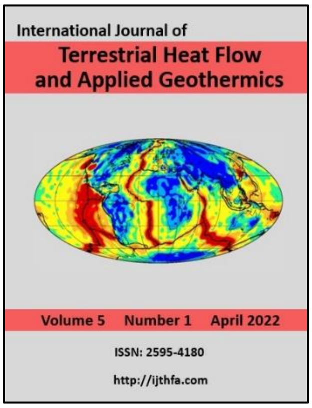
International Journal of Terrestrial Heat Flow and Applied Geothermics
VOL. 5, NO. 1 (2022); P. 26-33.
ISSN: 2595-4180
DOI: https://doi.org/10.31214/ijthfa.v5i1.85
IJTHFA
http://ijthfa.com/



Geothermal Resources of the Asian Continent: A regional Assessment

Valiya M. Hamza[1], Fábio P. Vieira[1], Suze N. P. Guimarães[1], Jorge L. S. Gomes[2]

[1] National Observatory, Rio de Janeiro, Brazil.
[2] Institute of Science Engineering and Technology, Federal University of the Jequitinhonha and Mucuri Valleys, Teófilo Otoni, Brazil.

Email address
valiyahamza@gmail.com (V. Hamza)
Corresponding author

Abstract

The present work is an attempt for regional assessment of geothermal resources of the continental region of Asia. It is based on integrated analysis of the results of experimental data on heat transfer by conduction as well as hydrothermal and magmatic processes in the upper crust. The current compilation makes use of geothermal data reported at the website of IHFC but also estimates based on available information on occurrences thermal springs and volcanic events. The resource assessment has been carried out for 11260 sites distributed in 46 countries. A modified method of magmatic heat budget (MHB) has been employed in deriving estimates of geothermal resources in areas of recent volcanic activity. These datasets were reevaluated and spatially gridded using kigrid interpolation to construction of regional distribution maps of geothermal resources and interpreted on the basis of available information on tectonic setting and geological characteristics. According to results obtained the total resource base (RB) is estimated to be 47024 ± 4525 GJ. The mean resource base per unit area (RBUA) is 1765 GJ. The most prominent features in geothermal maps are the significantly high values of resource base of greater than 1000 GJ in countries such as Japan, Indonesia, China, Bhutan, Nepal and Pakistan. In addition, vertical distributions of temperatures were calculated in such areas for depths reaching down to 6 km. The results obtained indicate potential availability of high temperature resources in vast regions of the Asian continent.

Keywords
Geothermal Resources,
Regional Assessment,
Asian Continent.

Received: February 11, 2022

Accepted: March 13, 2022

Published: April 02, 2022

1. Introduction

Asia is recognized as the largest of the world's continents, covering nearly thirty percent of the Earth's land area. On the western side it is bordered by the African continent and on the northwest by Europe. Along the eastern and southern sides are the oceanic regions of Arctic, Pacific, Indian and Pacific. Most geographers define Asia's western border as an indirect line that follows the Ural Mountains, the Caucasus Mountains, and the Caspian and Black seas. The subregions on the western side are the Arabian Peninsula, Indian subcontinent, Indochinese Peninsula, Maritime Southeast Asia, and the Japanese archipelago. The mountain systems considered include the Himalayas with the Karakoram range, the Pamir and the Kunlun and the Tien Shan, the Hindu Kush in Afghanistan, and the Urals in Russia.

According to physiographic characteristics there are six major regions, classified as Northern, Central, Eastern, South, Southeast, and Western. The map of Figure (1) illustrates this geographic setting and outlines of countries in the Asian continent. The geothermal dataset of the present work refers to 46 countries.

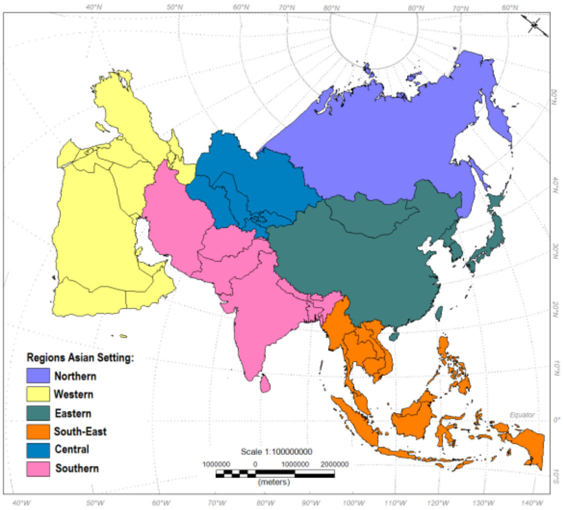


Figure 1 – Geographic setting and country outlines of the Asian continent.

2. Procedures for Resource Estimates

The terms resource and resource base (RB) used in this work refer to geothermal energy. The geothermal resource base calculations in the present work were carried out following the methodology proposed in earlier studies (see for example: Muffler and Cataldi (1978), Battocletti (1999), Huttrer (2001), Barbier (2002), Cardoso et al. (2010). Volumetric method was considered adequate for this purpose. In the terminology proposed by Muffler and Cataldi (1978) the resource base (RB) is the excess thermal energy up to a specified depth. In gridded data sets the resource base (Q_{RBi}) for the ith cell, of thickness d_i, associated with its temperature distribution is calculated using the relation:

$$Q_{RBi} = \rho_i \, C_{pi} \, A_i \, d_i \left(T_i - T_{0i}\right) \qquad (1)$$

