Assess the potential of geothermal resources using fuzzy logic and binary index overlay (Case Study: South Khorasan province, eastern Iran)

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Abstract

The South Khorasan province is located in eastern Iran. Identifying potential geothermal zones is a pre-requisite for any Thermal power plant and recreation center project. Geothermal exploration involves a high degree of uncertainty and financial risk, and requires reliable exploration data to constrain development decisions. The present study focuses on identifying the potential zones of geothermal in South Khorasan. In this research, 5 effective factors in potential geothermal such as Land surface temperature (L.S.T), Lithology, Surface evidence, Geomagnetic and Fault are used. Finally Data are combined together by using fuzzy logic and binary index overlay methods to effect of various factors in potential geothermal are measured together. The results of potential geothermal zonation indicate L.S.T factor are most important in geothermal zonation in this area. The results of potential geothermal zonation based on fuzzy logic and binary index overlay methods, respectively 10.34, 17.3, 24.9, 16.7 and 30.6% of the area are at very high risk class, high, medium, low and very low. Therefore, it was recognized that the South, Southwest, Northwest and East parts of the study area have more potential for detailed exploration in the future, and it was proved that these combination methods can be very practical in geothermal resource studies.

Keywords: Geothermal; Binary Index Overlay; Fuzzy logic; Land surface temperature (L.S.T); South Khorasan.

1- Introduction

Energy consumption has been increased recently, and the lack of energy resources is a significant challenge to all countries, especially the developed ones. The main problem is their limited resources which are not renewable. However, in recent years, scientists have proposed several new renewable sources of energy such as solar, wind, biomass and geothermal energy sources. These kinds of energy are cleaner and more economical than the last ones although they need an initial heavy investment. As a result, they are taken into consideration as useful substitutes for fossil energy (Kiavarz Moghaddam *et al*., 2014; Arianpoo, 2009; Jennejohn, 2009; Calvin *et al*., 2005). Geothermal energy is thermal energy which is generated and stored in the Earth. The main sources of geothermal energy in the Earth's crust are from the original formation of the planet (20%) as well as radioactive decay of minerals (80%) (Calvin *et al*., 2005). Based on recent researches, around 1% of this energy which is confined to the Earth's crust is comparable to about 500 times of fossil energy (Kiavarz Moghaddam *et al*., 2014). The geothermal resources of the Earth are theoretically more than humanity's energy needs; however, just a very small fraction of them is utilized by humans because drilling and exploration for deep resources is pretty expensive. Geothermal energy sources have been given more emphasis since 1827 with the use of geyser steam to extract boric acid from volcanic mud in Larderello, Italy (Kiavarz

Moghaddam *et al*., 2014). At the most subterranean layers of the Earth, the temperature increases to extremely high, and as a result the stones and soils are melted. If underground water flows near the melted soils and rocks at the subterranean layers of the Earth, it becomes hot, and eventually, its temperature sometimes even rises up to 150 1C. In some locations, this hot water reaches the Earth's surface and generates geysers. Geothermal resources are mostly near these geysers in addition to volcanoes (Ghobadian *et al*., 2009).

One of the most important applications of this energy is electricity generation. By way of illustration, some countries such as New Zealand, America, Japan, Iceland, Turkey, and so on, have some power plants to generate electricity from geothermal energy. The percentage of the total production of electricity using geothermal energy is approximately 0.3%, which is around 11,025.8 MV (Ghobadian *et al*., 2009); however, this amount is located in the first rank among all kinds of renewable energy resources.

As far as the issue of geological conditions is concerned, geothermal resources can be found in a wide range of geological systems, e.g., limestones, shales, volcanic rocks and granites (Kiavarz Moghaddam *et al*., 2014). Among these examples, volcanic rocks are of utmost importance in the issue of the application of this kind of energy as a practical industrial source of energy (Kiavarz Moghaddam *et al*., 2014; Huenges, 2010). Geothermal energy comes in two forms, vapor-dominated and liquid-dominated. Vapor- dominated sites have temperatures from 240 to 300 1C that produce superheated steam. Liquid-dominated reservoirs have usually temperatures more than 200 1C. They can be found near young volcanoes surrounding the Pacific Ocean and in rift zones and hot spots Kiavarz Moghaddam *et al*., 2014).

Lots of geothermal systems are indicators of superficial evidence such as hot springs, geysers, volcanoes and mud volcanoes. These discharge systems occur especially in some areas with hydrothermal alterations. Considering these facts, the geothermal exploration operations are done based on the surface evidence as well as geological, geochemical and geophysical maps and data. In nearly all exploration plans for geothermal resources, these operations are done step-by-step and with prospection and evaluation of the targets. In the final steps, the less important areas, e.g., the areas with environmental problems will be ignored (Yousefi *et al*., 2010).

2- Geothermal energy in Iran

2.1- The previous and recent activities

James R. McNitt, a geothermal expert, visited Iran around the year 1974. Based on his investigations on the geothermal potentials, an international contract was signed in 1975 between the Ministry of Energy (MOE), ENEL (Entes Nazionale per LEnergia Elettrica) of Italy and TB (Tehran Berkeley) of Iran in order to do geothermal exploration in NW Iran. After that, in 1983, four regions, which are Damavand, Sahand, Sabalan and Khoy-Maku, were proposed as the main geothermals in NW Iran (Najafi and Ghobadian, 2011; AEOI, 2002); Meshkinshahr, in Sabalan region, was the first area in which the initial exploration operations and drillings were concentrated. After 1990, two main organizations, which are Renewable Energy Organization of Iran (SUNA) and Electric Power Research Center (EPRC) concentrated their studies and operations on the exploration of the promising areas which have good potentials of clean sources of energy such as wind power, solar, thermal, geothermal, photovoltaic, biomass, biogas, hydrogen and fuel cell. Ten new geothermal potentials have been explored recently although around four sites had been recognized in advance (Najafi and Ghobadian., 2011; Iran Renewable Energy Organization).

All these kinds of renewable energy in Iran, as a developing country, will have decisive roles especially for supplying electrical energy. One of the best potentials for achieving this aim is geothermal resources. This kind of energy can be a good substitution for fossil fuels although it has several environmental effects which have to be managed. For instance, Turkey and Russia are two important countries in the vicinity of Iran utilizing their geothermal resources in order to generate electrical energy (Najafi and Ghobadian, 2011; Noorollahi *et al*., 2009).

In addition to the generation of electrical energy from the geothermal potentials in NW Iran, numerous balneology places are located in the Ferdows area and are at tourists' disposal (Porkhial and Kahrobaeian, 2004; Ahmadi, 1995; Abbaspour and Atabi., 1995). Many of them are located in the province of South Khorasan. Damavand area is another geothermal potential situated around the northern part of Iran and in parallel with the trend of Alborz mountains belt. This site has been designated for future investigations (Najafi and Ghobadian, 2011).

2.2- The future of geothermal energy in Iran

Due to the fact that Iran has a large number of fossil fuel reserves, especially oil and gas, which is the main source of the national power grid ($ 95% of 29,000 MW), attention to the other kinds of energy and particularly clean and renewable energy resources is not at the same level as other countries which have these resources as well as Iran. As a result, it is a demanding and time-consuming process that this kind of energy could be replaced by renewable energy like geothermal one in the near future (Najafi and Ghobadian, 2011). Considering these facts, it can be concluded that in spite of the fact that there are a lot of appropriate geological, lithological, geochemical and even topographical and structural conditions in Iran, the lack of several facilities like modern technologies and instruments in drilling and excavating and constructing is the most problematic thing in this country. Hence, Iran is still in its initial steps regarding them (Noorollahi *et al*., 2007 and 2008; Saffarzadeh and Noorollahi, 2005; Yousefi *et al*., 2007; National Geoscience Gatabase of Iran; Futuhi, 1994a, 1994b). Based on the trend of energy production from fossil resources, it is obviously anticipated that this kind of energy production will witness a downward trend parallel to the decreasing fossil fuel resources in 2019, and consequently countries like Iran which have economies on the basis of their fossil resources must try to replace it with new types of energy (Bakhoda, *et al*., 2012). Thus, in the fourth national development plan of Iran, several strategies have been taken into consideration (e.g., completing the Ferdows geothermal project) (Noorollahi *et al*., 2009).

In Iran, several geothermal projects are under construction, and among these projects the Ferdows generation project is of utmost importance. This project is situated in South Khorasan province, Ferdows region (E Iran), which is the two location that experienced the exploration operations for detecting geothermal resources in Iran (Yousefi *et al*., 2010; Ghobadian *et al*., 2009; Porkhial and Kahrobaeian., 2004; Hosseini *et al*., 2013). As far as the issue of geothermal resources in Iran is concerned, South Khorasan province is the richest one (Noorollahi and Itoi, 2011). The aim of this research is the prospection and reconnaissance of the promising geothermal potentials in South Khorasan province (E Iran). Most data of this region exist in 1:1250,000 scale, and as a result these data were collected, combined and studied using two methods (Fuzzy logic and Binary Index Overlay) in GIS environment.

In many countries, the Geographic Information Systems (GIS) are used for combination of informative layers such as exploration of promising mineralization’s and potentials in geological studies (Bonham-Carter *et al*., 1988, 1991, and 1994; Katz, 1991; Chung *et al*., 1992). Consequently, the GIS methods can be applicable and appropriate for the discrimination of high potential geothermal resources (Yousefi *et al*., 2010; Noorollahi *et al*., 2007; Prol-Ledesma, 2000; Coolbaugh *et al*., 2002; Coolbaugh *et al*., 2005a, 2005b).

