Provisional chapter

Volcanic Natural Resources and Volcanic Landscape Protection: An Overview

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Additional information is available at the end of the chapter

1. Introduction

Many land resources are formed by volcanoes. In the vast oceans, there are numerous sporadic islands, big and small. Take Kosrae and Azores Archipelago for example. Kosrae (5°9′N, 163°00′E), Federated States of Micronesia, is a small (112 km^2) volcanic island in the west-central Pacific Ocean [1]. Compared with Kosrae, Azores Archipelago (36°55′~39°43′N, 25°01′~31°07′W) is a much larger volcanic island. It consists of nine volcanic islands and covers 2,247 km^2 [2].

These volcanic islands not only offer space for humans to live on, they have also become courier stations for shipping and communication. They were particularly more important in ancient times when seamanship was not well developed. Some typical lands which have been created by volcanic activities will be introduced below.

The Hawaiian Islands in the Pacific Ocean are a typical example of islands constructed by volcanoes. With continuous oceanic volcano eruptions and magma pouring into the ocean constructing islands, the young Hawaiian Islands keep growing. This situation also happens in Iceland and Reunion.

Indonesia is the biggest archipelagic state in the world and also a "volcano country", most of the islands there have been constructed by volcanoes, for example, Anak Krakatau is called Krakatoa's son. It was formed both by volcanic activity and wave-cut erosion. Eventually the growth speed of the volcano exceeded the wave-cut erosion and emerged in 1930, piled up from an ocean floor of over 100 m depth, forming islands of cinder and lava covering more than 2 km^2 in area [3]. This new island, with an elevation of 9 m in 1930, grew relatively quickly in the first decade of its existence, to 67 m in 1933, and 132 m by 1941 and subsequently to 170 m by 1966. Changes in height were accompanied by enlargement of the island's area. By 1981

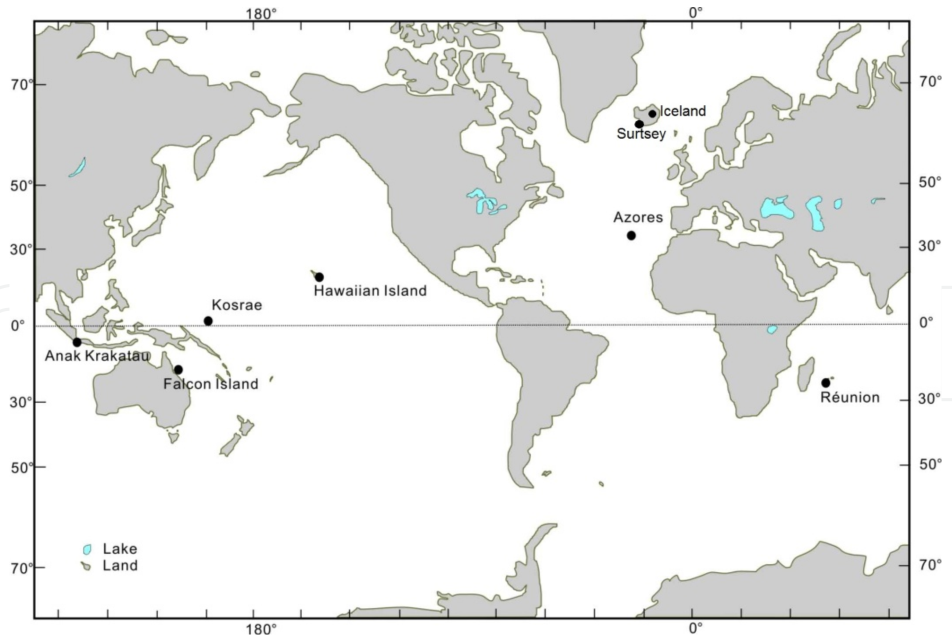

Figure 1. Locations of the volcanic islands referred to in the article

the diameter of Anak Krakatau was reported to be about 2,000 m, with the highest elevation at about 200 m above sea level [4].

Falcon Island (Australia) is a small, uninhabited, rocky island, bounded by a fringing reef, at the south of the Palm Islands, formed under the joint action of submarine volcanic eruptions and waves. It is approximately 35 km offshore, 40 km from the nearest city and river estuary, and 8 km from an aboriginal settlement on Great Palm Island [5]. It is in the Pacific Ocean about 1600 km from the eastern coast of Australia. In 1915, Falcon Island disappeared suddenly due to the dominant role of seawater erosion [6]. Eleven years later, the accumulative effect of submarine volcanic eruptions made it re-emerge out of the seawater.

Surtsey (63.3°N, 20.6°W) is also a new island which was formed by volcanic eruptions in 1963-1967. It is a volcanic island off the southern coast of Iceland. It was formed in a volcanic eruption which began 130 metres below sea level and reached the surface on 15 November 1963. The eruption lasted until 5 June 1967, when the island reached its maximum size of 2.7 km^2. Since then, wind and wave erosion have caused the island to steadily diminish in size: as of 2002, its surface area was 1.4 km^2 [7]. The heavy seas around the island have been eroding it ever since the island appeared and since the end of the eruption almost half its original area has been lost. The island currently loses about 1.0 hectare of its surface area each year [7]. This island is unlikely to disappear entirely in the near future. The eroded area consisted mostly of loose tephra, easily washed away by wind and waves. Most of the remaining area is capped by hard lava flows, which are much more resistant to erosion. In addition, complex chemical reactions within the loose tephra within the island have gradually formed highly erosion resistant tuff material, in a process known as palagonitization [8]. Estimates of how long Surtsey will survive are based on the rate of erosion seen up to the present day. Assuming that the current rate does not change, the island will be mostly at or below sea level by 2100 [9].

China has few volcanic islands. They were mainly formed by volcanic eruptions and principally include the Penghu Islands, Pengjia Islet, Mianhua Islet and Huaping Islet in the north of Taiwan Island, Green Island, Orchid Island and Gueishan Island on the continental slope in the east of Taiwan, Diaoyu Islands in the East China Sea and so on.