where ρ_i is the average density, c_{pi} the specific heat, A_i the area of the cell, T_i the bottom temperature and T_{0i} upper surface temperature. Recoverable resource (RR) is defined as that part of the resource base associated with pore fluids that can be extracted using current technology (see Muffler and Cataldi, 1978; Lund and Freeston, 2001). In areas of positive geothermal gradients, temperatures of the rock matrix and the pore fluids increase with depth. However, porosity and permeability of most common rocks decrease with depth, which imply a corresponding decrease in quantity of circulating fluids in deeper levels. The nature of opposing roles of temperature and porosity variations with depth can be understood by considering the relation for total geothermal resource (Q) of a volume element (of area A and thickness h) with rock temperature T_r and porosity ϕ:

$$Q = \left[\phi C_f + (1-\phi) C_r\right](T_r - T_0). A. h \qquad (2)$$

where C_f and C_r are the heat capacities of the fluid and rock matrix respectively. The variation of T_r with depth z depends on the local value of geothermal gradient (Γ). The variation of porosity ϕ with depth z is usually represented by a relation of the type:

$$\phi = \phi_0 \, e^{-z/\Pi} \qquad (3)$$

where Π is the parameter specifying decrement of porosity with depth. The substitution of equation (3) in equation (2) leads to:

$$Q = (z\Gamma A h)\left[\phi_0 e^{-\frac{z}{\pi}} C_f\right] + (z\Gamma A h)\left[\left(1 - \phi_0 e^{-\frac{z}{\pi}}\right) C_r\right] \quad (4)$$

It is fairly simple to note that the first term in equation (4) represents the recoverable resource (RR) while the second term represents the resource associated with the solid rock matrix (RM). The sum of RR and RM represents the resource base (RB). For purposes of the present work, the estimates of resource base and recoverable resources have been set to a reference depth limit of 6 km. Mean values of porosity adopted for the main rock types are 0.25 (soft sediments), 0.15 (hard sediments), 0.1 (fracture zones) and 0.05 (igneous and metamorphic rocks). The values of resource base per unit area (RBUA) provide a better indication of the regional distribution. In this sense the distribution of RBUA is similar to that of heat flux. Resource base per unit area (RBUA) is a useful indicator in regional comparative studies.

3. Resource Assessment for Volcanic Areas

A number of factors affect resource assessment in volcanic areas. These include likelihood and duration of an eruption, the eruption style, relate to the depth of the magma chambers. In previous works by Vieira and Hamza (2019) and Gomes et al. (2021) the magma chamber depths were postulated to lie in the depth range of 10 to 15 km and estimates of resource base values were tied to this assumption. Clearly, we need better methods of estimating magma chamber depths.

A modified approach has been adopted in the present work for calculating the depths to the source magma chambers of active volcanoes. The relation employed for depth to magma chamber by Becerril et al. (2013) is:

$$h = \frac{\Delta u_1 E}{2L(1-\nu^2)} - \frac{P_e + \sigma_d}{(\rho_r - \rho_m) g} \qquad (5)$$

where Δu_i is the opening of feeder dikes, E the young's modulus L is the strike or dip of the fracture, ν the Poisson's ratio P_e is the excess fluid pressure in the magma chamber, σ_d is the differential stress (difference between the vertical stress and the minimum principal horizontal stress at the surface where the volcanic fissure forms) and g acceleration due to gravity. Also ρ_r and ρ_m refer to the densities of host rock and magma. In the approach of Becerril et al. (2013) these were assumed to have constant value. Thus, magma chambers at shallower depths have relatively low-density values compared to those at deeper levels. It indicates chamber depths of less than 7 km for magmas rich in volatiles. We consider this as a representative value for depths of shallow magma chambers in Indonesia.

Illustrated in Figure (2) is the relation between chamber depth and density of magma chambers based on the use of equation (5). It is clear that magma intrusion systems with significant volatile contents with density less than 2000 kg/m^3, emplaced at depths as low as of 5 km, contribute significantly to occurrence of shallow resource systems. Such low-density intrusions may occur as a result of significant proportions of volatiles. There is no doubt that shallow magma chambers occur at depths less than 5 km., in volcanic systems of Southeast Asia. It implies occurrence of high temperature resources at relatively shallow depths.

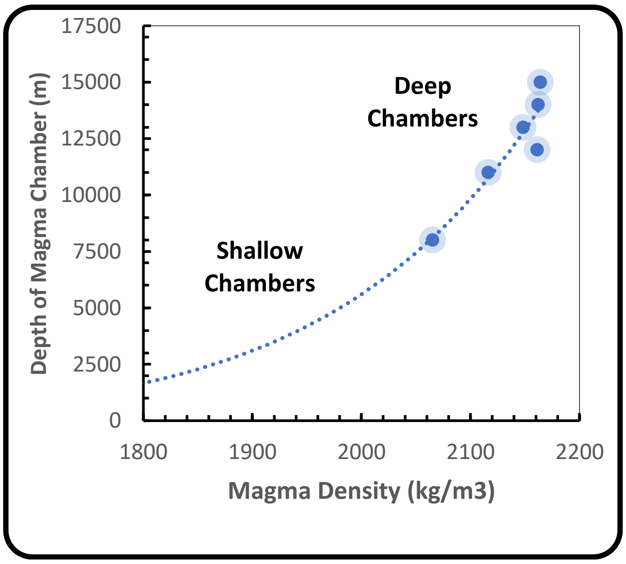


Figure 2 – Relation between chamber depth and magma density.

The relation illustrated in Figure (2) also opens up the possibility of obtaining first order estimates of the depths of geothermal resources. However, determining the relevant equations require a careful examination of available experimental data. These have remarkable influence on thermal fields of local crustal segments. Presented in Table (1) are examples of values of RBUA for selected volcanic areas of Sumatra. Note that in almost all cases values are in excess of 1000 GJ. Similar values are also expected to prevail for volcanic areas of Japanese archipelago. Examples of intense volcanic activity occur mainly along the island arcs of southeast Asia.

