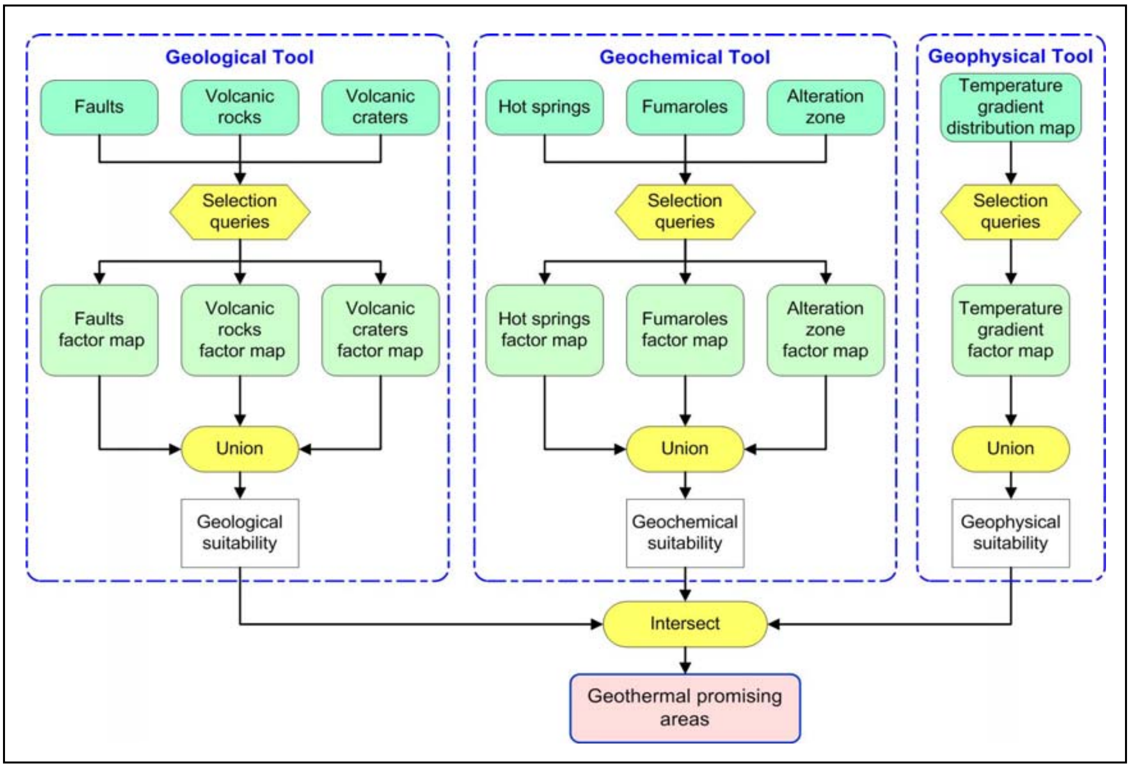

Figure 1 Flowdiagram of the GM-GRE presents the employed layers, tools, and operators and derived final suitability layer.

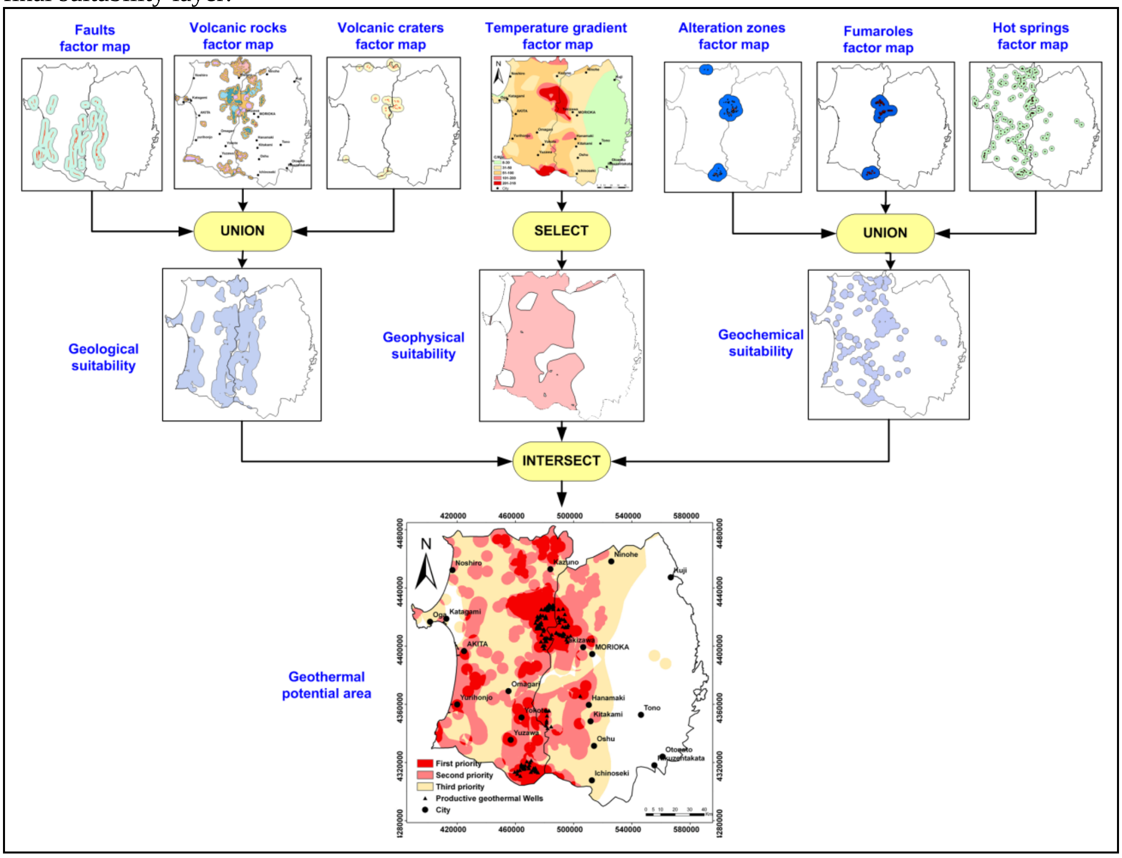

Figure 6 Input and output maps and flowdiagram of the Akita and Iwate geothermal potential