3- Geological setting of the study area

South Khorasan province refers to a part of E Iran, which is located in 570 01/E-610 30/E and 300 01/N-350 30/N. The study area is located in the North part of the Lut Block Microcontinent and North part of the Sistan suture zone (CEIM; Takin 1972) (Fig. 1). Iran represents part of the Alpine–Himalayan orogenic system and consists of various microcontinental blocks separated by narrow belts of Mesozoic ophiolitic rocks (Şengör *et al*., 1988; Ghazi *et al*., 2004). Despite a complex tectonic history from the Permian to Quaternary, most regions of the country are underlain by Paleozoic platform strata similar to those of the Arabian platform (Stöcklin, 1968). The microcontinental blocks are therefore suggested to share a common paleogeographic position close to the northern margin of Gondwanaland (Ramezani and Tucker, 2003), rifted in successive stages and were accreted to the southern margin of Eurasia (Şengör and Natal'in, 1996). Iran consists of three orogenic belts juxtaposed with major suture zones and magmatic belts; these belts surround an assembly of continental blocks collectively known as the central Iranian micro-continent (CIM), consisting of the Lut, Tabas and Yazd blocks from east to west. The CIM is suggested to have undergone anti-clockwise rotation from the Late Cretaceous to Early Tertiary (Conrad *et al*., 1981; Shafiei *et al*., 2009). The Alborz–KopehDagh ranges are associated with a Paleotethyan suture in northern Iran (Alavi *et al*., 1997) and magmatic rocks, mostly Eocene–Oligocene in age, crop out to the south of and roughly parallel to the suture. The Zagros fold and thrust belt and the Bitlis–Zagros suture in southwestern Iran mark the closure of Neotethys and the collision between the Afro–Arabian continent and Eurasia. The collision is interpreted by different workers to have started in the Late Eocene (Allen and Armstrong, 2008; Hatzfeld and Molnar, 2010), the Late Oligocene (Allen *et al*., 2004; Agard *et al*., 2005; Fakhari *et al*., 2008), or the Miocene (McQuarrie *et al*., 2003; Verdel *et al*., 2007). The Sanandaj–Sirjan zone (SSZ) and the Urumieh–Dokhtar magmatic arc (UDMA), both of which are roughly parallel to the Zagros orogen, are manifestations of the prolonged subduction of Tethyan oceanic lithosphere beneath the Eurasian continental margin prior to the Arabia–Eurasia collision. The SSZ consists mostly of metamorphic rocks with minor Mesozoic intrusions while the UDMA is dominated by Eocene–Oligocene volcanic rocks. Post-collisional magmatic rocks along the UDMA include ultrapotassic volcanic rocks (Ahmadzadeh *et al*., 2010), kamafugitic rocks (Pang *et al*., 2011), and adakitic rocks (Jahangiri, 2007; Omrani *et al*., 2008). The east Iranian ranges and the Sistan suture zone mark the closure of the Sistan Ocean, a narrow branch of Neotethys that opened during the Middle Cretaceous (Camp and Griffis, 1982; Tirrul *et al*., 1983). This was accompanied by the suturing between the Lut block and the Afghan block to the east at the Late Cretaceous (Saccani *et al*., 2010; Zarrinkoub *et al*., 2010). Magmatism for the Lut block was active from the Jurassic to Quaternary with a dominant pulse during the Eocene– Oligocene (see Karimpour *et al*., 2011 for review), which resulted in calcalkaline rocks covering a region of at least ~300×400 km^2. The N–S-trending Nayband fault separating the Lut and Tabas blocks appears to be the westernmost boundary for this rock suite and The N–S-trending Nehbandan fault separating the Lut and Sistan suture zone appears to be the Easternmost boundary for this rock suite (Fig. 2).

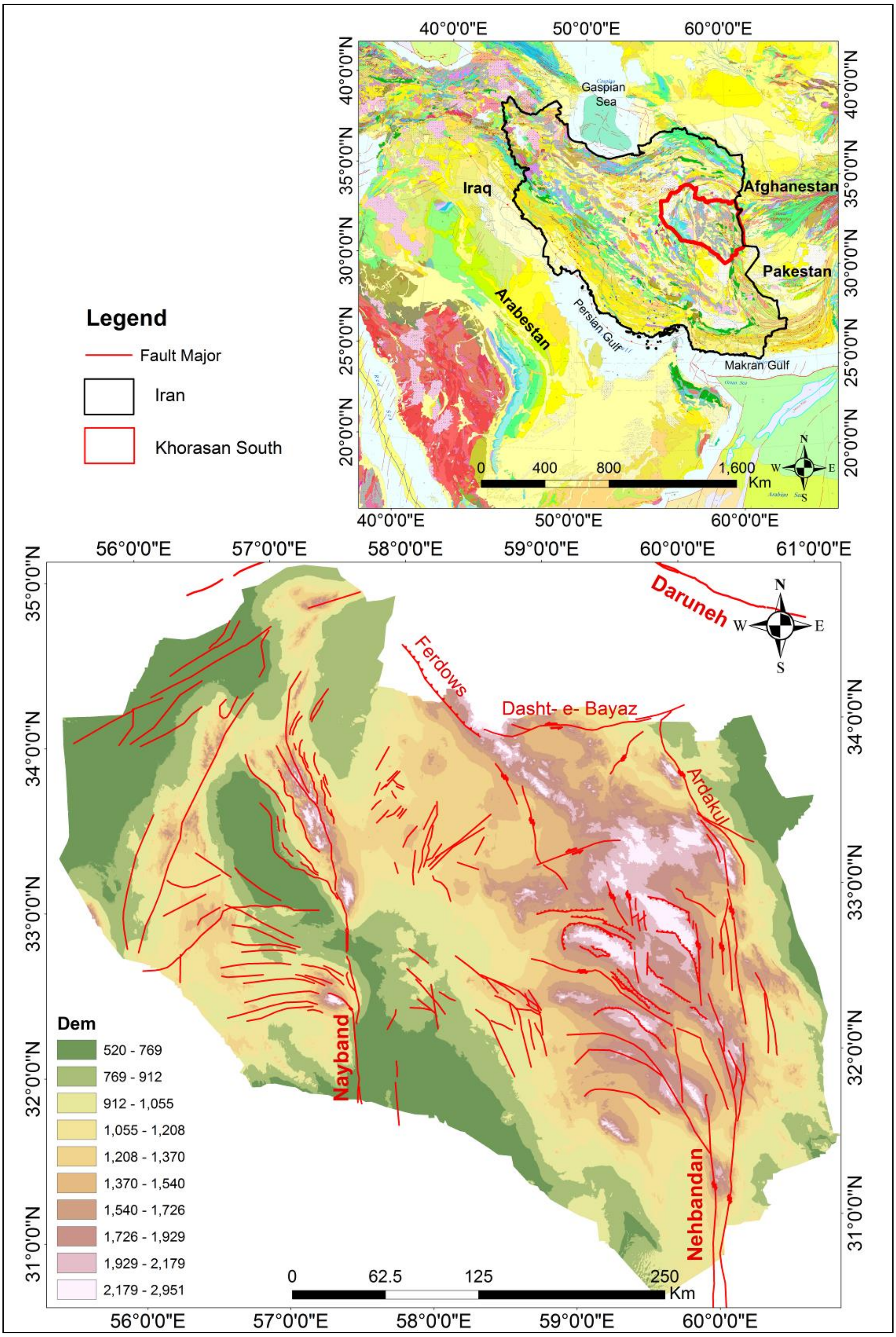

Figure 1) Geological sketch map of the northern Block Lut and northern of the Sistan suture zone, eastern Iran, showing the sampling locations in the Lut–Sistan region.