Table 1 – Estimated values of resource base per unit area (RBUA) for selected volcanic areas of Sumatra.

Name	Longitude	Latitude	Age	RBUA (GJ)
Belirang-Beriti	102.18	4.43	unknown	1384
Besar	103.67	3.38	April 1940	2046
Bukit Daun	102.37	4.23	unknown	1384
Bukit L. Balai	103.62	4.03	Unknown	1384
Dempo	103.13	4.81	2018	2046
Geureudong	96.82	2.03	1937	2046
H.-Tarutung	98.93	5.35	Pleistocene	1384
Hulubelu	104.60	2.33	1836	2046
Hutapanjang	101.60	2.16	unknown	1384
Imun	98.93	3.52	unknown	1384
Kaba	102.62	3.85	2000 (1)	2046
Kembar	97.66	1.70	Pleistocene	1384
Kerinci	101.26	2.59	2019	2046
Kunyit	101.63	1.48	unknown	1384
Lubukraya	99.21	0.38	unknown	1384
Marapi	100.47	4.27	2018	2046
Patah	103.30	2.82	unknown	1384
Pendan	102.02	4.91	unknown	1384
Peuet Sague	96.33	5.78	Jun-05	2046
Rajabasa	105.63	4.83	1798	1717

Note that at occurrences of geothermal systems with temperatures higher than 150°C are common in areas of volcanic complexes. The possibility that crustal blocks with temperatures higher than 150°C, at depths less than 3 km, is important for planning exploration of Hot Wet Rock (HWR). At depths of 3 to 5 km it is likely to find Hot Dry Rock (HDR) systems.

At larger depths of more than 4km, other high temperature systems appear along vast areas in the central parts of Asia. Note that in these cases occurrences of geothermal systems with temperatures higher than 150°C are not limited to the volcanic areas. Significantly large high temperature targets occur not only in the western sectors but also spread out to wide regions in the central stable platform areas.

4. Results of Regional Assessments

In this item the regions for resources assessments are organized by geographical contiguity. Thus, the sequence of data analysis adopted for regions of the Asian continent refers to those of the regions mentioned above, namely northern, central, western, southern, eastern and southeastern. We refrain from quoting heat flow values, as such data has been discussed in detail in the companion work present in this volume by Zhu et al. (2022). Hence only selected data sets (complete with values of essential parameters employed for resources assessments) are employed in deriving estimates reported in data tables.

3a. Northern Regions of Asia

This is the region that extends from west to east spanning over much of the eastern parts of Russia. It is bounded on the south by the northern plains of China. The mean values are listed in Table (2). The statistical uncertainty in resource estimates is indicated by respective values of standard deviation (STD). The letter N indicates the number of data.

Given in the second and third columns of this table are the surface areas and numbers of localities of data acquisition for each country or region. The fourth column gives the mean values of the resource base (RB) for each unit, expressed in units of 10^{21} Joules. However, it is clear that resource base per unit area (RBUA) is a better indicator of the geographic distribution. Given in the last column of this table are values of RBUA expressed in units of gigajoules (GJ).

Table 2 – Summary of resource base data (RB and RBUA) in the Northern Region (Russia).

Region/ Country	Area (10^{11} km^2)	N	RB (10^{21} J)		RBUA (GJ)
			Total	STD	Mean
Platform area	1430.00	1634	13600	6.2	952
Baikal Rift zone	0.32	374	111	0.19	3490
Volcanic areas	1.74	115	136	1.4	600
Subtotal/Ave.	1.75	2134	13711	6.39	2221

The map in Figure (3) illustrates the geographic distribution of resource base per unit area (RBUA) for northern segment of the Asian continent. Note that values of RBUA are relatively low, less than 800 GJ, in the central parts of this regional subunit, which overlies the cratonic area of Siberian platform. The region of low values of resource base appears to extend to the adjacent regional segments to the northeast as well as to those in the southwest.

On the eastern side of this region of the contours of resource base encircles an oval shaped region with moderate values of RBUA in the range of 800 to 1200 GJ. It is situated in the Vitim area of Siberia, known for volcanic activities during Cenozoic times.

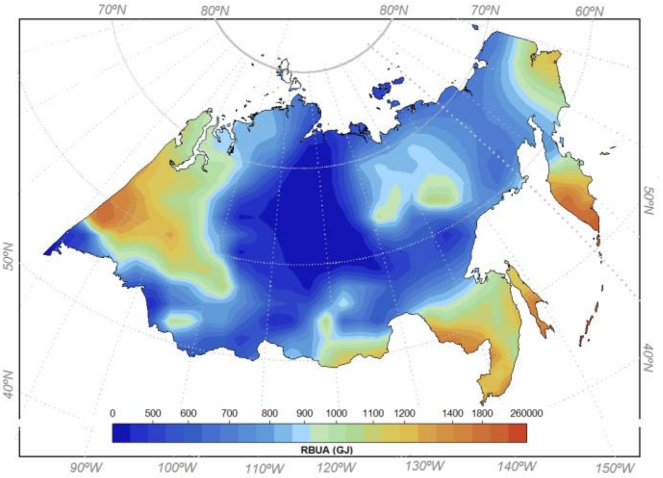


Figure 3 – Distribution of geothermal resource base per unit area (RBUA) in the Northern Region of Asia.

4b. Central Region of Asia

The Central region of Asia includes the orogenic belt of Tien Shan and a series of sedimentary basins such as the South Caspian, the Amu Darya, the Afghan-Tajik, the Fergana as well as the Junggar, Tarim and south Maskell. Table (3) provides a summary of geothermal resource data for this region. The area of Kazakhstan appears as a region of low RBUA values (< 650 GJ). This is an area adjacent to the cratonic region of Siberia platform. The highest value of RBUA of 1410 GJ is found for area of Kirgizstan. The other countries of Central Asia (Tajikistan and Turkmenistan) have slightly higher values of RBUA.