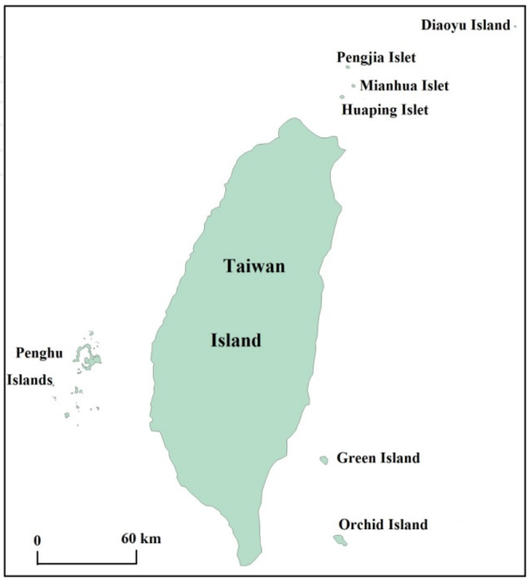

Figure 2. Location of volcanic islands in China

Figure 3. Penghu Island

2. Geothermal energy

In addition to the land resources introduced above, volcanoes provide us with clean energy - geothermal energy. So it has received the attention of all countries as a new energy source and the reserves are much more than the whole amount energy people are using currently. Its exploitation and utilization are developing rapidly. The definitions, distribution, present exploitation and utilization situation, and some typical examples would be introduced below.

Geothermal energy is the heat energy stored inside the Earth that originates from the melted magma of the Earth and the decay of radioactive substances. Most geothermal energy gathers around plate borders where most volcanic eruptions and earthquakes happen.

Volcanically active areas normally have a background of high geothermal energy. Volcanic eruption is the most violent exhibition of the internal thermal energy of the Earth on the Earth's surface [10]. Areas with more volcano activities are generally areas with high geothermal flow of geothermal energy. This is because the hot magma chamber under the volcano may heat the circulating groundwater. The heated groundwater is either stored under the ground or spurts out of the ground surface to form hot springs, boiling springs (e.g., the Sirung Volcanic Boiling Spring, Lesser Sunda Islands, Indonesia and Great Boiling Spring, Nevada, United States), geysers (e.g., the Fly Ranch Geyser, Nevada, United States, the Strokkur Geyser, Iceland), fumaroles (e.g., the Valley of Ten Thousand Smokes, Katmai National Park, Alaska, United States) and boiling mud pots (Fountain Paint Pots, Yellowstone National Park, United States, the mud pool at Orakei Korako, north of Taupo, New Zealand and the mud pool at Hverir, Iceland)[10].

The formation of a useful geothermal system needs to possess three essential conditions: an underground heat source (hot rocks), a heat transfer medium (groundwater) and a heat conducting channel (the fissures or boreholes communicating the underground heat reservoir and ground surface).

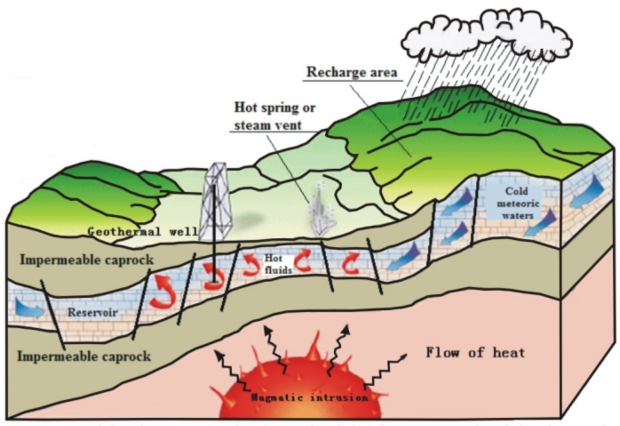

Figure 4. A natural geothermal system [11]

Geothermal energy may be classified into four categories [12]: (1) hydrothermal: the hot water or hydrothermal steam in the shallow layer with a depth of hundreds of metres ~ 2,000 metres; (2) geopressured geothermal energy: the high-temperature high-pressure fluid sealed thousands of metres under the ground in some large sedimentation basins; (3) magmatic thermal energy: the enormous thermal energy stored in magma pockets; (4) hot dry rock: it is a high-temperature rock mass stored deep underground without water or steam with the depth (thousands of metres) that can be reached with current drilling technology. Usually, the geothermal energy contained in hot dry rocks and magma pockets is much more than the geothermal energy of hydrothermal and geopressured heat reservoirs.

Hot dry rock is mainly metamorphic rock or crystalline rock. The key technology of heat collection is to build a heat exchange system in the body of hot dry rock without percolation. Generally, high-pressure water is injected into the rock stratum of 2,000~6,000 metres underground through a injection well which permeates the gaps of rock stratum and obtains geothermal energy; then the high-temperature water and steam in the gaps of rocks are picked up through a dedicated production well (at a distance of 200~600 metres) to the ground; the water and steam can be used to generate electricity after pouring into a heat exchange system; the water after refrigeration will be injected into the underground heat exchange system again via a high-pressure pump for recycling. The entire procedure is a closed system.

There are many problems in trying to tap Earth's internal heat as an alternative clean energy source. Earthquake risks and poorly understood geology are the two most important aspects. Domenico Giardini called for a better understanding of earthquake risk in pursuing deep geothermal energy using an enhanced geothermal system (EGS) [13]. In fact an EGS demonstration project in Geysers, north California, was halted by the geological anomalies. The California-based company AltaRock Energy was unable to penetrate the formation capping the hot rocks after months of drilling in 2009. Similar frustrations were encountered during EGS drilling projects at Paralana and the Cooper Basin, both in South Australia. In general, depths of 3–10 km are optimal for geothermal exploitation because they are extremely hot and accessible to modern drilling techniques. But this rule can be broken by geological surprises. In order to improve our geological understanding and enable us to find optimal drilling sites, China is launching the deep exploration technology and experimentation project, SinoProbe, to locate mineral resources and to find out more about earthquakes and volcanism. Meanwhile, the United States and China will inject US$150 million over the next five years into a joint Clean Energy Research Center [13].

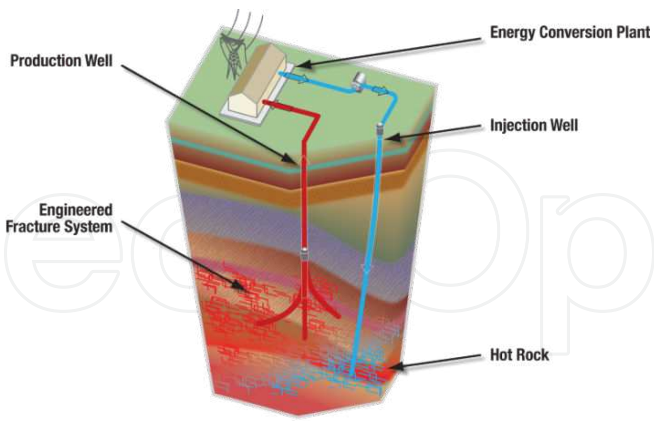

Figure 5. EGS Cutaway Diagram [14]

After the Second World War, countries around the world began to pay attention to exploiting and utilizing geothermal energy. Both the number of countries producing geothermal power and the total worldwide geothermal power capacity under development appear to be increasing significantly (Table 1 and Table 2) [15].

