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Estimation of Earth Surface Heat Flow by Geological Ages and Settings for Geothermal Energy Exploration in Afghanistan

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Abstract

The purpose of this research is to estimate the earth's surface heat flow on the basis of geological ages and globally observed continental mean heat flow values for geothermal energy exploration in Afghanistan. Empirical estimation and curve fitting in MS. Excel isapplied to determine the heat flow estimation equations as a function of time. First, thesingle criterion of tectonic thermal event's end time and mean heat flow value are examined, and the result is analyzed with neighboring countries' heat flow data and geothermal prospect regions in the country. Then the GIS Geographical Information System is used to distinguish the prospect high and low heat flow regions in the same geological age areas such as hot springs, hydrothermal mineral waters, faults, intrusive rocks, geopressured, and petroleum. The result has been mapped in ArcMap. The predicted mean heat flow values are in the range of 34.6 to 108.8mW/m^2. The highest heat flow value is estimated in intrusive bodies of the young Quaternary period.

Keywords : Mean Heat Flow; Geological Age; Afghanistan Geothermal Energy; GIS

Introduction

Geothermal energy has been used only for medical bathing in Afghanistan. There isevidence for the existence of abundant geothermal resources such as hot springs, hydrothermal mineral resources, volcanic rocks and domes, intrusive or igneous rocks, petroleum, and geopressured areas. Theses geothermal resources need further geological, geophysical, and geochemical investigation for electrical power potential determination and reservoir characterization [1].

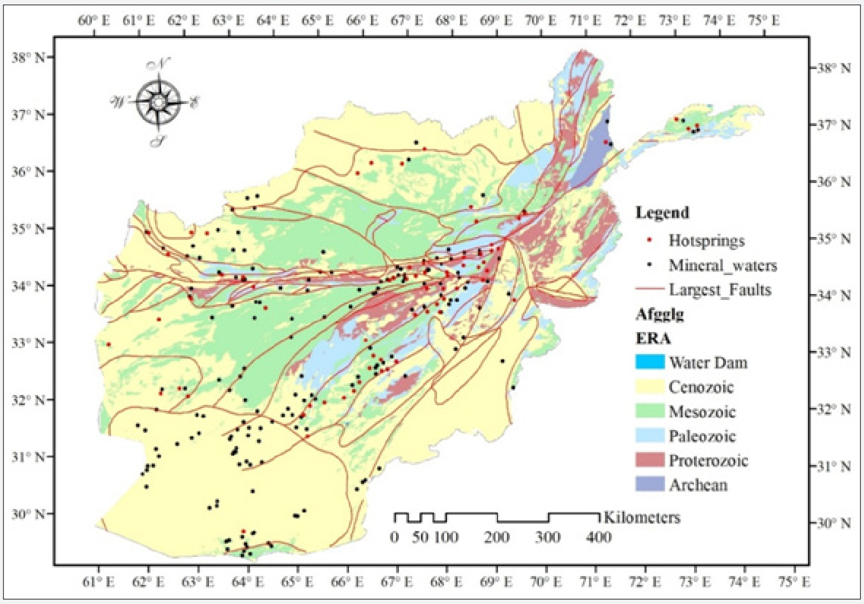

Figure 1: Afghanistan geological ages, largest faults, and hydrothermal manifestations.

Regarding geothermal reconnaissance in the country; the Curie point (580ºC temperature) depth is estimated from 13 to 40km by spectral analysis of aeromagnetic data. Also, it is determined that the geothermal gradient is from 14 to 36ºC/km and heat flow value is in the range of 36 to 90mW/m^2 from the CPD in the west of Afghanistan considering constant thermal conductivity (2.5W/m ºC) [2]. We had applied the GIS techniques, geological, geophysical, and geochemical evidence layers to map the best prospect areas of geothermal energy for further exploration [3]. The geothermal energy exploitation in Afghanistan needs further investigation. Such as: determining of geothermal resources potential, earth's crust temperature and pressure at depth, and most prospect areas for well siting. Understanding of surface heat flow is the main factor for earth crust temperature and potential calculation [4]. Unfortunately, the surface heat flow measurement is not available so far. Alternatively, it is possible to estimate the mean heat flow value from the tectonic ages, tectonic activity, geostructure, and hot spring data. Figure 1 show the thermo tectonic events era of the land surface, largest faults, hot springs, and hydrothermal mineral waters locations in Afghanistan.