Table 3 – Summary of data for resource base (RB and RBUA) for countries in Central region of Asia.

Region/ Country	Area (10^{11} km^2)	N	RB (10^{21} J)		RBUA (GJ)
			Total	**STD**	**Mean**
Kazakhstan	2.72	185	166	0.4	610
Kirgizstan	2.00	98	282	2.0	1410
Tajikistan	1.43	36	170	2.0	1190
Turkmenistan	0.49	169	57	0.2	1170
Uzbekistan	0.45	125	44	0.6	978
Subtotal	7.10	613	625	3.2	1072

The map of RBUA of Figure (4) illustrates variations in the resource base for central Asia. The resource base values are relatively low (in general less than 800 GJ) in the eastern parts. while higher values of > 800 GJ occur in the western parts of Kazakhstan, along the border with Caspian Sea. This is a well-known region for widespread occurrence of mud volcanos. It is possible that the mechanisms responsible for occurrence of mud volcanos (a large number of which are manifestations of seepages of natural gas) are related also to occurrence of geothermal resources.

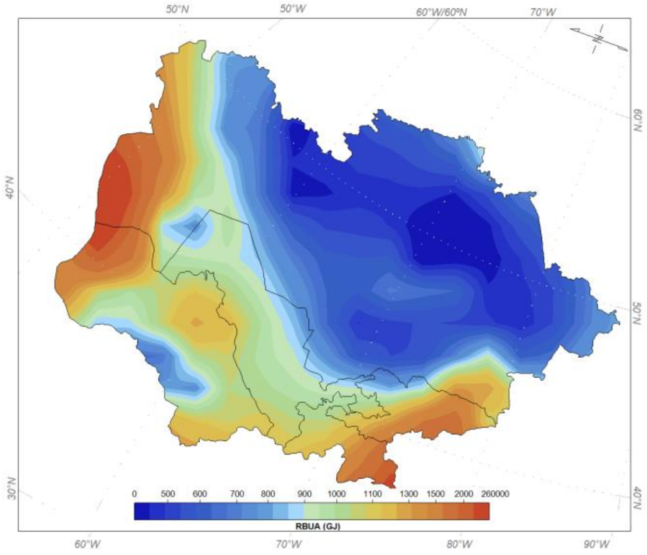


Figure 4 – Distribution of geothermal resource base per unit area (RBUA) in Central Asia.

It points to an implied relation between areas of geothermal resources and occurrence of mud volcanos. The regions of relatively high resource base continue onto Uzbekistan and Turkmenistan. On the western side the belt of relatively high RBUA values in the range of 900 to 1450 GJ) extends onto the northern parts of Tajikistan and seems to continue along the region adjacent to the western border of Tibet.

4c. Western Region of Asia

West Asia is composed of 18 countries of which relevant geothermal data have been reported only for 14 of them. Table (4) provides a summary of resource estimates for western Asia. The data distribution for the western region is illustrated in. the map of Figure (5).

Table 4 – Summary of data for resource base (RB and RBUA) in Western region of Asia.

Region/ Country	Area (10^{11} km^2)	N	RB (10^{21} J)		RBUA (GJ)
			Total	**STD**	**Mean**
Armenia	0.300	52	29.80	0.200	1000
Azerbaijan	0.870	254	78.10	0.130	902
Cyprus	0.090	31	4.60	0.090	495
Gaza Strip	0.004	9	0.37	0.004	1020
Georgia	0.070	47	41.70	0.300	633
Israel	0.220	85	18.20	0.130	822
Jordan	0.890	52	129.00	2.200	1450
Oman	3.100	26	235.00	2.470	759
Palestine	0.060	7	3.80	0.300	635
Sinai	0.600	7	750.00	4.700	1240
S. Arabia	21.500	16	2510.00	81.000	1170
Syria	1.850	10	208.00	9.300	1130
Turkey	7.840	328	835.00	1.200	1070
Yemen	5.550	9	48.30	0.600	870
Subtotal	42.900	933	613.00	7.300	943

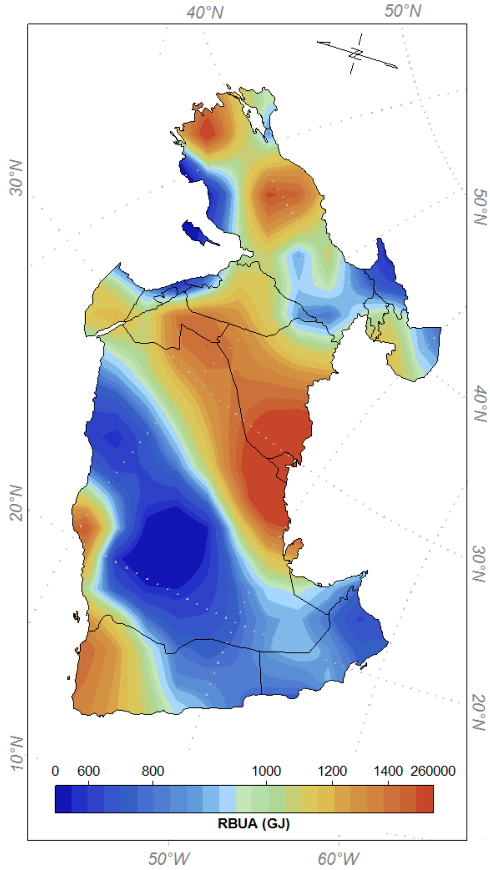


Figure 5 – Distribution of geothermal resource base per unit area (RBUA) in the region of Western Asia.