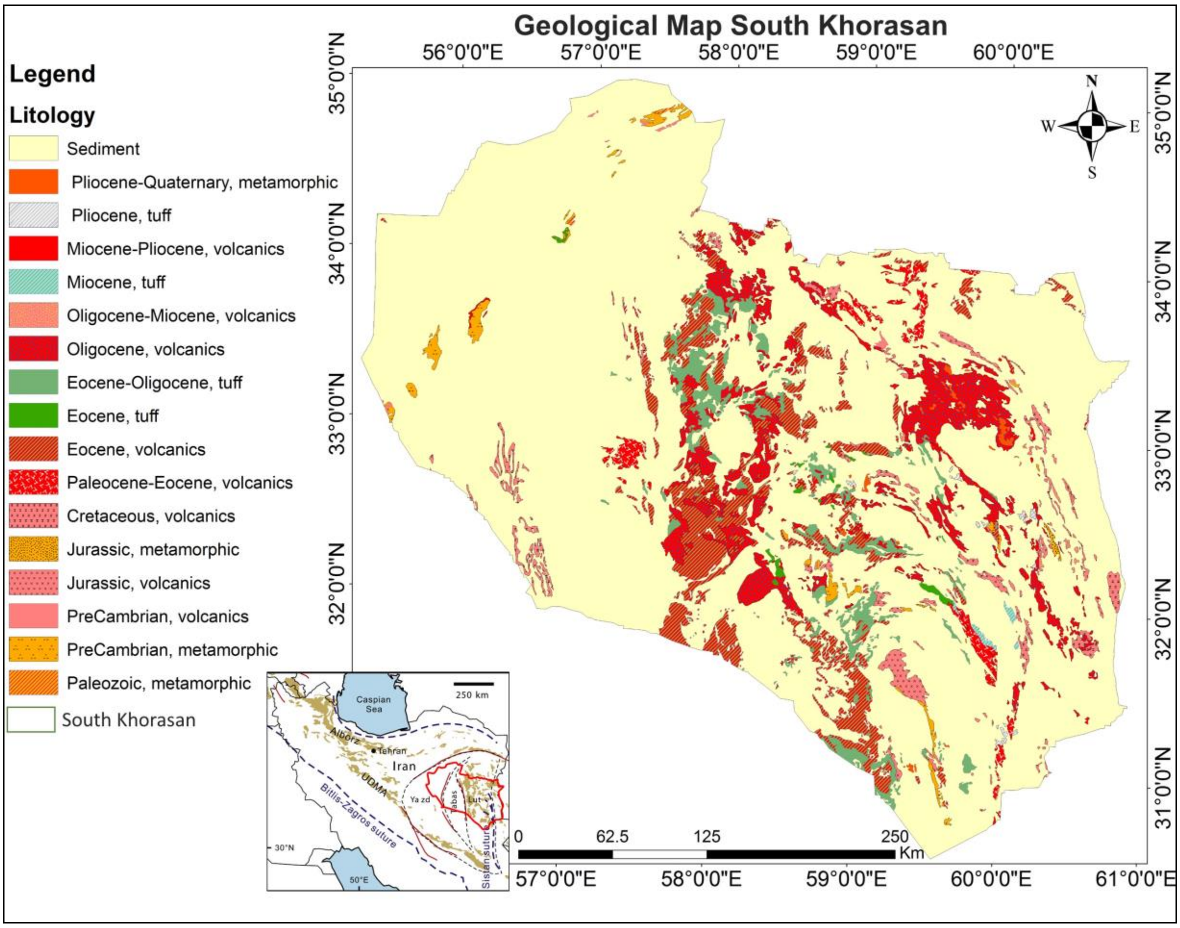

Figure 2) Geological Map of South Khorasan province in the northern part of Lut block and the northern part of Sistan suture zone.

4- Methodology

The costs of geothermal exploration projects are around 42% of the projects' total charges (Kiavarz Moghaddam *et al*., 2014; Jennejohn, 2009). Considering the fact that exploration operations have several steps which are reconnaissance, pre-feasibility studies, feasibility studies, semi-detailed exploration and detailed exploration from regional to local scale (Noorollahi *et al*., 2008; Wright *et al*., 1989; Goldstein, 1988), during each step, investigations are concentrated on the most important areas (Noorollahi *et al*., 2008; Carranza, 2009a; Berkovski, 1995). All these steps consist of some information layers like geological, geophysical and geochemical characteristics. After generating each layer, all of them will be integrated with each other in order to generate a union predictive model (Kiavarz Moghaddam *et al*., 2014; Noorollahi *et al*., 2007; Carranza, 2009b; Healy, 1970). The most appropriate tool for this aim is Geographical Information Systems (GIS) (Bonham-Carter, 1994) which can decrease the errors of the integration process significantly. A GIS is a system for computer-based mapping and information integrating used for the management of data layers and decision making based on combined geological, geographical, environmental and other kinds of information layers in order to detect the best targets for more evaluation in the future steps (Yousefi-Sahzabi *et al*., 2011; An, 2008). The conceptual generated model illustrates the relation of the informative layers and targets (Carranza, 2009a; Lisitsin and Rawling., 2011; Bonham-Carter, 1985). The integration of informative layers, especially in geosciences can be useful for generating conceptual models of geosciences can be useful for generating conceptual models of mineralizations and alterations (Carranza, 2009a; Carranza and Hale, 2002; Vearncombe and Vearncombe, 1999).

Several kinds of models and methods are used for simulation of various events in GIS environment. For example, the Legend Integration method is used for site selection by integrating related spatial data. The integration methods have two main branches (Prol-Ledesma, 2000; Abedi and Norouzi, 2012; Yousefi *et al*., 2012; Carranza *et al*., 2008): (1) Knowledge driven and (2) Data driven. Knowledge driven methods are based on the experts' experience and science; however, data driven methods are based on the existent solutions and the values of data. There are some kinds of GIS integration methods such as Weights of Evidence (e.g., Coolbaugh *et al*., 2002), Boolean Logic (e.g., Yousefi *et al*., 2010), Binary Index Overlay and Fuzzy Hierarchical Aggregation models (e.g., (Prol-Ledesma, 2000) and Analytical Hierarchy Process (AHP) methods (e.g., Noorollahi *et al*., 2007; Carranza *et al*., 2008), etc. In this research Binary Index Overlay and Fuzzy Logic methods were selected and utilized. Considering the previous studies (e.g., Bonham-Carter, 1991), the Index Overlay models are more flexible and helpful than Boolean ones, particularly for priority indication on factor maps.

4.1- Binary Index Overlay method

This method is a knowledge driven modeling method. The knowledge-based methods are proper for the initial steps of the exploration operations in areas which are geologically appropriate; however, the amounts of these operations are not adequate. In this method, attributes or classes of spatial data are assigned a class score of 1; otherwise, they are assigned a class score of 0. Thus, this method is similar to a Boolean map, except that the values in the former are both symbolic and numerical. Consequently, each binary evidential map Bi (i=1, 2, ..., n) can be given a numerical weight Wi based on `expert' judgment which is based on the importance of the geological features. These weights are positive integers or real numbers. In other words, each class of a single map has its own specific weight (Bonham-Carter, 1994). The equation of this method is expressed as follows (Bonham-Carter, 1994; Carranza, 2008; Yousefi and Kamkar Rouhani., 2010):

$$S = \frac{\sum_i^n W_i B_i}{\sum_i^n W_i} \quad (1)$$

Where Wi denotes the weight of each binary evidential map: Bi (i= 1, 2, ..., n). In the output map S, each location or pixel value ranges from 0 (i.e., completely non-prospective) to 1 (i.e., completely prospective). Even though the input maps have only two classes, the output one can have intermediate prospective values, classes, the output one can have intermediate prospective values, (Kiavarz Moghaddam *et al*., 2014; Bonham-Carter, 1994; Carranza, 2002, 2008; Thiart and De Wit, 2000; Malczewski, 2006; Yousefifar *et al*., 2007; Yousefi *et al*., 2010; Clarke, 1999).

The Binary Index Overlay model is used for performing subjective-based analyses. All the informative layers, which are in the same category, are combined so as to recognize the promising areas. After that, the factor maps, which are the extracted layers, are weighted, overlaid and eventually combined in order to detect the more detailed promising areas (Kiavarz Moghaddam *et al*., 2014).

4.2- Fuzzy logic method

The fuzzy logic was proposed by Zadeh (Zadeh, 1965), which is a knowledge-driven method as well (Carranza and Hale, 2001; Ziaii *et al*., 2010). Fuzzy logic modeling is based on the fuzzy set theory (Rojas, 1996; Ponce-Cruz and Ramirez-Figueroa., 2010; Zadeh, 1996, 1999, 2003). The inference process in this method, which is known as Mamdani (Roisenberg *et al*., 2009), is based on a transformation and mapping from a given input to an output utilizing a set of fuzzy (Gaines, 1976) which is from actual world to fuzzy values (Kiavarz Moghaddam *et al*., 2014). Demicco and Klir (Demicco and Klir, 2004) discussed and illustrated the applications of fuzzy logic modeling in geological studies; how- ever, many researchers neglect its application in mineral prospec- tivity mapping. Several fuzzy operators (fuzzy AND, fuzzy OR, fuzzy algebraic sum, fuzzy algebraic product and fuzzy gamma) are used for flexible combinations of input maps. Some other researchers have utilized this method in prospectivity mapping in recent years (e.g., (Coolbaugh *et al*., 2003; D'Ercole, 2000; Knox-Robinson, 2000; Porwal and Sides, 2000; Venkataraman *et al*., 2000; Porwal *et al*., 2003; Tangestani and Moore, 2003; Ranjbar and Honarmand, 2004; Eddy *et al*., 2006; Harris and Sanborn-Barrie, 2006; Rogge *et al*., 2006; Nykanen *et al*., 2008a and 2008b). In a fuzzy map, the value of each pixel (between 0 and 1 based on the subjective judgment) represents the relative importance of the factors and the values of different locations on the map (Zadeh, 1965; Carranza and Hale., 2001; Ziaii *et al*., 2010; Roisenberg *et al*., 2009; Gaines, 1976; Chi KH *et al*., 2001).

This method has three functions, OR, Algebraic SUM and Gamma Operation. The OR function is useful when there is not enough evidence, so each evidence can be beneficial (Carranza, 2008; Yousefifar *et al*., 2012; Alesheikh *et al*., 2008):

$$\mu Combination = MAX\ [\mu A, \mu B, \mu C, ...] \quad (2)$$

The fuzzy OR is the same as the Boolean OR (logical union) in output membership values which are controlled by the maximum values. The results of the algebraic SUM function are similar to the OR results; however, in this function, all numbers and inputs are used entirely (Carranza, 2008; Yousefifar *et al*., 2012; Alesheikh *et al*., 2008):

$$\mu Combination = \prod_{i=1}^{n}(1-\mu) \quad (3)$$

The Gamma Operation function fluctuates between the other functions and is based on the identification of γ (Carranza, 2008; Yousefifar *et al*., 2012; Alesheikh *et al*., 2008):

$$\mu Combination = (FuzzyA\lg.Sum)^{\gamma} * (FuzzyA\lg.\mathrm{PRooduct})^{1-\gamma} \quad (4)$$

where γ is a parameter between 0 and 1.

Fuzzy gamma can control the relation between the increasing of the fuzzy algebraic sum and the decreasing effect of the fuzzy algebraic product. With γ (gamma) the decreasing or increasing tendency can be controlled. For $\gamma = 1$, it can be said that the combination equals the fuzzy algebraic sum, and when $\gamma = 0$, the combination equals the fuzzy algebraic product.