The earth'scontinental crust average heat flow is around 55±5 [mW/m^2] [5]. There is a correlation between globalobserved continental heat flow and tectonic ages. The surface heat flow of the earth's crust decrease with age increasing. As the surface heat flux is the summation of heat flow from the interior, residual heat from a transient thermal perturbation combined with Tectogenesis, and radiogenic heat generation in the crust. The heat flux due to last two components decline with age [6]. Many researchers used single criterion of tectonic age to estimate the heat flow in the region with no measurement on the basis ofobserved data of other areas. First, we also followed the global continental observation data [7], Asia data [4], and Eurasia [8] mean heat flow values in empirical estimator and the result was mapped for each predictor separately. The result of each heat flow map is compared with the neighboring countries' adjacent areas heat flow data. Also, the estimated heat flow (on the base of single criterion of age) is analyzed in the geothermal prospect areas and non-prospect areas. The single criterion of tectonic age estimated the highest heat flow in all quaternary sediments of the country, where there is no geothermal evidence. Viceversa the low surface heat flow are estimated in the region of high prospect geothermal resources, such as hot springs and intrusive rocks. In addition, there are differences in mean heat flow values of each reference according to geological structures within same geological age. Finally, we have used the GIS model for heat flow mapping to consider the geological, geophysical and geochemical evidences of geothermal resources. Also the GIS has distinguished the prospected high and low heat flow regions in the same geological age. The next section explains in detail the methodology, calculation, and mapping process, the third section presents the resulting map and estimated mean heat flow value.

Material and Methodology

The mean heat flow map is estimated on the basis of geological age, geophysical, and geochemical evidence of geothermal layer maps in GIS. Figure 2 shows the calculation process. First the single criterion of last tectonic age is applied to calculate mean heat flow according to the global heat flow data; the global mean heat flow values of three sources with geological age are examined in empirical predictors 1, 2, and 3 to estimate the corresponding heat flow maps 1, 2, and 3 respectively. The estimated heat flow maps 1, 2, and 3 are compared and analyzed in geothermal prospect and non-prospect areas. Then the geothermal resource evidence layers are studied in GIS model to determine the heat flow map considering more criteria such as hot springs, hydrothermal mineral water, petroleum and geo pressured areas, faults, and intrusive rocks. Both steps are explained in detail as follows (Figure 2):

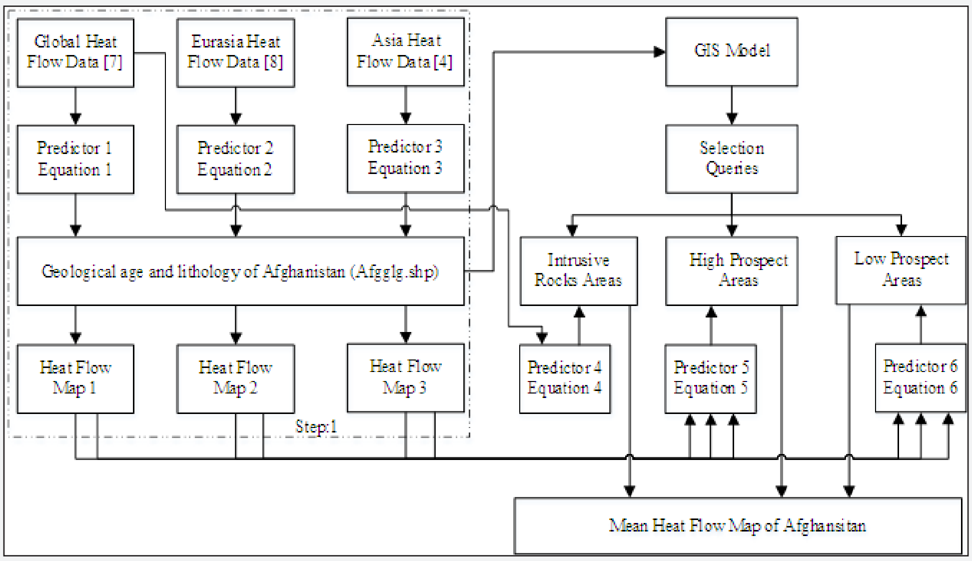

Figure 2 : Heat flow calculation model.

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a) **Step 1:** The shape file of geological age and lithology of Afghanistan is considered to apply the empirical estimators 1 to 3 for heat flow calculation. The shape file has attribute table which contains; the thermo tectonic events begin and end times absolute age in millions of years of rocks deposition and emplacement, name of geologic period, geologic time and lithology symbol, lithology and its narrative, generalized geologic age, generalized geologic age and lithology symbol, and index number for lithology and generalized geologic age to draw the geologic layer in ArcMap. For instance, the index number 4010 and from 5011 to 5060 is the different types of intrusive or igneous rocks considering the age and lithology of the rocks. This kind of data management facilitates the selection of rocks according to the age, lithology and geophysical structure for criteria application.