Country	1990 (MWe)	1995 (MWe)	2000 (MWe)	2005 (MWe)	2010 (MWe)
Argentina	0.7	0.6	0	0	0
Australia	0	0.2	0.2	0.2	1.1
Austria	0	0	0	1	1.4
China	19.2	28.8	29.2	28	24
Costa Rica	0	55	142.5	163	166
El Salvador	95	105	161	151	204
Ethiopia	0	0	8.5	7	7.3
France	4.2	4.2	4.2	15	16
Germany	0	0	0	0.2	6.6
Guatemala	0	33.4	33.4	33	52
Iceland	44.6	50	170	322	575
Indonesia	144.8	309.8	589.5	797	1197
Italy	545	631.7	785	790	843
Japan	214.6	413.7	546.9	535	536
Kenya	45	45	45	127	167
Mexico	700	753	755	953	958
New Zealand	283.2	286	437	435	628
Nicaragua	35	70	70	77	88
Papua New Guinea	0	0	0	39	56
Philippines	891	1227	1909	1931	1904
Portugal	3	5	16	16	29
Russia	11	11	23	79	82
Thailand	0.3	0.3	0.3	0.3	0.3
Turkey	20.6	20.4	20.4	20.4	82
USA	2774.6	2816.7	2228	2544	3093
Total	5831.7	6866.8	7974.1	9064.1	10716.7

Table 1. Installed geothermal electric generating capacity worldwide from 1995 to 2000 in five-year intervals[16]

Country	1990-2010 (increase in MW_e)	Increase(%)
Iceland	530.4	1189.24
Portugal	26	866.67

Country	1990-2010 (increase in MW_e)	Increase(%)
Indonesia	1052.2	726.66
Russia	71	645.45
Turkey	61.4	298.06
France	11.8	280.95
Kenya	122	271.11
Nicaragua	53	151.43
Japan	321.4	149.77
New Zealand	344.8	121.75
El Salvador	109	114.74
Philippines	1013	113.69
Italy	298	54.68
Mexico	258	36.86
China	4.8	25
USA	318.4	11.48
Thailand	0.3	0
Costa Rica	166	--
Papua New Guinea	56	--
Guatemala	52	--
Ethiopia	7.3	--
Germany	6.6	--
Austria	1.4	--
Australia	1.1	--
Argentina	-0.7	n/a
Total	4885	83.77

Table 2. Development of generating geothermal power from 1990 to 2010

Indonesia is a "volcano country". It owns 40% of the world's geothermal energy reserves [17]. According to the latest data released by the Indonesian Ministry of Energy and Mineral Resources, the potential installed capacity of geothermal power generation in the country is as much as 27,140 MW, equivalent to the power generated by 12 billion barrels of petroleum, twice the oil deposit of Indonesia and about 40% of the total reserves of geothermal resources in the world [18]. Indonesia ranks third in the world in terms of geothermal energy consumption, after the US and the Philippines. At present, the geothermal power generation capacity of Indonesia is 1,197 MW. It is also the third biggest emitter of greenhouse gases and aims to cut emissions by 16% by 2025 [15].

11.5% of the territory of Iceland is covered by modern glaciers. However, within the range of 103,000 km^2, it has at least 200 volcanoes formed in the last million years, including about 30 active volcanoes [19]. It has ample geothermal resources and more than 800 thermal fields. Called the "*Land of Ice and Fire*" it is one of the countries among a few with many thermal fields. The distribution of other thermal fields is closely related to the locations of volcanoes. In the volcanic zone running diagonally through the whole island from southwest to northeast, there are 26 high-temperature steam fields, about 250 low-temperature geothermal fields and more than 800 natural hot springs [19]. Within the range of the 0~10 km thick crust, the total amount of geothermal resources is 300 million TWh (1TWh is equivalent to 100 million kWh of electricity); within the range of the 0~3 km thick crust, the total amount is 30 million TWh; and the amount of geothermal resources technically exploitable is one million TWh [19]. Through long-term exploitation and utilization, Iceland has developed efficient geothermal utilization techniques and become the only country in the world almost non-dependent on petroleum. Heating and electric power both rely on natural geothermal energy [20].With a small population, the country is currently generating 100% of its power from renewable sources, deriving 25% of its electricity and 90% of its heating from geothermal resources [17]. Of course, the long-term exploitation and utilization of geothermal energy has also had some negative impacts on geothermal resources e.g., continual descent of the water level in some geothermal systems, temperature and chemical component changes because of the injection of cold water [21]. To address these impacts, Iceland has taken many measures, for example, according to Iceland's environmental law, any geothermal exploitation with a gross amount of above 25 MWe or a net amount of above 10 MWe must submit a detailed environmental impact assessment report [20]. This attitude of attaching importance both to resource exploitation and utilization, and to their conservation and future development is commendable.

New Zealand lies on the suture line between the southwestern margin of the Pacific Plate and the Indo-Australian Plate. This suture line extends from the sea southeast of North Island to the northwest of South Island and then goes further to the south along the western edge of South Island (see Figure 6). The Pacific Plate to its east subducts into the crust of North Island and forms the Taupo Volcanic Zone (see Figure 6), which is the home of the main active volcanoes and geothermal fields in New Zealand. Among the exploited geothermal fields, there are Wairakei, Broadlands, Rotokawa, Kawerau, Ohaaki and Mokai (see Figure 7). Wairakei Geothermal Power Station was the world's first geothermal power station which generates power from wet steam and also is the world's second largest geothermal power station, behind only Italian Larderello Geothermal Power Station [23]. This geothermal field is located in the central volcanic zone on North Island, New Zealand, and about 16 km to the northeast of Taupo Lake. It is the largest geothermal field in New Zealand. Wairakei Geothermal Power Station was developed in 1950 and started power generation in 1958. Now it has more than 100 gas wells, including 60 wells for power generation, with a total installed capacity of about 180 MW and annual power generation of 1501 GW h [23]. The "wet" steam extruded from the gas wells contains 80% water. Its temperature may reach 300℃ at most. During power generation, white water vapour spurts out of the well mouth continuously up to the sky and turns into clouds shortly after. Against the blue sky and over the green pines it looks majestic (Figure 8).