5- Informative layers

5.1- Land surface temperature (L.S.T)

5.1.1- Land surface temperature of the heat inside the earth.

Determining the energy balance of the Earth's surface and underground heat transfer leads to the identification of geothermal areas. These areas caused by heat inside the earth (Shakeri *et al*., 2008; Oskarsson, 1995; Valentino and Stanzione., 2004).

5.2- Surface evidence

5.2.1- Volcanoes

Another main parameter for prospecting geothermal resources is volcanoes (Yousefi *et al*., 2010; Shakeri *et al*., 2008). In this research, the 1:250,000 map of the distribution of volcanoes in the study area was used. According to the statistics, around 47 volcanoes are in Iran and most of them are located and spanned in the NW and eastern part of Iran. A 200 m buffer is selected for all volcanoes, and after that, it is turned to raster (Fig. 3a).

5.2.2- Hot springs

On the basis of general geological investigations across the world, a large number of hot and cold springs are spread in active volcanic regions and hydrothermal systems (Giggenbach, 1997; Valentino *et al*., 1999; Varekamp *et al*., 2001). The geo- chemistry studies on thermal waters could be a very useful tool for monitoring volcanic activities (Shakeri *et al*., 2008; Oskarsson, 1995; Valentino and Stanzione., 2004). Two important para- meters in these springs are their temperature and level of discharge which depend on several factors such as changes of temperature with depth, underground conditions and dilution of the heated water in depth and in ground water which is colder due to being near the surface (Shakeri *et al*., 2008). The main applications of thermal springs are related to these two factors (Shakeri *et al*., 2008; Wohletz and Heiken., 1992).

Hot springs are the main determiners of geothermal activities. These structures are directly in relation to the size and type of the superficial hydrothermal alterations, and even with the high potential geothermal resources. For instance, a spatial analysis about the relation between the distribution of hot springs and geothermal holes in North Japan displayed that 97% of the geothermal holes are situated in the 4000 m range from the hot springs (Noorollahi *et al*., 2007). Based on the national statistics, there are around 308 hot springs across Iran (Shabeik, 1993), and most of them are located in the northern and NW parts of Iran. More than 15 of them are in the South Khorasan province. A 3000 m buffer is selected for all these hot springs, and after that, it is turned to raster (Fig. 3. b).

5.2.3- Alteration parameters

Alteration methods are widely used in preliminary prospecting and at every stage of a geothermal project. The Alteration evidence layer incorporates the location of hydrothermal alteration zones given in (Fig. 3. B; Noorollahi *et al*., 2007).

5.2.4- Geochemical parameters

The geochemical parameters and methods have a comprehensive role in prospecting promising areas for concentration of exploration operations, especially in mineral exploration and also in geothermal projects. The geochemical evidence of geothermal potentials consists of hot springs (425 1C) (Phillips, 2010), mud volcanoes and hydrothermal alterations. Although this layer is important in combination, it was not used in this research because the alteration map of this study area has not been generated in this scale yet (Fig. 3b).

5.3- Lithology

The presence of volcanic and intrusive rocks in the study area is one of the most prominent evidences in order to prospect geothermal resources (Yousefi *et al*., 2010). From the geological point of view, about 9% of whole of Iran is of volcanic rocks (Dimitrijevic *et al*., 1971). Given this fact, and also the geological setting of the study area, it can be said that the South Khorasan province has a good potential of this parameter. As far as the issue of lithology is concerned, the acidic rocks are in priority (Marques *et al*., 2010). Therefore, all kinds of rocks in the study area were classified and mapped using their 1:250,000 geological map (Fig. 3c).

5.4- Geomagnetic parameters

Geophysical techniques have been successfully utilized to locate and characterize geothermal systems; gravimetric, aeromagnetic, seismic and thermal methods (i.e. thermal gradient and heat flow) are commonly used. In Iran geomagnetic survey data to aid geothermal resource identification is limited to the vicinity of the South Khorasan geothermal field, and is not available nationwide. However, aeromagnetic data have been collected and used to locate shallow intrusive rocks. It is envisaged that updated regional geomagnetic maps will be prepared as new data are gathered (Fig. 3d; Noorollahi *et al*., 2007).

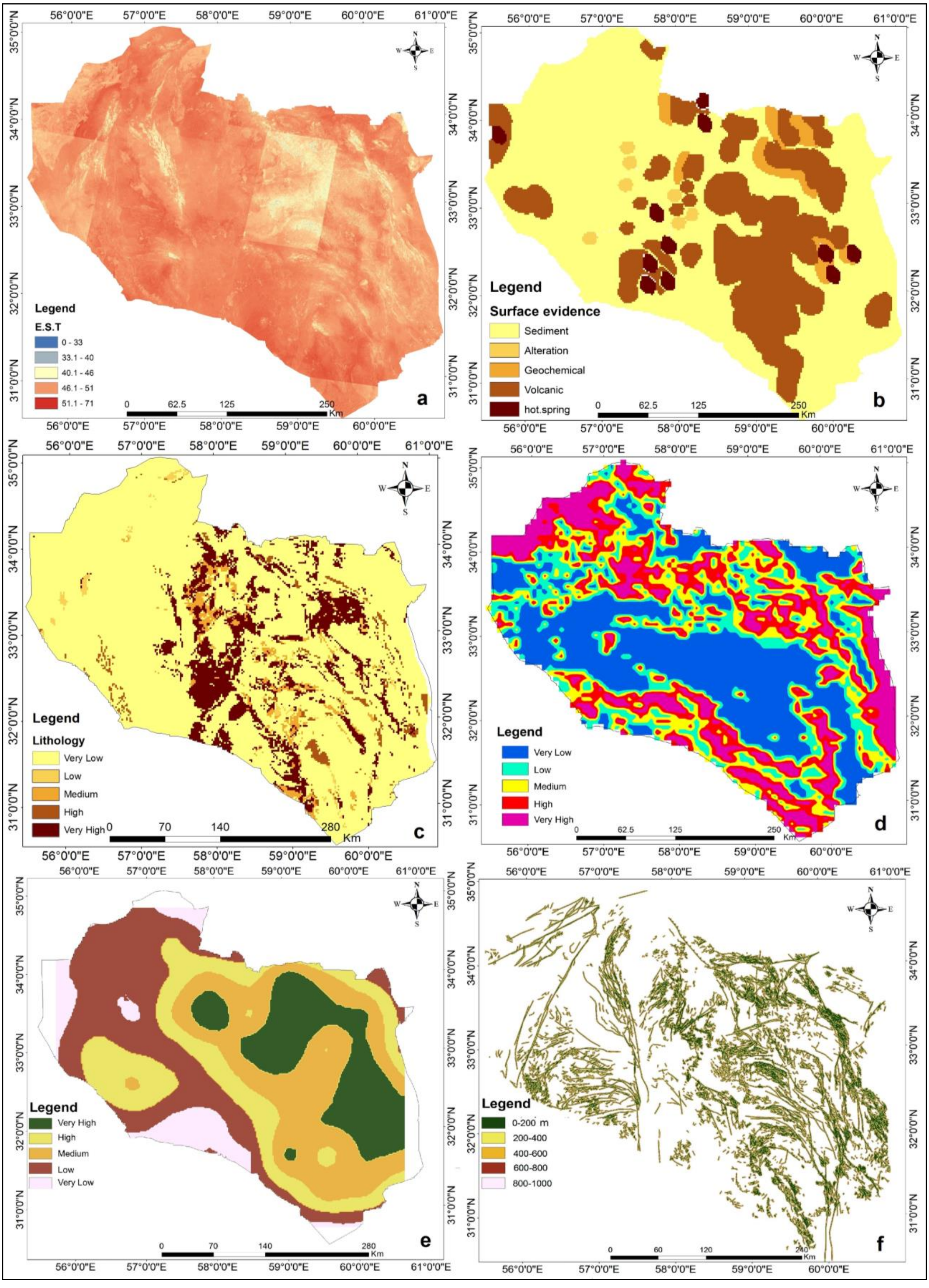

Figure 3) Parameters affecting the potential of geothermal resources in South Khorasan Province (a: L.S.T, b: Surface evidence, c: Lithology, d: Geomagnetic, e: Fault density, f: Distance to fault).

5.5- Faults and fractures

Faults and fractures have a decisive role in controlling nearly all subsurface fluid flows in geothermal areas. Hanano (2000) and many other researchers have confirmed this fact and its effect on the natural convection features. For example, Noorollahi *et al*. (2007) did a project in order to evaluate the relation between the location of these structures and the concentration of the geothermal holes in Japan in 1:250,000 scale. The results of their research revealed that around 95% of the geothermal holes are situated in the range of 6000 m from the main faults in the study area. This distance was more than what was expected. Given this fact, the correlation between the permeability in faults and the appropriate production was a little difficult. Based on this fact, in our study area, a 1000 m buffer was selected and carried out, and consequently was turned to raster (Figs. 3e and 3f).