According to the assumption that same geological age regions could have the similar mean heat flow value. Table 1 shows the mean heat flow values for empirical estimators used in this estimation. The each thermo tectonicevolution era of the lithosphere has mean heat flow value. The average age of each era and mean heat flow values are considered to plot the curve in M S Excel, then the curve fitting or trend line is used to determine the equations for heat flow calculation. The best functions are polynomial with root mean square (R^2) value 0.64, 0.99, and 0.70 for predictor 1, 2, and 3 respectively. In order to map the heat flow by equation 1, 2, and 3, the new fields of heat flow 1, 2, and 3 are added to the attribute table of Afghanistan's geologic age and lithology layer in Arc Map. The field calculator tool of GIS estimated the mean heat flow value as a function of last thermo tectonicevent time (Time End) by applying the following equations 1, 2, and 3.

$$Q_1(t) = 3*10^{-6}t^2 - 0.0159t + 71.776 \quad (1)$$

$$Q_2(t) = 9*10^{-6}t^2 - 0.0356t + 77.011 \quad (2)$$

$$Q_3(t) = 4*10^{-6}t^2 - 0.0222t + 65.126 \quad (3)$$

Table 1: Mean heat flow values for empirical estimators 1, 2, and 3.

Erathem / Era	Begin Time [10^6 years]	End Time [10^6 years]	Global Observation [7]		Europe and Asia [8]		Asia [4]
			Heat Flow [mW/m^2]	Standard Deviation	Heat Flow [mW/m^2]	Standard Deviation	Heat Flow [mW/m^2]
Cenozoic	0	65	63.9	27.5	76	52	63
Cenozoic igneous	0	65	97	66.9	76	52	
Mesozoic	65	251	63.7	28.2	76	52	Orogeny 73
Mesozoic igneous	65	251	64.2	28.8	76	52	
Paleozoic	251	542	61	30.2	63	18	Carboniferous 56
Paleozoic igneous	251	542	57.7	20.5	63	18	Non-orogenic 45
Proterozoic	542	2500	58.3	23.6	45	7	45
Archean	2500	4000	51.5	25.6	44	13	36
Total average			64.66		64.88		53

Where Q is the mean heat flow value, and t is the end time of geological age. The result was mapped in ArcGIS. Figure 3 shows the estimated heat flow map 1 by Equation 1, Figure 4 shows the estimated heat flow map 2 by Equation 2, and Figure 5 shows the estimated heat flow map 3 by Equation 3 associated with neighboring heat flow values respectively. Also, Figure 6 shows the comparison of the estimated mean heat flow maps 1, 2, and 3. Each geological time (from Holocene to Paleoarchean) in Afghanistan has minimum and maximum values for heat flow estimation.

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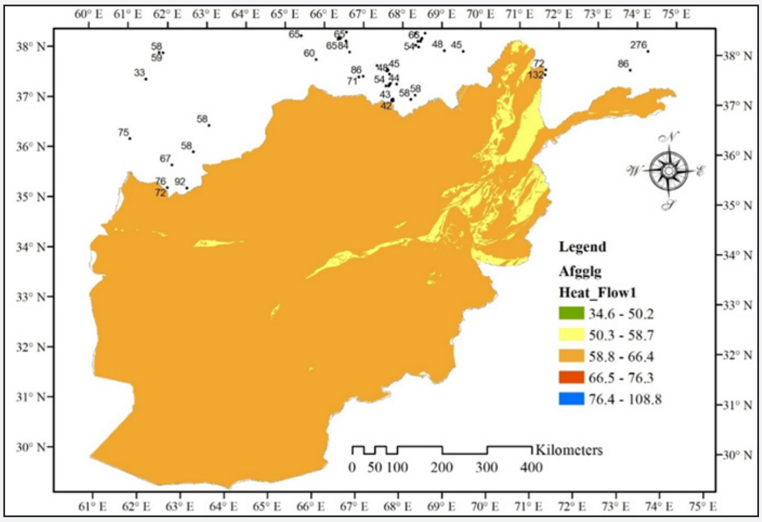

Figure 3 : Estimated heat flow map 1 by predictor 1.