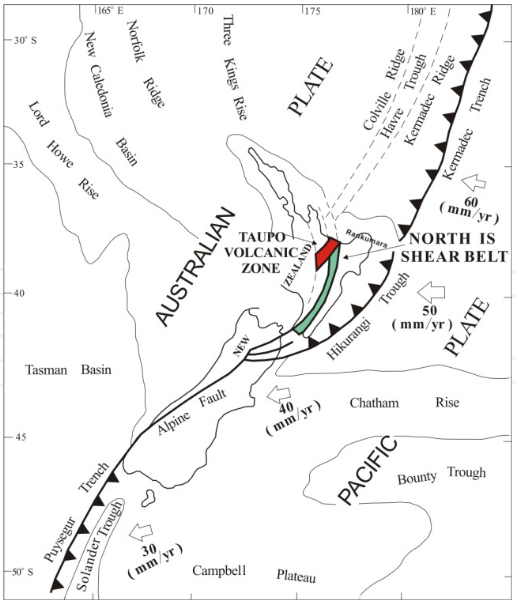

Figure 6. Location of Pacific-Australian plate boundary and Taupo Volcanic Zone[22]

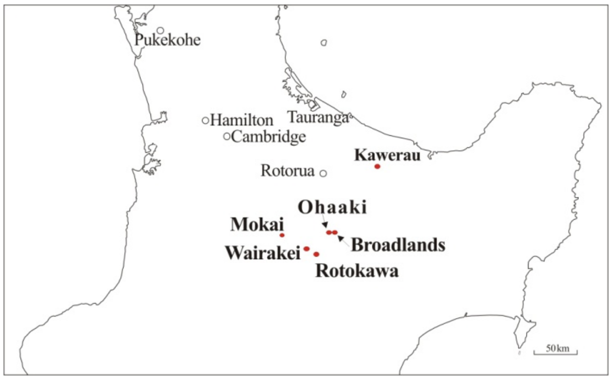

Figure 7. Location of the Wairakei Geothermal Power Station in the Taupo Volcanic Zone, New Zealand

Figure 8. Steam pipelines towards the Wairakei Geothermal Power Station [24]

3. Hot springs and mineral springs

3.1. Hot springs

A hot spring is a kind of spring belonging to ground water. It is called a hot spring if the temperature of the spring pouring out of the Earth's surface is higher than that of the local ground water. If the temperature of the spring is lower than that of the local ground water, it is called a cold spring. Hot springs are a display of geothermal energy.

A hot spring can be created in many ways; generally it is created by the ground water percolation cycling system effect. The average geothermal gradient of the Earth's near-suface is 3 degrees Celsius per 100 metres, the atmosphere penetrates into the underground, becomes aquifer and absorb heat from the deep underground rocks. The heated water can produce steam as well as the air included in the water expanding, that increases the pressure of the water-containing system, and then it pours out at the surface along cracks and gaps to become the hot spring.

Most hot springs are located in volcanic areas and are closely related to volcanic activities. No matter if the volcanoes are erupting or dormant (even extinct ones, under which magma pockets existing or magma activities always exist), lots of heat energy is accumulated, which heats the surrounding ground water and make it pour out as hot springs.

During the storing and moving process, due to the interaction of water and rocks, the hot spring includes many chemical components. Because of the different features of these components, the medical effects are also different.

For example [25], when people have a bath in hot spring containing carbonic acid gas, i.e., carbon dioxide gas, carbonic acid gas will adhere to the skin in bubbles and form a carbonic acid gas film which will keep exchanging with new small bubbles leading to a warm and cosy feeling. They also can stimulate the blood capillaries to expand and promote blood circulation. The carbon dioxide gas breathed into the lungs can strengthen gas metabolism and help balance acid-base organism.

Bicarbonate hot springs can soften and clean skin. People will feel smooth and cool after the bath. As the calcium in the spring can slightly dry the skin out, it is also a good medical treatment for trauma, chronic eczema and ulcers.

When people take a bath in a hot spring including hydrothion, sodium sulphide will be formed on the skin, which can stimulate the skin's blood circulation and nutrition metabolism, promote softer skin and dissolve cutin, reduce inflammation and increase immunity; it also can adjust blood pressure in two ways - improve the insufficiencies of coronary arteries. However, hydrothion is a poisonous gas; excessive hydrothion can lead to neurotoxicity, from headaches to dizziness to respiratory paralysis. Therefore, be aware when bathing in hydrothion hot springs.

Sulphate hot springs can be used for a bath and the water can be drunk; as a bath, the water stimulation from salt to skin can lead to the expansion of blood capillaries and promote the body's metabolism, it can also assist in the treatment of some skin diseases. Drinking sodium sulphate and magnesium sulphate in hot spring waters can promote the secretion and excretion of bile, clean the stagnancy of bile and prevent calculus forming, so it can act as a medical treatment for cholecystitis and gall-stones; drinking calcium sulphate hot spring water can help purine supersession and promote excretion of uric acid, so it can act as a medical treatment for gout and urethra inflammation.

A chloride hot spring is called a "nerve painkiller" as the excitement of the nerve can be reduced when bathing in chloride springs - a good medical treatment for neuralgia. The osmotic pressure of a chloride hot spring with medium concentration (content is above 5g/l) is close to a salt solution, therefore bathing in a hot spring of 36~38 degrees Celsius will help to treat trauma, haemorrhoids and skin diseases; chloride hot springs with a high concentration will help to promote the constitution, to recover the function of the ligament arthroclisis, muscle atrophy and dyskinesia.

Drinking from a hot spring with silicate (metasilicate) can help to adjust the metabolism and promote gastrointestinal motility and strength digestion; when bathing, silicate will adhere to the skin, clean the skin and skin mucosa.

In addition, hot springs with radon, arsenic, bromine, iodine and other microelements also have medically positive effects for humans.

There are hot springs on all continents and in many countries around the world. We list some of the famous hot springs with medical value around the world – see Table 3 and Figure 9.