Values of RBUA less than 700 GJ are found for Cyprus, Georgia and Palestine. Intermediate values in the range of 700 to 1000 GJ of resource base are encountered for areas in Oman, Yemen, Israel and Azerbaijan. The remaining countries have RBUA values in excess of 1000 GJ. The highest value of 1450 GJ has been found for Jordan.

A remarkable set of high values of RBUA (> 1000 GJ) occur along a belt extending from the Mediterranean to the region of Persian Gulf. This belt has a branch extending through middle of Jordan to northern parts of Saudi Arabia.

The southward extension of this belt of high RBUA values seems to cut across the eastern coastal zone of Saudi Arabia. Further to the south high values of RBUA occur along an east-west belt along the northern border of Yemen.

4d. Southern Region of Asia

The countries of this region include Afghanistan, Bangladesh, Bhutan, India, Iran, Nepal, Pakistan and Sri Lanka. The data distribution for this region is given in Table (5). Figure (6) illustrates the distribution of RBUA values for this region.

Table 5 – Summary of data for resource base (RB and RBUA) for countries in the region of southern Asia.

Region/ Country	Area (10^{11} km^2)	N	RB (10^{21} J)		RBUA (GJ)
			Total	STD	Mean
Afghanistan	6.53	11	812	20.0	1420
Bangladesh	1.48	49	134	0.6	904
Bhutan	0.38	6	46	0.8	1190
India	32.90	467	2500	2.6	762
Iran	1.65	38	1350	1.4	816
Pakistan	4.49	125	1780	31.0	2010
Nepal	6.53	30	450	6.5	3050
Sri Lanka	0.66	10	95	0.8	1440
Subtotal	56.6	834	7167	9.4	1449

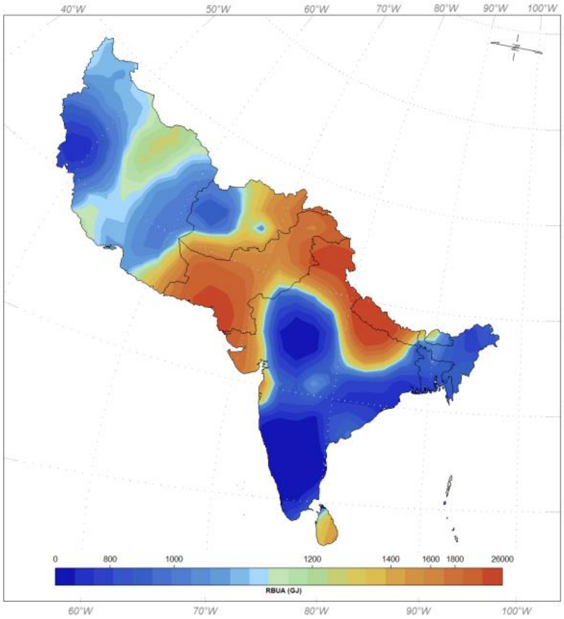


Figure 6 – Distribution of geothermal resource base per unit area (RBUA) in Southern Asia.

The lowest values of RBUA are found for India (762 GJ), Iran (816 GJ) and Bangladesh (904 GJ). A notable feature is the high values of RBUA (of 3050 GJ) for the mountainous region of Nepal. Relatively high values are also found for the adjacent high plateau region of Tibet. The data set for this region also include estimates for the Sri Lanka (Previously Ceylon), located in the southern parts of Bengal Sea.

Low values of RBUA are found for the northern region of Iran and also for the cratonic region of south India and areas of Bangladesh. Relatively high values of RBUA are found for southern parts of Afghanistan, region of Pakistan and much of the northern parts of India, including the mountainous regions of Nepal and Bhutan. Such conclusions are mostly based on estimated values of resource base derived using data for thermal springs reported by Todaka et al. (1999).

4e. Eastern Region of Asia

The main countries in the eastern region of Asia are China, Japan, Mongolia, North Korea and South Korea. Most of the measurements have been carried out in Japan and China. Details of data for resource base are given in Table (6). It is important to point out the high values of resource base for China. However, the highest value of resource base per unit area is that for Japan.

Table 6 – Summary of resource base (RB and RBUA) for countries in the region of east Asian.

Region/ Country	Area (10^{11} km^2)	N	RB (10^{21} J)		RBUA (GJ)
			Total	STD	Mean
China (Mainland)	96.10	1418	10400	7.0	1090
Japan	3.78	1919	4820	24.0	12800
Mongolia	15.64	63	2010	58.0	1280
South Korea	1.00	79	104	0.6	1040
Tibet (China)	12.30	50	3100	71.0	2520
Subtotal	128.80	3529	20434	32.0	3746

The map in Figure (7) illustrates variations of resource base in Eastern Asia. Most of the northern parts of China and Mongolia have relatively low RBUA values of less than 800 GJ. Higher values of RBUA occur in regions adjacent to Nepal and the plateau region of Tibet.

The northern regions, mainly Mongolia and Manchuria seem to be characterized by relatively low values of resource base.

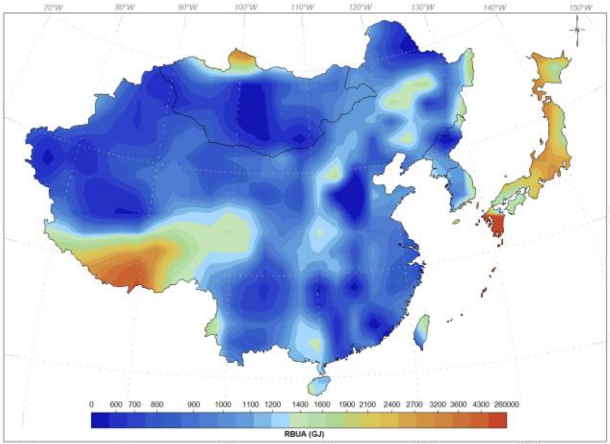


Figure 7 – Distribution of geothermal resource base per unit area (RBUA) in Eastern Asia.