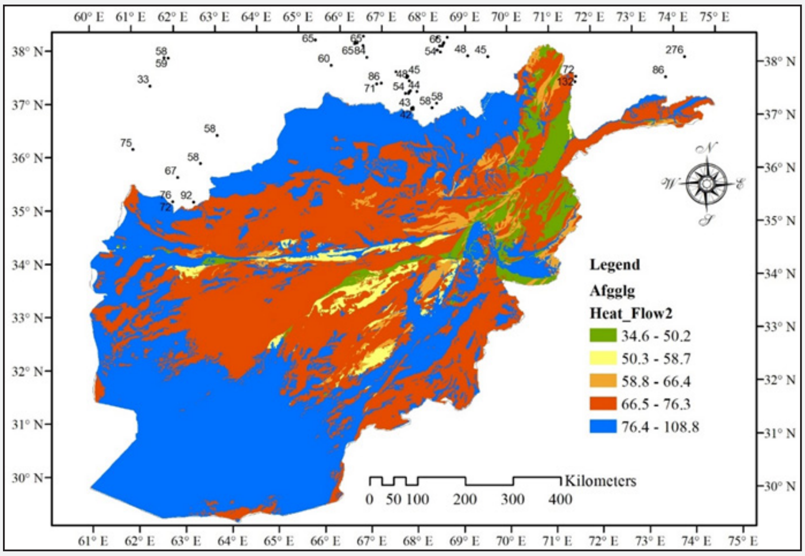

Figure 4 : Estimated heat flow map 2 by predictor 2.

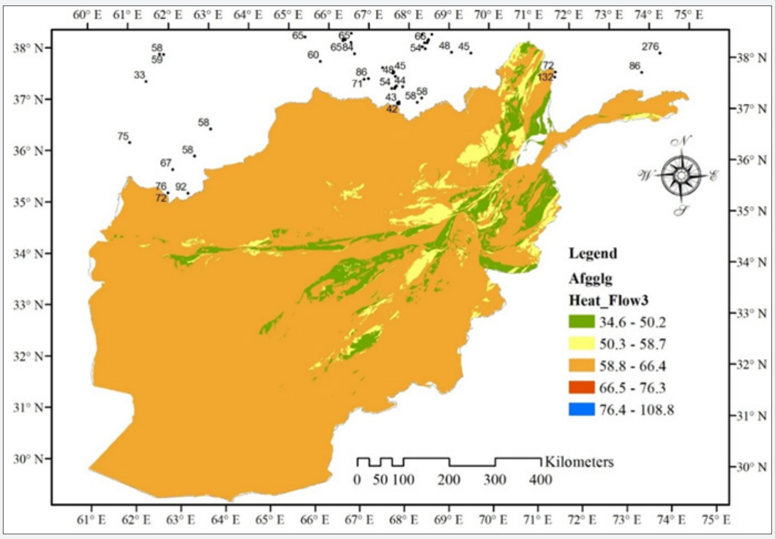

Figure 5 : Estimated heat flow map 3 by predictor 3.

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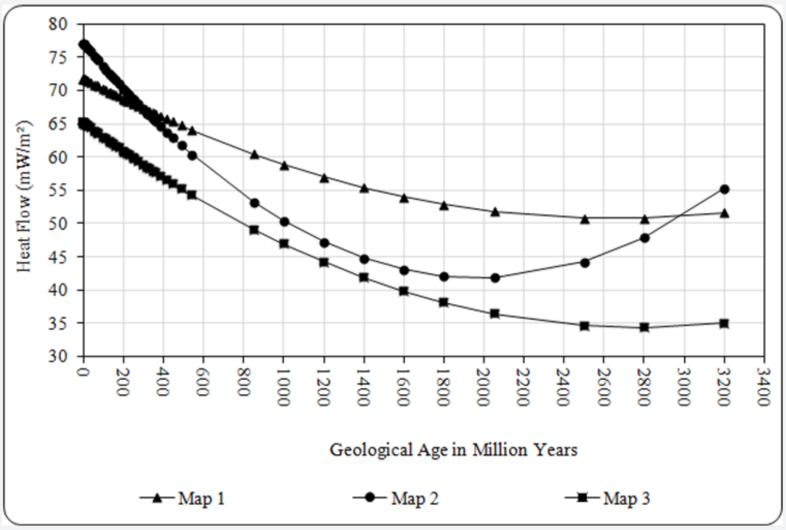

Figure 6 : Comparison of mean heat flow values for map 1, 2, and 3.