Country	Hot Spring
USA	Glenwood Springs
Chile	Chihuío
Ecuador	Baños de San Vicente
China	Tengchong Hot Spring Zone Taiwai (Beitou Hot Spring, Yangmingshan Hot Spring)
Indonesia	Maribaya Hot Spring
Japan	Kusatsu Onsen, Arima Onsen, Gero Onsen
Iceland	Blue Lagoon Spring, Geysir Hot Springs
Italy	Bormio, Sondrio Province, Lombardy (geothermal spa)
New Zealand	Rotorua Volcanic Hot Spring

Table 3. Some famous hot springs with medical value around the world

3.2. Mineral springs

Mineral springs are springs with lots of mineral substances. They may be hot, defined by Mazor as having a temperature of >6 degrees Celsius above that of the mean annual surface temper-

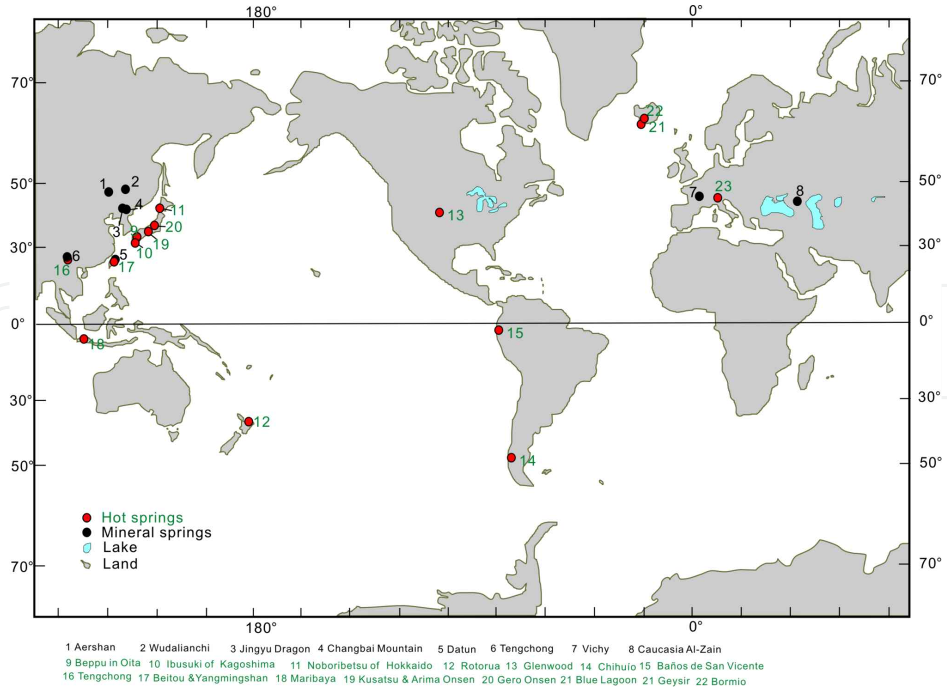

Figure 9. Location of famous hot springs and mineral springs around the world

ature, or cold [26]. Different stipulations had been set up by different organizations. The element content standards of the mineral spring water which has been adopted by the Codex Alimentarius Commission in 1993 can be seen in Table 4 [27]. But according to the stipulations of the International Mineral Spring Association, in natural water, if one or more microelements and mineral substances needed for humans, such as lithium, strontium, zinc, copper, barium, cadmium, selenium, arsenic, manganese, antimony, nickel, bromide, iodide, metasilicate, free carbon dioxide, etc. reaches the standard required, it can be called "mineral springs" [28]. The French Vichy spring contains four, the Russian Caucasia Al-Zain spring contains two and the Chinese Wudalianchi mineral spring contains more than six (Figure 9). However, the Russian Caucasia Al-Zain spring is created by the melting of Mount Elbrus' glaciers, while the French Vichy and Wudalianchi springs are closely related to volcanoes.

The French Vichy Mineral Spring was formed by a volcanic eruption and can be found at 103 locations. At present, only 15 mineral spring wells have been exploited and utilized. As none of the mineral springs is an artesian spring, the extraction is not easy and wells must be dug. In the downtown of Vichy there is a mineral spring called Célestins. It is the only mineral spring for daily drinking.

In China, Wudalianchi Yaoquan (Figure 10) (literally "Medicated Spring") Mountain in Heilongjiang province, the Aershan Wuli Spring in Inner Mongolia and the Jingyu Dragon Spring in Jilin province are all high-quality volcanic mineral springs (Figure 9). In Wudalianchi Yaoquan Mountain, the mineral water contains multiple desired elements and components such as carbonic acid, iron, zinc, strontium, lithium and germanium. The water features large reserves, is high quality and has medical value. It has an obvious curative effect on stomach disease, skin disease and arthritis. The mud there may be used for pelotherapy and many sanatoriums have been built there. The former wasteland around the area has become an emerging modern city - Wudalianchi today. It is probably the only city established by relying on volcanic resources and it has become a famous geopark.

Zn	Cu	Ba	Cd	Cr_{Total}	Pb	Hg	Se	As_{Total}	Mn	Sulphide	Sb	Ni
-	-	0.7	0.003	0.05	0.01	-	-	0.01	0.5	-	0.05	0.02

Table 4. The elements content standards of the mineral spring water [27]

3.3. Mineral spring culture

The historic culture of mineral springs can be traced back to two thousand years BC. In ancient Greek stories, the goddess who can cure human diseases lives in mineral springs, which made people desperate to attain the waters [29]. In the ancient Rome era third century AD, the development and utilization of mineral springs took shape, it is said that there were more than 860 mineral spring bathing places in the city of Rome.

After the 18th century, people began to study mineral spring as a science. In 1742, a German doctor called Hoffmann confirmed some components of mineral springs based on a predecessor's research, which laid a foundation for the development of mineral spring science [29].

The 20th century saw the development of theoretical research and applied research, and a specialized agency was founded in developed countries like Japan, France, Germany and the US to develop the research and train talent, even putting crenology on required courses of advanced medical schools.

Each country of the world has its own mineral spring historical cultural expression, especially Japan which is called the country of hot springs - thousands of hot springs and mineral springs are located across the Japanese islands. Every family has bathing equipment and it seems that Japanese people like to bathe in hot springs the most. Hot spring bathing can not only reduce tiredness, cure disease and strengthen the body, it can also be a place to communicate with fellow bathers.

Volcanoes have caused natural disasters in Japan, but have also created abundant hot spring resources across the country. Among the 2,200 natural hot springs, the most favoured hot springs are located in Oita, Kagoshima and Hokkaido with different features [29].