6- Integration of the informative layers

In this section, each informative layer, according to the values of its units, has various classes and special weights based on the studies and experts' ideas. It can be combined with different data layers using different methods. All available data layers were integrated using the presented methods, and their final results were analyzed and compared with each other:

6.1- Binary Index Overlay modeling

This method was carried out using two forms: (1) getting out the ordinary mean of the informative layers and (2) using weighted data layers. In the first form, this equation was utilized:

$$\frac{(\mathrm{L.S.T})+(\mathrm{Surfaceevidence})+(\mathrm{Lithology})+(\mathrm{Geomagnetic})+(\mathrm{Fault})+(\mathrm{Distance\ to\ Fault})}{6} \quad (5)$$

However, in the second form, the values of each layer must be multiplied by the weight assigned by experts in order to increase the value of the main layer (Table1). Finally, their sum will be multiplied by 100 (total coefficients):

$$\frac{(\mathrm{L.S.T}\times 35.1)+(\mathrm{Surface\ evidence}\times 27.9)+(\mathrm{Lithology}\times 12)+(\mathrm{Geomagnetic}\times 10)+(\mathrm{Faults}\times 8.6)+(\mathrm{Distance\ to\ Fault}\times 6.4)}{100} \quad (6)$$

Table 1) Expert weights assigned to each data layer.

Informative layer	Expert weights
L.S.T	0.351
Surface evidence	0.279
Lithology	0.12
Geomagnetic	0.1
Fault	0.086
Distance to fault	0.064

In comparison, in this case, the results of the second form are better. Because of the importance of the L.S.T layers, their weights were assumed to be less than the weight of Distance to Fault layer due to lack of Fault data in comparison with them in this scale since in some areas there are no hot springs; however, there are acidic volcanic parts. Based on the results of Figs. 4, it can be seen that the high potential geothermal resources (Figs. 4 blue areas) are concentrated in the South, Southwest, Northwest and East part of the study area.

6.2- Fuzzy logic modeling

In this method, after applying the appropriate classes to the parts of each layer based on the expert evaluations, tow functions, SUM for L.S.T, Lithology and Geomagnetic layers and OR for Surface evidence faults and Distance to fault, and γ = 95% were used. After processing, the final results map was generated (Fig. 4). The blue areas, which are located in the south, Southwest, Northwest and East part of the study area (Table. 5), are the high potential areas that need to be concentrated on in the future explorations.

Areas with potential for geothermal resources (Figure. 5. Blue area) was tested using field data provided. The hot springs active in South Khorasan province has a high potential geothermal areas were inside. Structural study shows that the active spring springs enable all over South Khorasan province in the range of igneous rocks, active faults and areas with thermal alteration (Table 2). Accordingly Purses field data confirms the high level of validation has been done.

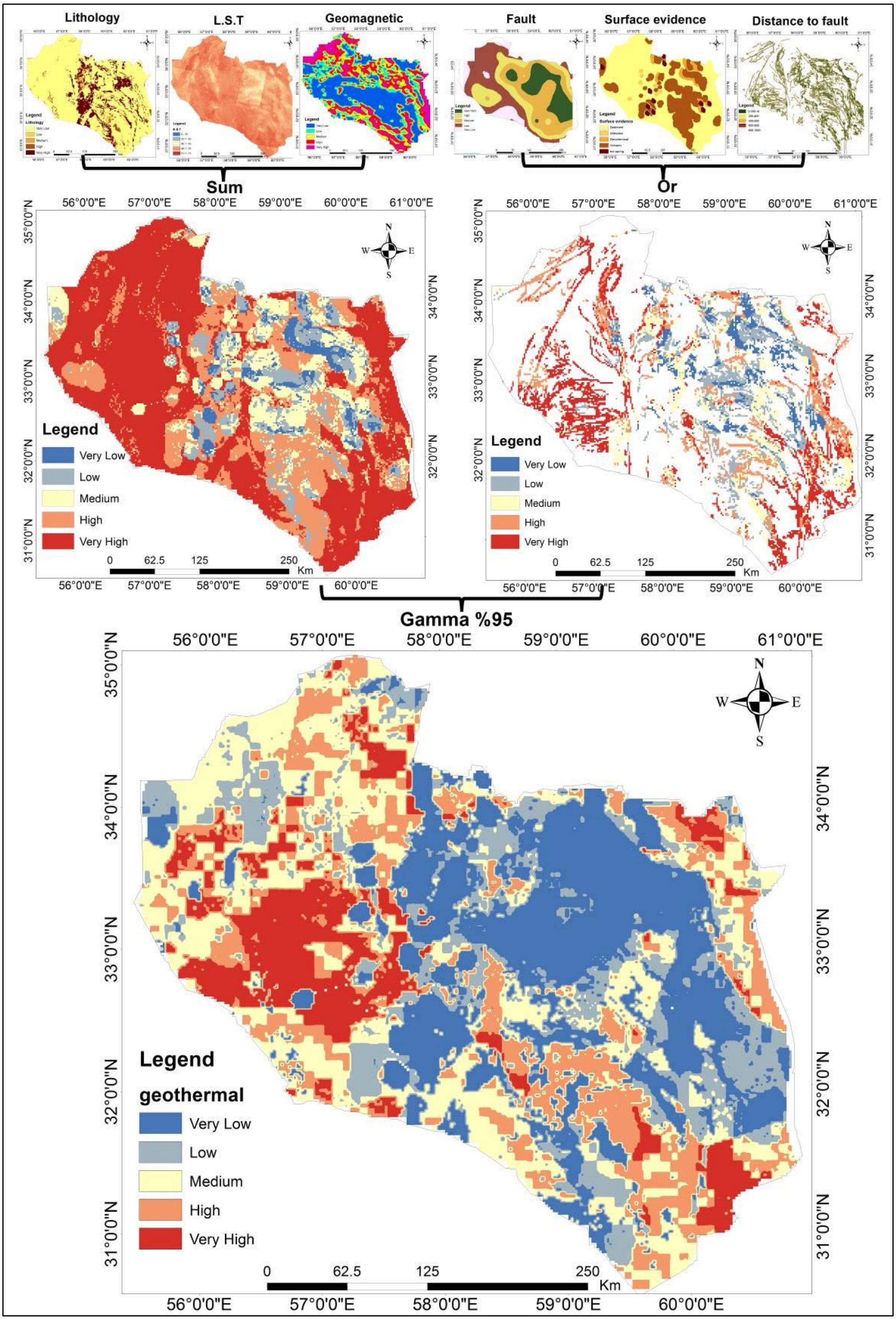

Figure 4) Promising area using the Fuzzy Logic method.

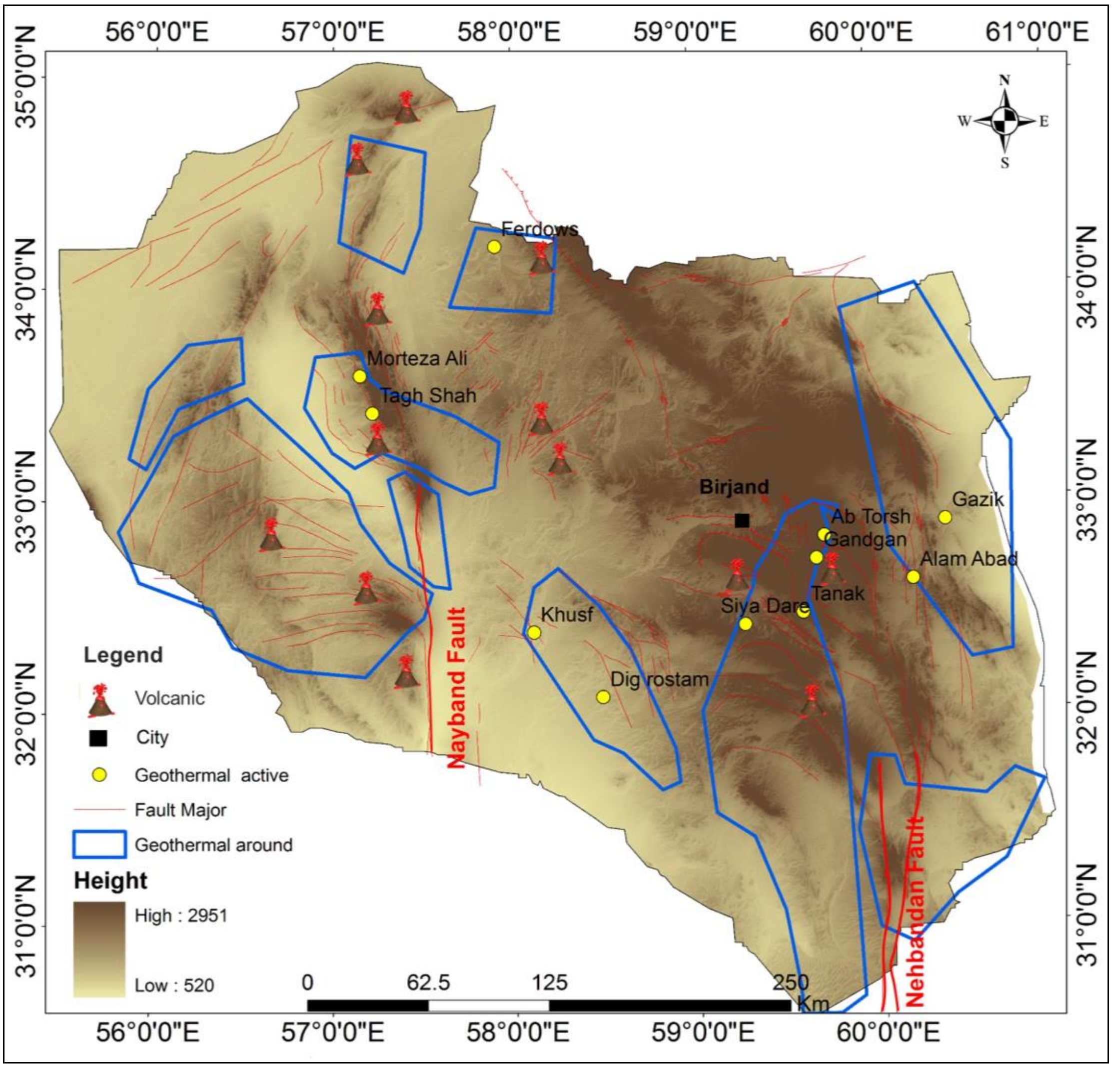

Figure 5) Promising area using the Fuzzy Logic method.