The comparison of estimated heat flow maps data, between each other, and with the neighbouring countries' adjacent areas heat flow data reveal that; the different values had been estimated at northern border area for example; from 50 to 66mW/m^2 in map 1, from 34 to 108 mW/m^2 in map 2, and from 34 to 66 mW/m^2 in map3. The observed heat flow in Tajikistan are 276, 86, 132, and 72 mW/m^2, in Uzbekistan are in the range of 42 to 71mW/m^2, and in Turkmenistan are from 58 to 92 mW/m^2. The highest heat flow in neighbouring countries could be seen around hot spring, largest faults, intrusive rocks, and petroleum regions such as; 132 and 72mW/m^2 around the largest faults, and 276, and 86 mW/m^2 around Hot springs and intrusive rocks region in Tajikistan. The 72, 76, and 92 mW/m^2 are located in the petroleum prospect areas of Turkmenistan. In addition, the estimated heat flow by predictor 1 to 3 are analysed in the geothermal prospect areas and non-prospect areas in the country. The single criterion of age assigned the highest heat flow value for all quaternary, mostly for Holocene regions, also in the regions, where no geothermal manifestations exist. Vice versa the low heat flow had been estimated in the region of high prospect geothermal resources, such as hot springs. Intrusive rocks, fault system, geopressured, and petroleum prospect areas. Moreover, there are differences in mean heat flow values of each reference [4,7,8] according to geological structures within same geological age. For example the mean heat flow value for intrusive rocks in the Cenozoic era is 97mW/m^2 [7]. Also in Mesozoic era displaced region the global observed mean heat flow value is 63.7 while the observed mean heat flow in Orogeny region is 73mW/m^2. As a result of the analysis and comparison of calculated heat flow by predictors 1, 2, and 3 and neighbouring countries heat flow data. That there is a relationship between minimum and the maximum value of heat flow in the same geological age considering the geological structure, and geothermal prospect areas such as hot spring, hydrothermal mineral waters, faults system, petroleum, and intrusive rocks.

b) Step2: to map the mean heat flow value in the country, considering the higher and lower heat flow values in the same geological age. The objective has been divided in three categories; intrusive or igneous rocks, higher heat flow prospect area, and lower heat flow prospect region. The GIS model and multi criteria decision analysis system are designed to distinguish the intrusive bodies, high and low prospect areas for heat flow estimation. The higher heat flow area, GIS model, and the input layers of the model are illustrated in detail in the following sections.

High Heat Flow Prospect Areas

The geothermal manifestation on land surface such as hot springs, hydrothermal minerals, petroleum, geopressured, volcanic, and fault system regions could be the higher heat flow areas. For distinguishing of higher heat flow prospect regions the geothermal prospect areas have been mapped as follows.

Hot Springs and Mineral Waters

The surface manifestations of hydrothermal resources in the country are hot springs and hydrothermal mineral waters. The hot springs shape file was obtained from the NREL data for Afghanistan (from geospatial toolkit) [9]. The geochemical condition of these hot springs are the CO_2, Nitrogen, and Hydrogen sulphide (H_2S) bearing hot water originating from metamorphic, reducing, and oxidizing environments respectively. The highest recorded temperatures are 52°C in Obe of Herat, 55°C in Sarab of Baghlan and Chah Ganj of Balkh provinces [10]. The hydrothermal mineral water data are received from the Kabul PolytechnicUniversity, geological exploration, and extraction of minerals department. The geochemical condition of these water springs and well resources also contain CO2, Nitrogen, Hydrogen sulphide, and silicon. The data of 187 springs and water well resource are mapped in ArcMap GIS. The measured water temperature is between 9 to 70ºC. The high heat flow value is possible around the hot springs such as the 97% of geothermal

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wells in Akita and Iwate of Japan are located within 4000m of hot springs. Therefore, the 4000m buffer zone around hot springs and mineral waters considered for high heat flow prospect area detection.

Fault Systems

Faults have significant contribution in investigation of geothermal resources and region in the vicinity of fault system may have higher surface heat flow. Major faults in the country provide the infiltration of water into the superheated zones of the crust to produce the geothermal reservoirs. For instance, the largest east-west strike-slip fault has up to 700km depth into the mantle [1]. As a result, the regions in the vicinity of faults system are the most promising location to have the high surface heat flow. The three kinds of fault shapefiles and database available so far have been considered: First, the largest faults in the country. Second, the active young (Quaternary) faults, mapped from remote-sensing imagery data, and the faults' slip rates which were determined in major (more than 10mm per year), minor (1 to 10mm per year), and immeasurable categories [11]. The third fault system data is the secondary faults. They almost cover the entire country and contains the normal faults (such as proven, buried and inferred) with thrust faults (including inferred and proven). To consider high heat flow prospect areas around the fault system; the buffer zone is taken into account for each fault system. Because the geothermal wells are located around fault system. For example, the geothermal wells distance from the faults in Akita and Iwate of Japan reveals that 95% geothermal wells are located around 6000m of faults system. Therefore, the 5000m buffer zone for largest faults, 5000m buffer zone for active young faults shape file (Faults), and 1000m buffer zone for secondary faults system (afg_faults) are considered to identify the higher heat flow prospect areas.