Beppu Hot Spring in Oita (Figure 9) has been known about in Japanese since ancient times, there are more than 3,800 spring water holes and the water inflow is more than 200 thousand tons every day [29]. Known as the city of spring, it is the biggest natural hot spring area in Japan and also a world-class hot spring city. Sand Steam Hot Spring (Figure 9) in Ibusuki, Kagoshima, attracts more women (Figure 10). It is the only sand steam hot spring in Japan. To "*sand steam*" is to bury the body except the head in hot sand, termed "*sand happiness*". It is similar to having a sauna to make you sweat - in less than five minutes your body will feel hot. The sand pressure and hot water promote blood circulation, sweating from the whole body and tiredness to reduce, which is a fantastic medical treatment for preventing rheumatism and nerve ache. There is "sodium" in the sand which makes skin fair, so it is favoured by women for cosmetic reasons. In Noboribetsu, Hokkaido (Figure 9), the hot spring has another fun aspect – the spring, rock, flowers and grass form extremely pleasant scenery. Hot spring hotels are located along the main street, the bathroom in the Noboribetsu International View Club is especially well-known - with length of 90 m and width of 20 m there are more than ten hot spring pools of different sizes and temperatures to choose from, and men and women can bathe together.

Figure 10. Sand steam hot spring in Ibusuki, Kagoshima [30]

Hot springs in New Zealand are located across the country. Rotorua (Figure 9) sitting on volcanic-prone area is called the "*New Zealand Hot Spring City*" and is home to the largest hot spring waterfall in the southern hemisphere and the only mud bath pool in New Zealand - "*Wai Ora Spa*". The mud contains abundant mineral substances, which have health benefits. In addition, the unique Maori culture all combine to make this area a thriving tourist attraction.

In China, there are fewer present-day volcanic eruptions, but the hot springs and mineral springs related to volcanoes widespread and some volcanic areas, such as Wudalianchi in Heilongjiang, Changbai Mountain in Jilin, Aershan in Inner Mongolia, Tengchong in Yunnan and Datun in Taiwan, produce hot springs and mineral springs (Figure 9). Aershan in Inner Mongolia in particular contains hot and cold springs, and mineral springs [31, 32]. Hot springs in Tengchong are not only located widely and with numerous spring holes, but it is also well-known that they have a high temperature and water flow [33, 34].

4. Volcanic materials

Volcanic rocks forming volcanic edifices and surrounding volcanic ring plains consisting of volcanic ash, scoria, pumiceous deposits and the coherent volcanic rocks part of lava flows, lava domes or exposed subsurface facies of a core of a volcano such as dykes, sills, laccoliths are all good building materials widely used for construction such as paving and building

Figure 11. Landscape of Tengchong, China

houses. Scoria and the volcanic ash of basalt can be used directly as a filling in clinker-free cement to produce high-quality cement [35]; cast stone bricks, tiles and panels made of basalt are good fire-proof materials, which are not only heat-resistant, but also crush-resistant and corrosion-resistant, so much so that they are considered as a substitute for steel in machine tool and the chemical industry [36-38]. What attracts people's attention is basalt fibre, which takes basalt as the raw material. It has the advantage of good combination properties and cost effectiveness, and no poisonous substances, waste gas, waste water, residue or pollution in normal machining processes. It is applied widely in fire-fighting, environment protection, aviation, the arms industry, automobile and ship making, engineering plastics, the construction industry and the so-called "green industrial materials" of the 21st century. The classifications are continuous basalt fibre, thick fibre, narrow fibre, super-narrow fibre and subtle scale, among which the continuous basalt fibre has been previously studied and studies of the others are developing at present.

4.1. Development background of basalt fibre

In 1840, the trial production of rock wool with basalt as the primary raw material succeeded in Wales, UK [39]. In the early 1950s, Germany, the then Czechoslovakia, Poland and Hungary produced basalt wool with an average fibre diameter of 25 μm~30μm from basalt using the centrifugal method [40]. In the early 1960s, the USA, the former Soviet Union and Germany vigorously developed a vertical blowing production process, resulting in the rapid growth of basalt wool output. The former Soviet Union introduced a German patent for producing mineral wool using the vertical blowing method. On the basis of digestion and absorption, it succeeded in applying this technology to the production of basalt wool. The production capacity is 38~40 tons of basalt wool a day [41].

Basalt fibre was successfully developed by the Russian Moscow Glass and Plastic Research Institute in 1953~1954. The first furnace for industrial production was built and put into operation in the Ukraine Fibre Laboratory (TZI) in 1985. The fibre-drawing process of a 200-hole bushing and combination furnace was adopted with an annual output of 260 t [40]. Then, they adopted a 400-hole tank furnace fibre-drawing process to produce CBF and its products. The annual output is about 700 t. In recent years, China, Japan, South Korea and Germany have also carried out relevant research and achieved some new research results [41]. At present, the USA, Germany, China, Japan and South Korea are also carrying out relevant research and are achieving some new research results [41].

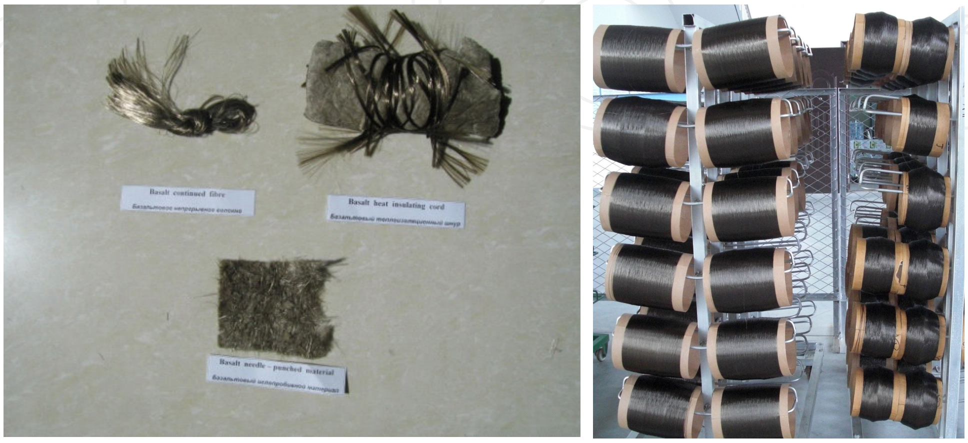

Figure 12. Basalt fibre

4.2. Properties and use of basalt fibre

Compared with glass fibre, rock wool, asbestos and chemical fibre, basalt fibre and its products have extraordinary performance and have multiple application capabilities (Table 5):