However, the most remarkable features are segments with high resource base along the Himalayan mountains and along the southern coast of China. In addition, there are several zones with relatively high values of resource base spread out over wide areas in the eastern parts of China, including parts of South Korea.

4f. Southeast Region of Asia

The region consists of several countries with RBUA values higher than 1000 GJ. This includes Cambodia, Borneo, Malaysia, Sumatra, Philippines and Thailand. The highest value of 1800 GJ was found for the island of Sumatra. However, some areas of Cambodia, Thailand, Laos, and Philippines appear as containing regions where RBUA is less than 1000 GJ. A notable feature is the low values of < 1000 GJ for countries such as Guinea. Additional details of data distribution are provided in Table (7).

Table 7 – Summary of resource base (RB and RBUA) data for southeast region of Asia.

Countries/ Regions	Area (10^{11} km^2)	N	RB (10^{21} J)		RBUA (GJ)
			Total	STD	Mean
Cambodia	1.81	1	290	-	1600
Borneo	7.43	39	861	5.5	1160
Sumatra	4.73	633	852	0.7	1800
Laos	2.37	11	207	4.0	875
Malaysia	3.30	88	564	2.0	1710
New Guinea	8.83	6	625	14.0	707
Philippines	3.00	44	308	3.0	1030
Thailand	5.13	161	629	3.0	1220
Vietnam	3.32	41	138	4.0	415
Subtotal	39.90	3555	7079	18.0	1497

The map in Figure (8) illustrates distribution of resource base for Southeast Asia. Most islands of Indonesia appear as regions of normal values of resource base.

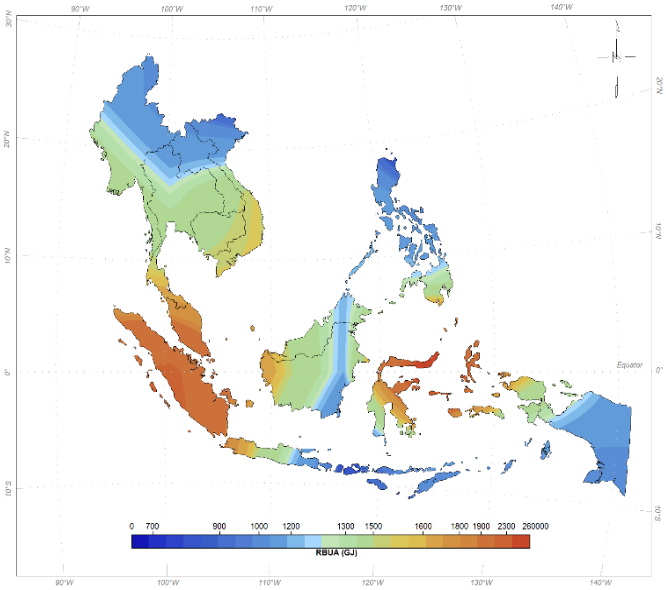


Figure 8 – Distribution of geothermal resource base per unit area (RBUA) in Southeastern Asia.

5. Integrated Resource Base for the Asian Continent

According to results of the present work resource assessments were carried out for 45 regions. Out of these 26 have RBUA values higher than the overall weighted mean value of 1000 GJ/m^2. It includes, in addition to sites of heat experimental measurements, 30 localities where resource assessments were carried out on the basis of estimated values of source depths.

Japan stands out as the country with the highest value of RBUA of 12800 GJ. The second largest value of RBUA is found for the region of Nepal. A summary of the final results obtained for the resource base (RB) and resources base for unit area (RBUA) is provided in Table (8).

Table 8 – Summary of resource base (RB and RBUA) data for the six major regions of the Asian continent.

Region	Country/Group	Area	RB (10^{21} J)	RBUA (GJ)
Northern	Platform area	1200	12000	952
	Baikal Rift	0.317	111	3490
	Volcanic areas	230	1600	1200
	Subtotal	1747	13711	2221
Central	Kazakhstan	2.72	1660	610
	Kirgizstan	2.0	282	1410
	Tajikistan	1.43	170	1190
	Turkmenistan	0.49	574	1170
	Uzbekistan	0.45	439	978
	Subtotal	7.09	625	1072
Western	Armenia	0.3	29.8	1000
	Azerbaijan	0.87	78.1	902
	Cyprus	0.09	4.6	495
	Gaza Strip	0.0037	0.37	1020
	Georgia	0.07	41.7	633
	Israel	0.22	18.2	822
	Jordan	0.89	129	1450
	Oman	3.1	235	759
	Palestine	0.06	3.8	635
	Sinai Peninsula	0.6	75	1240
	S. Arabia	21.5	2510	1170
	Syria	1.85	208	1130
	Turkey	7.84	835	1070
	Yemen	5.55	48.3	870
	Subtotal	42.9	613	943
Southern	Afghanistan	6.53	812	1420
	Andaman	2.0	282	1410
	Bangladesh	1.48	134	904
	Bhutan	0.38	45.7	1190
	India	32.9	2500	762
	Iran	1.65	1350	816
	Pakistan	4.49	1780	2010
	Nepal	6.53	450	3050
	Sri Lanka	0.66	95	1440
	Subtotal	56.6	7449	2261
Eastern	China	96.1	10400	1090
	Japan	3.78	4820	12800
	Mongolia	15.64	2010	1280
	South Korea	1	104	1040
	Tibet (China)	12.3	3100	2520
	Subtotal	128.8	20434	3746
Southeastern	Cambodia	1.8	290	1600
	Borneo	7.4	861	1160
	Sumatra	4.7	852	1800
	Laos	2.4	207	875
	Malaysia	3.3	564	1710
	New Guinea	8.8	3230	3660
	Philippines	3.0	308	1030
	Thailand	5.1	629	1220
	Vietnam	3.3	138	415
	Subtotal	39.9	7079	1497
Total		**2022.3**	**49911**	**11740**

The integrated map of resource base for the Asian Continent is illustrated in Figure (9). In this figure, the most prominent feature is the region of elevated values of RBUA in the Himalayan region, extending to adjacent areas of Tibet and Nepal.