Geopressured and Petroleum Prospect Areas

Geopressured thermal regions have high temperature (296°C) and high pressure old fluid buried 3-8 km below clay and shale insulated surface in Afghanistan [1]. They are a dual source of geothermal and Methane gas, which is reported to be found in the north of the country [1]. The clay and shale areas are located in a northern and north-western part of the country adjacent to existing petroleum and gas fields. In addition, the clay and shale are observed in the Katawaz hypothetical petroleum basin [12]. Geopressured geothermal fields are associated with gas and oil industrial regions, where the power demand is high [13]. It also can be the top prospect area for geothermal energy and may have high heat flow. The clay and shale rocks have been selected from the geological age and lithology file (Afgglg), and the petroleum resources data (structafg.shp) of Afghanistan is downloaded from USGS website [14].

Intrusive or Igneous Rocks

Intrusive, plutonic, or igneous are the current young underground magmatic bodies which are not reached to the earth surface one of the best heat source that cool down slowly. The possibility of geothermal resource is very high in association with intrusive bodies in Afghanistan [1]. The active geothermal systems in USA, Philippines, Japan, and Italy are located above and around the intrusive bodies [15]. The observed global heat flow in igneous rocks region is higher in the Cenozoic era [16]. The mean heat flow value for Cenozoic is 97mW/m^2 with 66.9 standard deviations [17]. In this study the land surface heat flow above the shallow intrusive rocks are estimated separately considering the geological age and global observed heat flow value.

Heat Flow Selection Criteria

The only single criterion of geological age cannot be more valid for heat flow estimation. It is required to consider the geological structures, hot springs, intrusive rocks, and petroleum areas. The global observed mean heat flow values in igneous, orogeny and carboniferous are higher than others in the same geological age regions. Table 2 shows the high and low heat flow value for the prospect areas within the same geological ages. In addition, the heat flow map of Akita and Iwate in Japan [18] displays that the heat flow values are higher in the regions, geologically, geochemically, and geophysical suitable for geothermal energy exploitations than other regions. These suitable areas for geothermal energy exploration in the country are considered having higher heat flow values. For instance the areas: 4000m around the hot springs and hydrothermal mineral waters, 5000m around largest and active faults, 1000m around the secondary faults, petroleum and gas prospect region, geopressured areas, and intrusive rocks regions. The average age of geological era time scale is considered to plot the mean heat flow value for intrusive rocks, high and low heat flow prospect areas from Table 2. Figure 7 shows the heat flow predictor equation for igneous rocks. Figure 8 shows the high and low geothermal prospect areas heat flow estimator equations.

Table 2: Mean heat flow value for intrusive, high and low prospect areas predictors.

Erathem / Era	Intrusive Bodies		High Prospect Areas (HPA)		Low Prospect Areas (LPA)	
	Heat Flow [mW/m^2]	Standard Deviation	Heat Flow [mW/m^2]	Standard Deviation	Heat Flow [mW/m^2]	Standard Deviation
Cenozoic	97 [7]	66.9	76 [8]	52	63.9 [7]	27.5
Mesozoic	64.2 [7]	28.8	73 [4]		63.7 [7]	28.2
Paleozoic	57.7 [7]	20.5	61 [7]	30.2	45 [4]	

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Proterozoic			58.3 [7]	23.6	45 [8],[4]	7
Archean			51.5 [7]	25.6	36 [4]	

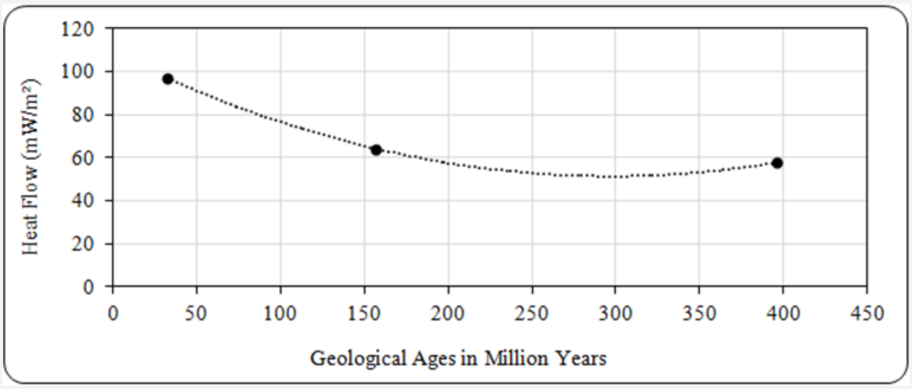

Figure 7 : Average heat flow predictor for intrusive/igneous rocks.