Table 2) Hot springs with their structural position indicators.

	Lat / Lon	L.S.T	Surface evidence	Lithology	Geomagnetic	Fault	Accreditation
Ferdows	583349 / 3785499	√ 48°	√ Alteration	√ Diorite	√ Very High	√ Ferdows	√
Khusf	604088 / 3584077	√ 55°	√ Geochemical	√ Andesite	√ Very High	√ Khusf	√
Gazik	816898 / 3644388	× 40°	× Non	√ Andesite	√ High	√ Gazik	√
Alam Abad	800338 / 3613295	× 37°	√ Hot spring	√ Tuff	× Medium	√ Dastgerd	√
Siya Dare	713604 / 3588607	√ 56°	√ Geochemical	√ Andesite	× Medium	√ Giv	√
Morteza Ali	513871 / 3717900	√ 50°	√ Volcanic	√ Tuff	√ Very High	√ Tabas	√
Tagh Shah	520335 / 3698477	√ 48°	√ Volcanic	√ Andesite	√ High	√ Tabas	√
Dig Rostam	639938 / 3550334	√ 53°	√ Volcanic	√ Andesite	√ High	√ Seydan	√
Ab Torsh	754290 / 3635315	× 43°	√ Geochemical	√ Andesite	× Medium	√ Zulesk	√
Gandgan	750197 / 3623462	√ 51°	√ Geochemical	√ Andesite	× Medium	√ Baghestan	√
Tanak	743542 / 3595085	√ 50°	√ hot spring	√ Andesite	× Medium	√ Giv	√

Table 4 Area and Percent of each class of potential geothermal output in the map by Fuzzy.

Fuzzy	Evaluation of geothermal resources									
	Very Low		Low		Medium		High		Very High	
Product	%	Km^2	%	Km^2	%	Km^2	%	Km^2	%	Km^2
	30.6	46	16.7	25.1	24.9	37.4	17.3	26	10.34	15.5

7- Conclusions

Based on the results of all the methods used, a good correspondence can be seen between them which can confirm their accuracy. Using the available informative layers and analyzing them, the high potential areas were discriminated, which are concentrated in the South, East, Northwestern part of the study area. The results showed that 10.34% (15.5×10^3 km^2) of the total studied area is suitable for geothermal. This study shows that 30.6% (46×10^3 km^2) percent of the total area of non-value heat source was mine. However, more work should be done for detailed exploration, and this problem needs more detailed informative layers on larger scales. Comparing all the methods used, the Weighted Index Overlay is found to be the best method in this study. Thus, it can be useful in future evaluations, especially when the number of informative layers is not enough since in all investigations the data layers are more completed and detailed, it is predictable that the results of fuzzy logic will be more accurate and closer to the fact. In addition, thanks to the ability of GIS in combination with all data layers based on the mathematical methods and experts' ideas, the integration methods can simplify exploration analysis and reduce their calculations and, as a result, decrease the exploration costs.

Considering the fact that the detailed studies on this part of Iran are not adequate, these methods can be pretty worthwhile especially when the data are limited or a lot is lacking. In addition, these studies can be developed for the other provinces and areas. The higher accuracy of these evaluations depends on more and detailed geological, geochemical, geophysical, lithological and even remote sensing studies.

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References

Abbaspour, M., Atabi, F. 1995. Wind energy estimation for production of electricity in Iran. In: Proceedings of the international conference in solar energy and the Islamic countries.

Abedi, M., Norouzi, G. H. 2012. Integration of various geophysical data with geological and geochemical data to determine additional drilling for copper exploration. Journal of Applied Geophysics: 83, 35–45.

Agard, P., Omrani, J., Jolivet, L., Mouthereau, F. 2005. Convergence history across Zagros (Iran): constraints from collisional and earlier deformation. International Journal of Earth Sciences: 94, 401–419.

Ahmadi, A. M. 1995. 1000 kW wind electric power plant in Manjil region. In: Proceedings of the international conference on solar energy and the Islamic countries.

Ahmadzadeh, G., Jahangiri, A., Lentz, D., Mojtahedi, M. 2010. Petrogenesis of Plio–Quaternary post-collisional ultrapotassic volcanism in NW of Marand, NW Iran. Journal of Asian Earth Sciences: 39, 37–50.

Alavi, M., Vaziri, H., Seyed-Emami, K., Lasemi, Y. 1997. The Triassic and associated rocks of the Nakhlak and Aghdarband areas in central and Northeastern Iran as remnants of the Southern Turanian active continental margin. Geological Society of America Bulletin: 109, 1563–1575.

Alesheikh, A., Soltani, M., Nouri, N., Khalilzadeh, M. 2008. Land assessment for flood spreading site selection using geospatial information system. International Society of Environmental Sciences Technology: 5, 455–62.

Allen, M., Jackson, J., Walker, R. 2004. Late Cenozoic reorganization of the Arabia–Eurasia collision and the comparison of short-term and long-term deformation rates. Tectonics 23, TC2008. doi:10.1029/2003TC001530.

Allen, M. B., Armstrong, H. A. 2008. Arabia–Eurasia collision and the forcing of mid-Cenozoic global cooling. Palaeogeography, Palaeoclimatology, Palaeoecology: 265, 52–58.

An, X., Ma, A., Liu, D. 2008. A GIS-based study for optimizing the total emission control strategy in Lanzhou city. Environmental Model Assessment: 13, 491–501.

Arianpoo, N. 2009. The geothermal potential of Clarke Lake and Milo Gas fields, Northeast British Columbia. Electronic Theses and Dissertations (ETDs): 33, 907–10.

Atomic Energy Organization of Iran (AEOI). 2002. Renewable energies: their present and future forecasts. A report prepared by CRERA. Tehran, Iran.

Bakhoda, H., Almassi, M., Moharamnejad, N., Moghaddasi, R., Azkia, M. 2012. Energy production trend in Iran and its effect on sustainable development. Renewable and Sustainable Energy Reviews: 16, 1335–1339.

Berkovski, B. 1995. Geothermal energy. West Sussex, England: Wiley and Sons Ltd.

Bonham-Carter, G. F. 1985. Statistical association of gold occurrences with LANDSAT derived lineaments, Timmins-Kirkland Lake area, Ontario. Canadian Journal of Remote Sensing : 11, 195–210.

Bonham-Carter, G. F., Agterberg, F. P., Wright, D. F. 1988. Integration of geological data sets for gold exploration in Nova Scotia. Photogrammetric Engineering and Remote Sensin: 54, 1585–1592.

Bonham-Carter, G. F. 1991. Integration of geoscientific data using GIS. Geographical information systems: principles and applications. Essex, UK: Longman: 171–184.

Bonham-Carter, G. F. 1994. Geographical information systems for geoscientists: modeling with GIS. New York: Pergamon. Digital Geologic and Geographic Information Systems; 54: 1585–92.

Calvin, W. M., Coolbaugh, M., Kratt, C., Vaughan, R. G., Calvin, W. 2005. Application of remote sensing technology to geothermal exploration. Nevada, US: Geological Survey of Nevada; 1083–1089.

Camp, V. E., Griffis, R. J. 1982. Character, genesis and tectonic setting of igneous rocks in the Sistan suture zone, eastern Iran. Lithos: 15, 221–239.

Carranza, E. J. M. 2002. Geologically-Constrained Mineral Potential Mapping (examples from the Philippines). The Netherlands, ITC (International Institute for Geo-Information Science and Earth Observation): Delft University of Technology. Natural Resources Research, 9(3). 253-271.

Carranza, E. J. M. 2008. Geochemical anomaly and mineral prospectivity mapping in GIS, handbook of exploration and environmental geochemistry. Amsterdam: Elsevier, pp270.

Carranza, E. J. M. 2009a. Controls on mineral deposit occurrence inferred from analysis of their spatial pattern and spatial association with geological features. Ore Geology Reviews: 35, 383–400.

Carranza, E. J. M. 2009b. Geochemical anomaly and mineral prospectivity mapping in GIS. Oxford, UK: Elsevier Science, pp310.

Carranza, E. J. M., Hale, M. 2001. Geologically constrained fuzzy mapping of gold mineralization potential, Baguio district, Philippines. Natural Resources Research; 10, 125–136.

Carranza, E. J. M., Hale, M. 2002. Whereare porphyry copper deposits spatially localized? A case study in Benguet Province, Philippines. Natural Resources Research: 11, 45–59.

Carranza, E. J. M., Mangaoang, J. C., Hale, M. 1999. Application of mineral exploration models and GIS to generate mineral potential maps as input for optimum land-use planning in the Philippines. Natural Resources Research: 8, 165–173.

Carranza, E. J. M., Wibowo, H., Barritt, S. D., Sumintadireja, P. 2008. Spatial data analysis and integration for regional-scale geothermal potential mapping, West Java, Indonesia. Geothermics: 37, 267–299.

Chi, K. H., Park, N. W., Chung, C. H. J. 2001. Fuzzy logic integration for landslide hazard mapping using spatial data from Boeun, korea. In: Proceedings of symposium on geospatial theory, Ottawa. p. 87–95.

Chung, C. F., Jefferson, C. W., Singer, D. A. 1992. A quantitative link among mineral deposit modeling, geoscience mapping, and exploration resource assessment. Economic Geology: 87, 194–197.