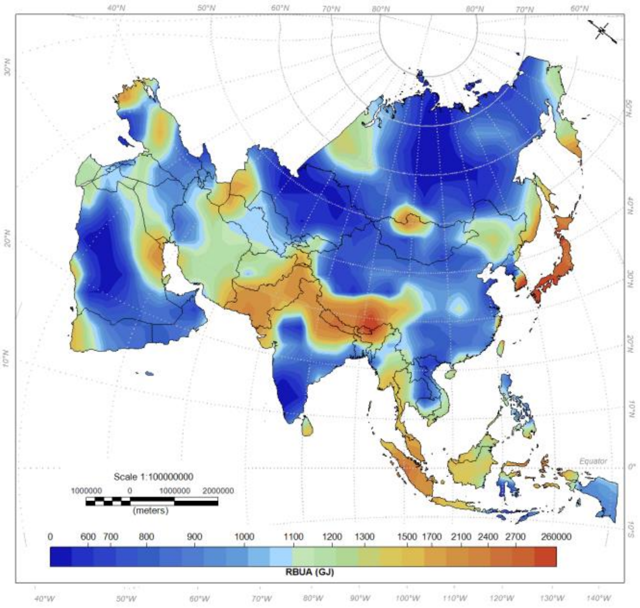


Figure 9 – Integrated geothermal resource base (RBUA in GJ) for the Asian Continent.

Also, significant values of RBUA (in excess of 2000 GJ) are also found for the Baikal region of Russia, the island of Sumatra (Indonesia), Tibet (China), Nepal, Bhutan and Pakistan. The entire mountain ranges of Himalayas seem to hold vast regions of significant resources (RBUA > 1000 GJ). At depths greater than 6 km this high temperature region of seems to have connection with high geothermal areas of the Mediterranean.

It is clear that areas of significant geothermal resources, with values higher than 1000 GJ of RBUA, occur across vast stretches of Asia, extending along discontinuous regional segments from the Japanese archipelago through the islands in the southern parts of Southeastern region, and then onto several parts of middle east.

6. Vertical Distributions of Crustal Temperatures

One of the convenient means of illustrating vertical distribution of excess temperatures is by using stacks of crustal temperature maps at conveniently chosen depth levels, which allow a sequential depth perspective. These datasets were reevaluated and spatially gridded using kigrid interpolation to construction of regional distribution maps of geothermal resources and interpreted on the basis of available information on tectonic setting and geological characteristics. Results of such an attempt is illustrated in Figure (10), where it is possible to identify areas with resource distribution of important geothermal resources, indicating as a basis for pointing resources in the estimates of resources in important geographic depths from 4 km.

The most prominent features are the relatively high values of resources covering much area of Himalayan Mountains, the islands of the southeastern region, eastern parts of China and the Japanese archipelago. It is clear that vast several regions of the Asian continent provide potential for occurrence of significant geothermal resources.