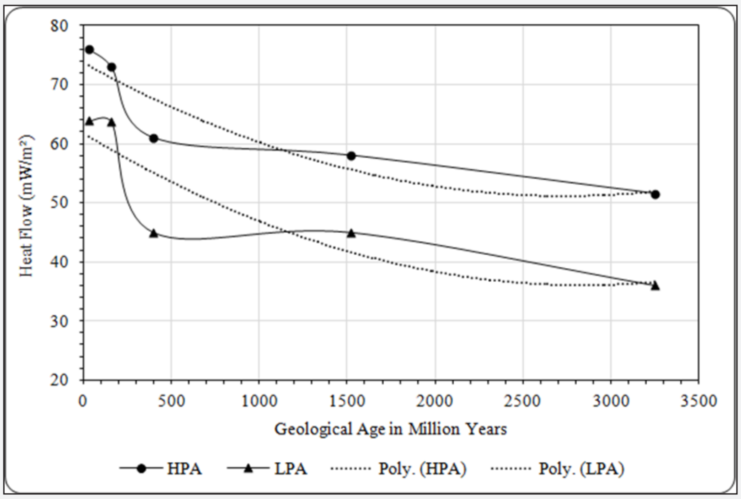

Figure 8 : Average heat flow predictors for prospected high and low heat flow areas.

GIS application

Table 3: The input layers of GIS model.

Name	Type	Reference
Mineral Waters	Points	[16]
Hotsprings	Points	[9]
Largest Faults	Polylines	[17]
Faults	Polylines	[12]
Afg_faults	Polylines	[17]
Structafg	Polygon	[14]
Afgglg	Polygon	[14]

Figure 9 describes the GIS model for heat flow estimation and criteria application. The available input files for GIS model are presented in Table 3. The 4000m buffer zone of hydrothermal mineral waters and hot springs are the geochemical prospect areas for high heat flow. The largest faults are located in tectonic regions between areas of: different aged folding, structural-facies zones, and the largest tectonic structures. The union of fault systems buffer zones constructs the geological prospect areas for high heat flow value. The union of geochemical and geological prospects with petroleum, geological age and lithology polygons creates the new Arc Map layer (Afgggg). The new layer also contains the attribute tables of input layers. Additionally, the new field has been added in attribute table to utilize field calculator tool of GIS for the heat flow calculation.

Select layer by attribute from the data management tool make it possible to apply the multi criteria decision analysis (MCDA) system for heat flow estimation. This tool has six type of selection options;

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a. New selection

b. Add to selection

c. Remove from selection

d. Subset selection

e. Switch selection

f. Clear selection

Figure 9 : GIS model for heat flow estimation in Afghanistan.

These selective capabilities of the tool are useful in applying the criteria for mean heat flow estimation. There is three permutation way to calculate step by step the heat flow values for intrusive rocks, high and low prospect heat flow regions on the basis of last thermo tectonic event time or geological age end time. The selection layer by attribute is used to;

a) Extract the intrusive and igneous rocks for mean heat flow estimation by equation 4 in Cenozoic, Mesozoic, and Paleozoic era.

b) Extract the high heat flow prospect areas, such as geochemical, geological, petroleum and geopressured. The equation5 is applied to calculate the high heat flow prospect regions mean heat flow values.

c) The remaining areas are supposed to be low heat flow region and equation 6 is applied to estimate the mean heat flow value.

$$Q(t) = 0.0006t^2 - 0.3866t + 108.9 \quad 0 \le t \ge 542 \text{ for intrusive only} \quad (4)$$

$$Q(t) = 0.000003t^2 - 0.0165t + 73.7 \quad \text{for high prospect geothermal areas} \quad (5)$$

$$Q(t) = 0.000003t^2 - 0.0181t + 61.8 \quad \text{for low prospect geothermal areas} \quad (6)$$

Where Q is the mean heat flow value, and t is the end time of geological age. The combined result of heat flow estimated for igneous rocks, geothermal prospect (high heat flow) areas, and other areas are discussed in next section.

Result and Discussion

The result of estimated mean heat flow value on the basis of geological age, considering the multi criteria decision analysis such as geological, geophysical, and geochemical prospect geothermal areas, ismapped as in Figure 10.The predicted mean heat flow value is from 34.6 to 108.8mW/m^2. The highest mean heat flow value could be possible in intrusive bodies, Helmand, Arghandab, Baluchistan, Farahrud, Harirud, and northeast (Badakhshan) geothermal fields. The second high heat flow value could be observed around fault system, geopressured, petroleum, and hydrothermal areas. The resulting map of mean heat flow estimation encourages the geothermal resources exploration in the high heat flow prospect areas. However, the obtained map is on the basis of geological ages, and geothermal evidence layers, the field measurement are recommended for mean heat flow validations.