1. Good thermal property and flame retardant property: basalt fibre is amorphous state inorganic silicate substance, with good temperature-resistance and heat insulation and without thermal contraction [42]. The temperature range of its usage is -269~700 degrees Celsius, the softening point is 60 degrees Celsius, which is much higher than that of glass fibre - 60~ 450 degrees Celsius and carbon fibre - 500 degrees Celsius. Under a temperature of 500 degrees Celsius, its stability of thermal shock resistance is unchanged. Initial mass fraction loss is less than 0.02 and it is 0.03 under 900 degrees Celsius. Under a temperature of 600 degrees Celsius, its breaking strength can still keep as 80% as the original intensity, and it will not shrink under 860 degrees Celsius while mineral wool with good temperature-resistance can only keep 50%~60%. Carbon fibre will produce CO and CO_2 under 300 degrees Celsius [43], while glass fibre is crushed completely. Therefore, basalt fibre can be used for the manufacture of flame retarding materials such as fire-proof suits, blankets and curtains, and high-temperature filters such as scrim, material and high-temperature resistant felt. In addition, with regard to low-temperature resistance, the intensity of basalt fibre will not change under the medium of low-temperature (-196 degrees Celsius) liquid nitrogen. So it is an effective low-temperature heat insulation material [41].

2. Good chemical stability and corrosion resistance: basalt fibre maintains favourable chemical stability and powerful acid and alkali resistance. With natural consistency and

high stability in alkali medium such as cement, it can be used as the enhancement material for concrete building structures to replace rebar. Flake coating made of basalt can offer protection to building and objects under water, including warships, to strengthen the capacity and life of corrosion prevention.

3. Good stretch ability and modulus of elasticity: the density of CBF is 2.65~3.00g/cm3 and its hardness is very high, Mohs hardness scale 5~9, so it has excellent wear resistance and tensile reinforcement [43]. The tensile strength of CBF is 3800~4800 MPa, higher than that of large-tow carbon fibre, aramid fibre, PBI fibre, steel fibre, boron fibre and aluminium oxide fibre, and equivalent to S glass fibre. The strength of basalt fibre may be maintained for 1200 h in 70 degrees Celsius water, while ordinary glass fibre will lose its strength at 200 h. At 100~250 degrees Celsius, the tensile strength of basalt fibre may be increased by 30%, while the tensile strength of ordinary glass fibre will decrease by 23% [41]. Therefore, basalt fibre material has a huge advantage in bridge building as well as in sport material usage such as fishing rods, hockey sticks, antennae, skis, umbrella handles, poles, bows and arrows, and crossbows [43].

Meanwhile, basalt fibre keeps high modulus of elasticity: 9100 kg/mm2 ~11000 kg/mm2, higher than that of alkali-free glass fibre, asbestos, aramid fibre, PP fibre and silicon fibre, and close to that of expensive S glass fibre. It may replace S glass fibre in the making of heat insulating products and composite materials, for example, hard armour and GFRP products [40, 41].

4. Low coefficient of heat conduction, good heat-proof quality: the conductivity factor of basalt fibre is 0.031 W/m•K~0.038 W/m•K, lower than that of aramid fibre, aluminium silicate fibre, alkali-free glass fibre, rock wool, silicon fibre, carbon fibre and stainless steel [40]. It may be used for heat preservation of heat treatment equipment, heat insulation of automobiles and ships, and heat preservation of pipelines.

5. High acoustical absorption coefficient and good stealth performance: the acoustic absorption factor of CBF is 0.9~0.99, higher than that of alkali-free glass fibre and silicon fibre. Basalt fibre has good wave permeability, certain wave absorbability, excellent acoustical absorption and insulation. In addition, it may be used as a stealth material [42].

6. High dielectric coefficient and good insulating property: the specific volume resistance of basalt fibre is 1x1012Ω•m, much higher than that of alkali-free glass fibre and silicon fibre. By relying on its good dielectric performance, low hydroscopicity and good temperature resistance, basalt fibre may be made into high-quality PCB and blades [40]. After basalt fibre is treated with a special impregnating compound, its dielectric loss angle tangent is 50% lower than that of ordinary glass fibre, and it may be used to produce new-type heat-resistant dielectric materials [41].

7. Low hygroscopicity and good seepage-proof and anti-crack property: the hygroscopicity of basalt fibre is below 0.1%, lower than that of aramid fibre, rock wool and asbestos [40]. Compared to glass fibre, the hydroscopicity of basalt fibre is 6~8 times lower [44]. It has strong seepage control and crack resistance, and may be widely used in expressways, runways, port terminals, hydroelectric engineering buildings and other infrastructure fields.

Properties	Performance	Basalt fibre	E-glass fibre	S-glass fibre	Carbon fibre-HS	Aramid fibre 1313
Physical properties	Density/g·m^{-3}	2.65-3.00	2.55-2.62	2.46-2.49	1.78	1.44
	Tensile strength/MPa	3000-4840	3100-3800	4590-4830	3100-5000	2758-3034
	Elasticity modulus/GPa	79.3-93.1	76-78	88-91	230-240	124-131
	Elongation after fracture/%	3.15	4.70	5.60	1.20	230
	Conductivity factor /w·(m·kg)$^{-1}$	0.031-0.038	0.034-0.04	0.036-0.04	5-185	Low
	Volume resistivity /Ω·m	1×10^{12}	1×10^{11}	1×10^{11}	2×10^{-5}	"/>1×10^{11}
	Acoustic absorption factor	0.9-0.99	0.8-0.93	0.8-0.93	Small	Small
Chemical properties	Softening point	960	850	1056	—	—
	Maximum operating temp/℃	700	380	300	2000	250
	Chemical resistance	Acid and alkali resistance	Moderate resistance to alkalis	Moderate resistance to alkalis	No effect	Moderate resistance to acids
	Price/yuan·kg^{-1}	38	17	20	300	200

Table 5. Comparison of the performance of the basalt fibre with other fibres [43]

The features of basalt decide the wide usage of basalt fibre, not only for aviation, the arms industry, fire-fighting, traffic, energy, environment protection and construction industry, but also espionage, communication and special materials under thermal shock. With abundant basalt resources, its future in industrial production and marketing promotion is bright.