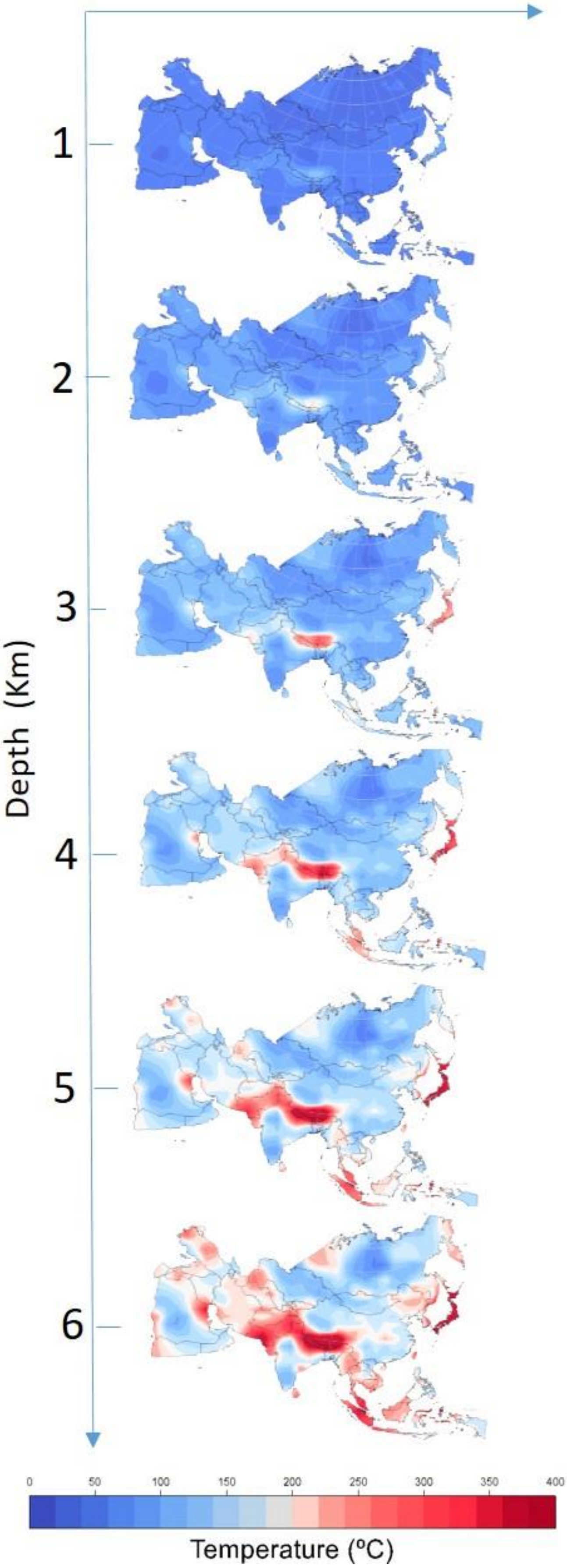


Figure 10 - Temperatures at depths of 1 to 6 km in mainland Asia.

6. Conclusions

A reappraisal of geothermal data of the mainland of Asia has been carried out based on data sets available at the IHFC (2013) website, incremented with updated information on volcanic activities of post Holocene times. The current compilation makes use of geothermal data reported at the website of IHFC but also estimates based on available information on occurrences thermal springs and volcanic events. The resource assessment has been carried out for 11260 sites distributed in 46 countries. A modified method of magmatic heat budget (MHB) has been employed in deriving estimates of geothermal resources in areas of recent volcanic activity. These datasets were reevaluated and spatially gridded using kigrid interpolation to construction of regional distribution maps of geothermal resources and interpreted on the basis of available information on tectonic setting and geological characteristics. According to results obtained the total resource base (RB) is estimated to be 47024 ± 4525 GJ. The mean resource base per unit area (RBUA) is 1765 GJ. The most prominent features in geothermal maps are the significantly high values of resource base of greater than 1000 GJ in countries such as Japan, Indonesia, China, Bhutan, Nepal and Pakistan. In addition, vertical distributions of temperatures were calculated in such areas for depths reaching down to 6 km. The results obtained indicate potential availability of high temperature resources in vast regions of the Asian continent.

Acknowledgments

The first author of this work held the position as Full Professor in Geophysics (before his retirement) of the National Observatory, Rio de Janeiro. The second author is Coordinator of the Department of Geophysics of the National Observatory (ON/MCTI) at Rio de Janeiro. The third author is recipient of a post-doctoral scholarship (PNPD) at the Department of Geophysics of the National Observatory - ON/MCTI. The fourth author is professor at the Institute of Science Engineering and Technology, of the Federal University of Jequitinhonha and Mucuri Valleys, Teófilo Otoni, Brazil.

References

Barbier, E. 2002. Geothermal energy technology and current status: an overview. Renewable and sustainable energy reviews, 6 (1-2), 3-65. Accessible at: https://doi.org/10.1016/S1364-0321(02)00002-3

Battocletti, L. 1999. Database of Geothermal Resources in Latin American & the Caribbean. Report for Sandia National Laboratories USA. Contract No. AS-0989, Bob Lawrence & Associates Inc.

Becerrill, L., Galindo, I., Gudmundson, A., Morales, J.M. 2013. Depth of origin of magma in eruptions. Scientific Reports, 3(1), 1-6. Accessible at: https://doi.org/10.1038/srep02762

Cardoso, R.R., Hamza, V.M., Alfaro, C. 2010. Geothermal resource base for South America: A continental perspective. In: Proceedings world geothermal congress, Bali, Indonesia, 25-29 April 2010.

Gomes J., Vieira, F.P., Hamza V.M. 2021. Reappraisal of Heat Flow Variations in Mainland Africa. International Journal of Terrestrial Heat Flow and Applied Geothermics, 4(1), 26-78. Accessible at: https://doi.org/10.31214/ijthfa.v4i1.64

Huttrer, G.W. 2001. The status of world geothermal power generation 1995 – 2000. Geothermics, 30, 7-27. Accessible at: https://doi.org/10.1016/S0375-6505(00)00042-0

Huber, C., Townsend, M., Degruyter, W., Bachmann, O. 2019. Optimal depth of subvolcanic magma chamber growth controlled by volatiles and crust rheology. Nature Geoscience, 12(9), 762-768. Accessible at: https://doi.org/10.1038/s41561-019-0415-6

IHFC, 2013. The global heat flow database provided by the international heat flow commission (IHFC). Accessible at: https://ihfc-iugg.org/products/global-heat-flow-database/data 2013

Lund, J.W. Freeston, D.H. 2001. World-wide direct uses of geothermal energy 2000. Geothermics, 30(1), 29–68. Accessible at: https://doi.org/10.1016/S0375-6505(00)00044-4

Muffler, P., Cataldi, R. 1978. Methods for regional assessment of geothermal resources. Geothermics, 7(2-4), 53-89. Accessible at: https://doi.org/10.1016/0375-6505(78)90002-0

Todaka, N., Shuja, T.A., Jamiluddin, S., Khan, N.A., Pasha, M.A., Iqbal, M. 1999. Preliminary study of geothermal energy resources of Pakistan. Geological Survey of Pakistan, Info Rel, 407, 93.

Vieira, F., Hamza, V. M. 2019. Assessment of geothermal resources of South America - a new look. International Journal of Terrestrial Heat Flow and Applications, 2(1), 46-57. Accessible at: https://doi.org/10.31214/ijthfa.v2i1.32

Zhu, W., Liu, S, Huang, S., 2022. Heat Flow in Asian Continent and Surrounding Areas. International Journal of Terrestrial Heat Flow and Applied Geothermics, 5 (This issue).