Clarke, K. C. 1999. Getting started with geographic information systems. 2nd ed. Upper Saddle River, NJ, USA: Prentice Hall, pp352.

Conrad, G., Montigny, R., Thuizat, R., Westphal, M. 1981. Tertiary and Quaternary geodynamics of southern Lut (Iran) as deduced from palaeomagnetic, isotopic and structural data. Tectonophysics: 75, 11–17.

Coolbaugh, M., Sawatzky, D., Oppliger, G., Minor, T., Raines, G., Shevenell, L., Blewitt, G., Louie, J. N. 2003. Geothermal GIS coverage of the Great Basin, USA: defining regional controls and favorable exploration terrains. Transactions- Geothermal Resources Council. p. 9–14.

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., Boyd, T. 2005b. Geothermal potential map of the Great Basin. Western United States: Nevada Bureau of Mines and Geology Map; 151.

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

Coolbaugh, M. F., Zehner, R. E., Raines, G. L., Oppliger, G. L., 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). GIS and spatial analysis: international association of mathematical geology annual conference proceedings. Toronto, Canada. p. 505–510.

Demicco, R., Klir, G. 2004. Fuzzy logic in geology. Amsterdam: Elsevier, pp347.

D'Ercole, C., Groves, D. I., Knox-Robinson, C. M. 2000. Using fuzzy logic in a Geographic Information System environment to enhance conceptually based prospectively analysis of Mississippi Valley-type mineralisation. Australian Journal of Earth Sciences. 47, 913–927.

Dimitrijevic, M. D., Dimitrijevic, M. N., Vulovic, D. 1971. 1:100,000 geological map of Iran. Ministry of Mines and Metals. Tehran, Iran: Geological Survey of Iran.

Eddy, B. G., Bonham-Carter, G. F., Jefferson, C. W. 2006. Mineral potential analyzed and mapped at multiple scales--a modified fuzzy logic method using digital geology. GIS for the Earth Sciences: 44, 143–162.

Entingh, D. J. 2000. Enhanced Geothermal Systems (EGS) R and D Program. Princeton Energy Resources International, Rockville, MD, pp475.

Fakhari, M. D., Axen, G. J., Horton, B. K., Hassanzadeh, J., Amini, A. 2008. Revised age of proximal deposits in the Zagros foreland basin and implications for Cenozoic evolution of the High Zagros. Tectonophysics: 451, 170–185.

Futuhi, M. 1994a. An analysis of the reports, the geothermal potential and feasibility studies in Sabalan. Renewable and Sustainable Energy Reviews: 15, 3946–3951.

Futuhi, M. 1994b. Geothermal energy explorations in Azarbaijan and Damavand and feasibility studies on the use of geothermal power plants in Iran. Tehran, Iran: Niroo Research Centre, pp. 225.

Gaines, B. R. 1976. Foundations of fuzzy reasoning. International Journal of Man-Machine Studies: 8, 623–668.

Ghazi, A. M., Hassanipak, A. A., Mahoney, J. J., Duncan, R. A. 2004. Geochemical characteristics, 40Ar–39Ar ages and original tectonic setting of the Band-e-Zeyarat/Dar Anar ophiolite, Makran accretionary prism, S.E. Iran. Tectonophysics: 393, 175–196.

Ghobadian, B., Najafi, G., Rahimi, H., Yusaf, T. F. 2009. Future of renewable energies in Iran. Renewable and Sustainable Energy Reviews: 13, 689–695.

Giggenbach, W. 1997. The origin and evolution of fluids in magmatic-hudrothermal systems. In: Barnes HL, editor. Geochemistry of hydrothermal ore deposits. 3rd ed. New York: Jone Wiley and Sons, Inc. p. 737–796.

Goldstein, N. E. 1988. Subregional and detailed exploration for geothermal- hydrothermal resources. Geothermal science and technology: 1, 303–431.

Hanano, M. 2000. Two different roles of fractures in geothermal development. World geothermal congress, Kyushu-Tohoku, Japan. p. 2597–2602.

Harris, J. R., Sanborn-Barrie, M. 2006. Mineral potential mapping: examples from the Red Lake Greenstone Belt, Northwest Ontario. GIS for the Earth Sciences: 44, 1–21.

Hatzfeld, D., Molnar, P. 2010. Comparisons of the kinematics and deep structures of the Zagros and Himalaya and of the Iranian and Tibetan plateaus and geodynamic implications. Reviews of Geophysics 48, RG2005. doi:10.1029/2009RG000304.

Healy, J. 1970. Pre-investigation geological appraisal of geothermal fields. Geothermics: 2, 571–577 special issue.

Hosseini, S. E., Mahmoudzadeh Andwari, A., Abdul Wahid, M., Bagheri, G. 2013. A review on green energy potentials in Iran. Renewable and Sustainable Energy Reviews: 27, 533–545.

Huenges, E. 2010. Geothermal energy systems. Federal Republic of Germany: Wiley-VCH pp445.

Iran Renewable Energy Organization (SUNA), http://www.suna.org.ir/homeen.

Jahangiri, A. 2007. Post-collisional Miocene adakitic volcanism in NW Iran: geochemical and geodynamic implications. Journal of Asian Earth Sciences: 30, 433–447.

James, R., McNitt, A. 1974. Report geothermal resources in Iran, Entes Nazionale per LEnergia Elettrica. p 987–1117.

Jennejohn, D. 2009. Research and development in geothermal exploration and drilling. Washington, US: Geothermal Energy Association; 1–25.

Karimpour, M. H., Stern, C. R., Farmer, L., Saadat, S., Malekezadeh, A. 2011. Review of age, Rb–Sr geochemistry and petrogenesis of Jurassic to Quaternary igneous rocks in Lut Block, Eastern Iran. Geopersia: 1, 19–36.

Katz, S. S. 1991. Emulating the prospector expert system with a raster GIS. Computers and Geosciences: 17, 1033–1050.

Kiavarz Moghaddam, M., Samadzadegan, F., Noorollahi, Y., AliSharifi, M., Itoi, R. 2014. Spatial analysis and multi-criteria decision making for regional-scale geothermal favorability map. Geothermics: 50, 189–201.

Knox-Robinson, C. M. 2000. Vectorial fuzzy logic: a novel technique for enhanced mineral prospectivity mapping with reference to the orogenic gold mineralisation potential of the Kalgoorlie Terrane, Western Australia. Australian Journal of Earth Sciences: 47, 929–942.

Lisitsin, V., Rawling, T. 2011. Regional prospectivity analysis of orogenic gold mineral systems in central Victoria, Australia. In: Proceedings of SGA conference, Antofagasta, Chile.

Malczewski, J. 2006. Ordered weighted averaging with fuzzy quantifiers: GIS-based multicriteria evaluation for land-use suitability analysis. International Journal of Applied Earth Observation and Geoinformation: 8, 270–277.

Marques, J. M., Matias, M. J., Bastoa, M. J., Carreira, P. M. 2010. Hydrothermal alteration of Hercynian granites, its significance to the evolution of geothermal systems in granitic rocks. Geothermics: 39, 152–160.

McQuarrie, N., Stock, J.M., Verdel, C., Wernicke, B. P. 2003. Cenozoic evolution of Neotethys and implications for the causes of plate motions. Geophysical Research Letters: 30, 2036. doi:10.1029/2003GL017992.

Najafi, G., Ghobadian, B. 2011. Geothermal resources in Iran: the sustainable future. Renewable and Sustainable Energy Reviews: 15, 3946–3951.

National Geoscience Database of Iran, Tehran, Iran http://www.ngdir.ir/GeoportalInfo.

Noorollahi, Y., Itoi, R. 2011. Production capacity estimation by reservoir numerical simulation of northwest (NW) Sabalan geothermal field, Iran. Energy: 36, 4552–4569.

Noorollahi, Y., Itoi, R., Fujii, H., Tanaka, T. 2007. Geothermal resources exploration and wellsite selection with environmental consideration using GIS in Sabalan geothermal area, Iran. In: 32nd workshop on geothermal reservoir engineering, Stanford University. SGP-TR–183.

Noorollahi, Y., Itoi, R., Fujii, H., Tanaka, T. 2008. GIS integration model for geothermal exploration and well siting. Geothermics: 37, 107–131.

Noorollahi, Y., Yousefi, H., Itoi, R., Ehara, S. 2009. Geothermal energy resources and development in Iran. Renewable and Sustainable Energy Reviews: 13, 1127–1132.

Nykanen, V., Groves, D. I., Ojala, V. J., Eilu, P., Gardoll, S. J. 2008a. Reconnaissance scale conceptual fuzzy-logic prospectivity modelling for iron oxide copper-gold deposits in the northern Fennoscandian Shield, Finland. Australian Journal of Earth Sciences: 55, 25–38.

Nykanen, V., Groves, D. I., Ojala, V. J., Eilu, P., Gardoll, S. J. 2008b. Combined conceptual/ empirical prospectivity mapping for orogenic gold in the northern Fennoscandia Shield, Finland. Australian Journal of Earth Sciences: 55, 39–59.

Omrani, J., Agard, P., Whitechurch, H., Benoit, M., Prouteau, G., Jolivet, L. 2008. Arcmagmatism and subduction history beneath the Zagros Mountains, Iran: a new report of adakites and geodynamic consequences. Lithos: 106, 380–398.

Oskarsson, N. 1995. Volcanic components in groundwater: monitoring and interpretation. In: Barberi F, Casale R, Fantechi R, editors. The mitigation of volcanic hazards course proceedings. European Commission, Brussels. p. 393–401.