The Table 4 explains the predicted mean heat flow value ranges for each thermo tectonic era in Afghanistan. The Cenozoic almost cover the 65% of the country land surface, where the main cities and population are located, may have the heat flow above 60mW/m^2. This region could be prospect areas for geothermal energy exploration. The Mesozoic, Paleozoic, and Proterozoic regions are located in the central, east, and northeast part of the country may have heat flow above 60mW/m^2 in and around

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geothermal manifestation areas such as hot springs, faults, petroleum, geo pressured, and intrusive rocks. The estimated mean heat flow value for Archean era region is less than 60mw/m^2, which cover the remote northeast part of the country in Badakhshan. However, this region also located between two large faults and has one hot spring, may not be prospect area for geothermal exploration according to this study.

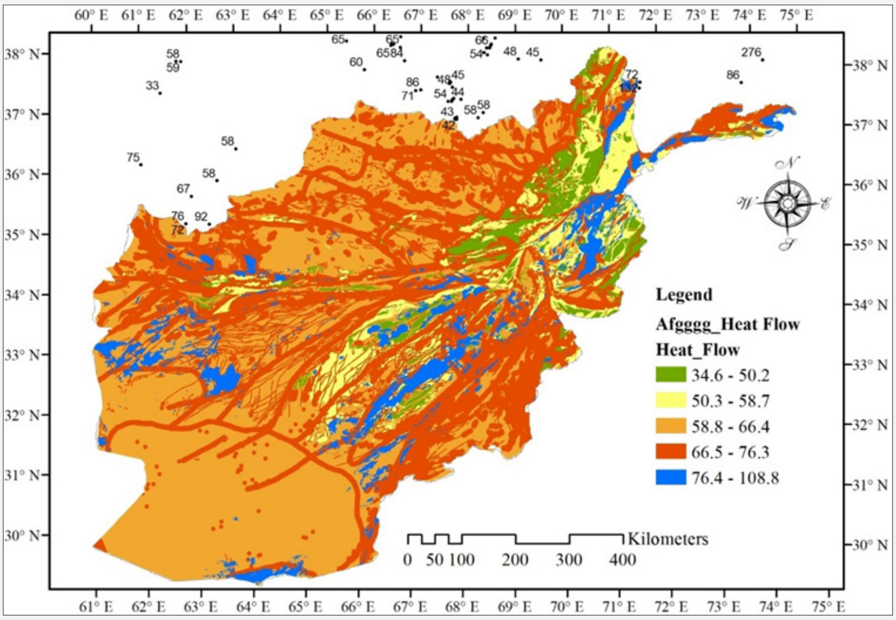

Figure 10 : Estimated surface mean heat flow value for Afghanistan.

Table 4: Estimated mean heat flow in Afghanistan.

Erathem / Era	Area [km^2]	Heat flow [mW/m^2]
Cenozoic	420,907.80	60.8 ~ 108.8
Mesozoic	166,392.74	50.2 ~ 89.2
Paleozoic	61,287.82	46.6 ~ 69.7
Proterozoic	47,372.29	37.3 ~ 65.6
Archean	7,690.91	34.6 ~ 51.6

Conclusion

The surface geological data and age are used to estimate the surface mean heat flow values. The single criteria of age are not enough to estimate the reasonable heat flow value for different kinds of geological structures within the same age scale areas. The geothermal prospect areas having high heat flow value need to be considered in the estimation. The surface heat flow is high in the region having geothermal manifestation such as hot springs, hydrothermal minerals, faults, petroleum, and intrusive rocks. The GIS is useful tool to accurately analyze the earth's surface geological age, lithology, structure, and geophysics for predicting the heat flow value. This tool has the capability to consider more criteria for further accuracy. It can be repeated when the new data is available for further development.

The estimated heat flow map is the first digital map for Afghanistan. It could be helpful in the geothermal energy exploration and exploitation. The surface heat flow is among the principle requirements for earth's crust temperature calculation at shallow depth. The predicted heat flow map could be useful for estimating earth's crust temperature at depth (for example 1 to 10km), and geothermal potential calculation in Afghanistan, as the geothermal exploitation and well siting require the understanding of resources potential, the geothermal reservoir characterization and feasibility studies. This finding is a starting point for further development and a roadmap for field works.

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