Pang, K. N., Chung, S. L., Zarrinkoub, M. H., Chu, C. H., Lin, I. J., Lee, H. Y. 2011. Qal'eh Hasan Ali maars, southeastern Iran: a rare example of Tethyan kamafugitic rocks. Abstract to the 8th Annual Meeting, Asia Oceania Geosciences Society. Aug 8–12, Taipei.

Phillips, J. 2010. Evaluating the level and nature of sustainable development for a geothermal power plant. Renewable and Sustainable Energy Reviews: 14, 2414–2425.

Ponce-Cruz, P., Ramirez-Figueroa, F.D. 2010. Intelligent control systems with Lab-VIEWTM. London, UK: Springer; 9–46.

Porkhial, S., Kahrobaeian, A. 2004. Status of geothermal energy in Iran. In: Proceedings of the 19th world energy congress.

Porwal, A., Carranza, E. J. M., Hale, M. 2003. Knowledge-driven and data-driven fuzzy models for predictive mineral potential mapping. Natural Resources Research: 12, 1–25.

Porwal, A., Sides, E. J. 2000. A predictive model for base metal exploration in a GIS environment. International Archives of Photogrammetry and Remote Sensing: 33, 1178-1184.

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

Ramezani, J., Tucker, R. D. 2003. The Saghand region, central Iran: U–Pb geochronology, petrogenesis and implications for Gondwana tectonics. American Journal of Science: 303, 622–665.

Ranjbar, H., Honarmand, M. 2004. Integration and analysis of airborne geophysical and ETM data for exploration of porphyry type deposits in the Central Iranian Volcanic Belt using fuzzy classification. International Journal of Remote Sensing: 25, 4729–4741.

Rogge, D. M., Halden, N. M., Beaumont-Smith, C. 2006. Application of data integration for shearhosted Au potential modelling: Lynn Lake Greenstone Belt, North western Manitoba, Canada. GIS for the Earth Sciences: 44, 191–210.

Roisenberg, M., Schoeninger, C., Da Silva, R. R. 2009. A hybrid fuzzy-probabilistic system for risk analysis in petroleum exploration prospects. Expert Systems with Applications: 36, 6282–6294.

Rojas, R., 1996. Neural networks. Berlin: Springer-Verlag; pp 289–310.

Saccani, E., Delavari, M., Beccaluva, L., Amini, S. 2010. Petrological and geochemical constraints on the origin of the Nehbandan ophiolitic complex (eastern Iran): Implication for the evolution of the Sistan Ocean. Lithos: 117, 209–228.

Saffarzadeh, A., Noorollahi, Y. 2005. Geothermal development in Iran: a country update. In: Proceedings of world geothermal congress. Antalya, Turkey, 24-29 April 2005. 1-7.

Şengör, A. M. C., Altlner, D., Cin, A., Ustaomer, T., Hsu, K. J. 1988. Origin and assembly of the Tethyside Orogenic Collage at the expense of Gondwana Land. In: Audley- Charles, M. G., Hallam, A. E. (Eds.), Gondwana and Tethys. Geological Society of London Special Publication, Blackwell, Oxford, pp. 119–181.

Şengör, A. M. C., Natal'in, B. A. 1996. Paleotectonics of Asia: fragments of a synthesis. In: Yin, A., Harrison, M. (Eds.), The Tectonic Evolution of Asia. Cambridge University Press, Cambridge, pp. 486–640.

Shabeik, A. 1993. Mineral and thermal waters (spring) of Iran. Tehran, Iran: Geological Survey of Iran. pp134-157.

Shafiei, B., Haschke, M., Shahabpour, J. 2009. Recycling of orogenic arc crust triggers porphyry Cu mineralization in Kerman Cenozoic arc rocks, southeastern Iran. Mineralium Deposita: 44, 265–283.

Shakeri, A., Moore, F., Kompani-Zare, M. 2008. Geochemistry of the thermal springs of Mount Taftan, southeastern Iran. Journal of Volcanology and Geothermal Research: 178, 829–836.

Stöcklin, J. 1968. Structural history and tectonics of Iran: a review. American Association of Petroleum Geologists Bulletin: 52, 1229–1258.

Tangestani, M. H., Moore, F. 2003. Mapping porphyry copper potential with a fuzzy model, northern Shahr-e-Babak, Iran. Australian Journal of Earth Sciences: 50, 311–317.

Thiart, C., De Wit, M. 2000. Linking spatial statistics to GIS: exploring potential gold and tin models of Africa. South African Journal of Geology: 103, 215–230.

Tirrul, R., Bell, I. R., Griffis, R. J., Camp, V. E. 1983. The Sistan suture zone of eastern Iran. Geological Society of America Bulletin: 94, 134–150.

Takin, M., 1972. Iranian geology and continental drift in the Middle East. Nature: 235, 147–150.

Valentino, G. M., Cortecci, G., Franco, E., Stanzione, D. 1999. Chemical and isotopic compositions of minerals and waters from the Campi Flegrei volcanic system, Naples, Italy. Journal of Volcanology and Geothermal Research: 91, 329–344.

Valentino, G. M., Stanzione, D. 2004. Geochemical monitoring of the thermal waters of the Phlegraean Fields. Journal of Volcanology and Geothermal Research: 133, 261–189.

Varekamp, J. C., Ouinette, A., Herman, S., Bermudez, A., Delpino, D. 2001. Hydrothermal elemental fluxes during the 2000 eruptions of Copahue, Argentina. A beehive volcano in turmoil. Geology: 29, 1059–1062.

Vearncombe, J., Vearncombe, S. 1999. The spatial distribution of mineralization; applications of Fry analysis. Economic Geology: 94, 475–486.

Venkataraman, G., Babu Madhavan, B., Ratha, D. S., Antony, J. P., Goyal, R. S., Banglani, S. 2000. Spatial modeling for base-metal mineral exploration through integration of geological data sets. Natural Resources Research: 9, 27–42.

Verdel, C., Wernicke, B. P., Ramezani, J., Hassanzadeh, J., Renne, P. R., Spell, T. L. 2007. Geology and thermochronology of Tertiary Cordilleran-style metamorphic core complexes in the Saghand region of central Iran. Geological Society of America Bulletin: 119, 961–977.

Wohletz, K., Heiken, G. 1992. Volcanology and geothermal energy. Berkeley: Univ California Press. pp 400.

Wright, P. M., Nielson, D. L., Ross, H. P., Moore, J. N., Adams, M. C., Ward, S. H. 1989. Regional exploration for convective hydrothermal resources. Geothermal Science Technologies: 2, 69–124.

Yousefi, H., Ehara, S. 2007. Geothermal power plant site selection using GIS in Sabalan area, NW Iran. In: Proceedings of Map Asia 2007, 6th annual international conference on geographical information technology and applications, KLCC. Paper number: 194.

Yousefi, H., Ehara, S., Noorollahi, Y. 2007. Geothermal potential site selection using GIS in Iran. In: Proceedings of the 32nd workshop on geothermal reservoir engineering, Stanford University. SGP-TR-183.

Yousefi, H., Noorollahi, Y., Ehara, S., Itoi, R., Yousefi, A., Fujimitsu, Y. 2010. Developing the geothermal resources map of Iran. Geothermics: 39, 140–151.

Yousefi, M., Kamkar Rouhani, A. 2010. Principle of mineral potential modeling techniques (in geographical information system). Tehran, Iran: Amirkabir University of Technology Press. Pp 356.

Yousefi, M., Kamkar-Rouhani, A., Carranza, E. J. M. 2012. Geochemical mineralization probability index (GMPI): a new approach to generate enhanced stream sediment geochemical evidential map for increasing probability of success in mineral potential mapping. Journal of Geochemical Exploration: 115, 24–35.

Yousefifar, S., Khakzad, A., Asadi Harooni, H., Jafari, M. R., Vosoughi Abedini, M. 2012. Using Index Overlay, Fuzzy Logic method and analytical hierarchy process in order to determine Au and Cu potential targets in north part of Dali porphyry deposit. Geosciences: 21, 49–58.

Yousefi-Sahzabi, A., Sasaki, K., Yousefi, H., Pirasteh, S., Sugai, Y. 2011. GIS aided prediction of CO_2 emission dispersion from geothermal electricity production. Journal of Cleaner Production: 19, 1982–1993.

Zadeh, L. A. 1965. Fuzzy sets. Information and Control. 8(3). 338-358.

Zadeh, L. A. 1996. Fuzzy Sets, Fuzzy Logic, Fuzzy Systems, World Scientific Press, ISBN 981-02-2421-4

Zadeh, L. A. 1999. From computing with numbers to computing with words—from manipulation of measurements to manipulation of perceptions. IEEE Circuits and Systems Society: 45, 105–119.

Zadeh, L. A. 2003. From search engines to question-answering systems. The need for new tools. In: Proceedings of the IEEE international conference on fuzzy systems. pp 1107-1109.

Zarrinkoub, M. H., Chung, S. L., Chiu, H. Y., Mohammadi, S., Khatib, M., Lin, I. J. 2010. Zircon U–Pb age and geochemical constraints from the northern Sistan suture zone on the Neotethyan magmatic and tectonic evolution in eastern Iran. Abstract to GSA Conference on “Tectonic Crossroads: Evolving Orogens in Eurasia–Africa–Arabia”, Oct. 4–8, 2010, p. 520. Ankara, Turkey.

Ziaii, M., Abedi, A., Ziaei, M., Rouhani, A. K., Zendahdel, A. 2010. GIS modelling for Au-Pb-Zn potential mapping in Torud-Chah Shirin area-Iran. International Journal Mining Environnent Issues: 1, 17–27.