5. Gemstones and other mineral resources

Many gemstones are related to or result from volcanic processes and therefore they are hosted in volcanic deposits and rocks. Gemstones in volcanic rocks include sapphire and ruby, and sometimes adamas can also be found; garnet, pyroxene and olivine with good crystals and bright colours can be found in basalt, which can be used directly as gemstones. Obsidian itself erupted from a volcano can be high quality pure volcanic glass with gem-quality. Crystal, agate and aragonite produced by volcano action are all valuable gemstones. Besides gemstones, many metal and non-metal minerals are related to volcano action, such as gold, silver, copper, lead, zinc and sulphur and diatomite.

5.1. Diamonds

Diamonds are commonly hosted in kimberlite pipes that are commonly looked upon as a specific type of maar diatreme volcano (Figure 13). Kimberlite is a type of potassic volcanic rock best known for sometimes containing diamonds. It is named after the town of Kimberley in South Africa, where the discovery of an 83.5 carat (16.7 g) diamond in 1871 spawned a diamond rush, eventually creating the Big Hole [45].

Diamonds form at a depth greater than 93 miles (150 kilometres) beneath the Earth's surface. After their formation, diamonds are carried to the surface of the Earth by volcanic activity. As this molten mixture of magma (molten rock), minerals, rock fragments and diamonds approaches the Earth's surface it begins to form an underground structure (pipe) that is shaped like a champagne flute. These pipes can lie directly underneath shallow lakes formed in the active volcanic calderas or craters [46].

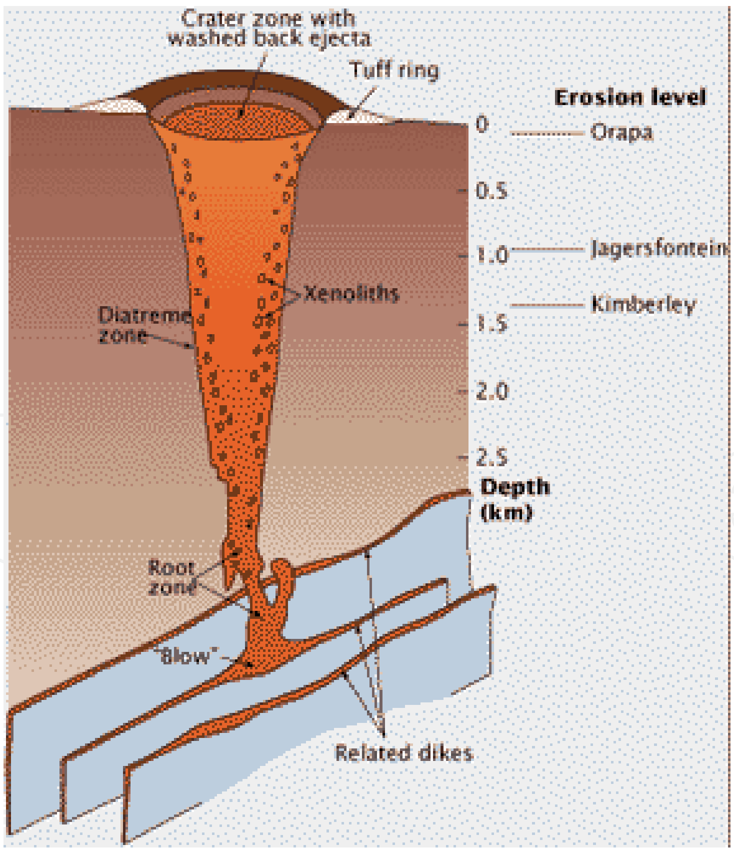

Figure 13. Kimberlite pipe [47]

Kimberlite occurs in the Earth's crust in vertical structures known as kimberlite pipes. According to the descriptions of Volker Lorenz [48], "the formations of maars and diatremes suggest a specific process. Magma rises along a fissure and contacts ground - or surface-derived water. The resulting phreatomagmatic eruptions give rise to base surge and air-fall deposits consisting of juvenile and wall-rock material. Spalling of the wall-rocks enlarges the fissure into an embryonic vent. At a critical diameter of the vent large-scale spalling at depth and slumping near the surface gives rise to a ring-fault of large diameter and subsidence of the enclosed wall-rocks and overlying pyroclastic debris. This subsidence leads to a maar crater at the surface. Various features of kimberlite diatremes seem to be consistent with this model. They extend into fissures along which hot kimberlite magma rise. The diatremes, however, indicate emplacement by a cool gas phase, probably steam. Indicators for subsidence along ring-faults may be diatremes with large diameter, slickenside on walls, saucer-shaped structures, subsided "floating reefs", concentration of xenoliths from specific horizons within certain areas, and zoning of diatreme rocks. It is suggested that formation of kimberlite diatremes may have been influenced by non-juvenile water." For example, the Premier kimberlite pipe and Jagersfontein kimberlite pipe in South Africa, and the Mwadui kimberlite pipe in Tanzania are all famous diamond mines around the world.

Lamproite pipes produce diamonds to a lesser extent than kimberlite pipes. Lamproite pipes are created in a similar manner to kimberlite pipes, except that boiling water and volatile compounds contained in the magma act corrosively on the overlying rock, resulting in a broader cone of eviscerated rock at the surface. This results in a martini-glass shaped diamondiferous deposit as opposed to kimberlite's champagne flute shape [46].

The Argyle diamond mine in Western Australia is one of the first commercial open-cast diamond mines that is dug along an olivine lamproite pipe. The Argyle pipe is a diatreme, or breccia-filled volcanic pipe that is formed by gas or volatile explosive magma which has breached the surface to form a "tuff" cone [46].

The complex volcanic magmas that solidify into kimberlite and lamproite are not the source of diamonds, only the elevators that bring them with other minerals and mantle rocks to the Earth's surface. Although rising from much greater depths than other magmas, these pipes and volcanic cones are relatively small and rare, but they erupt in extraordinary supersonic explosions [49].

Kimberlite and lamproite are similar mixtures of rock material. Their important constituents include fragments of rock from the Earth's mantle, large crystals and the crystallized magma that glues the mixture together. The magmas are very rich in magnesium and volatile compounds such as water and carbon dioxide. As the volatiles dissolved in the magma change to gas near the Earth's surface, explosive eruptions create the characteristic carrot- or bowl-shaped pipes [49].

Diamonds also can be formed by subduction (Figure14). When the ocean floor slides under the mantle, the basaltic rock becomes eclogite, and organic carbon in sediments may become diamonds [49].

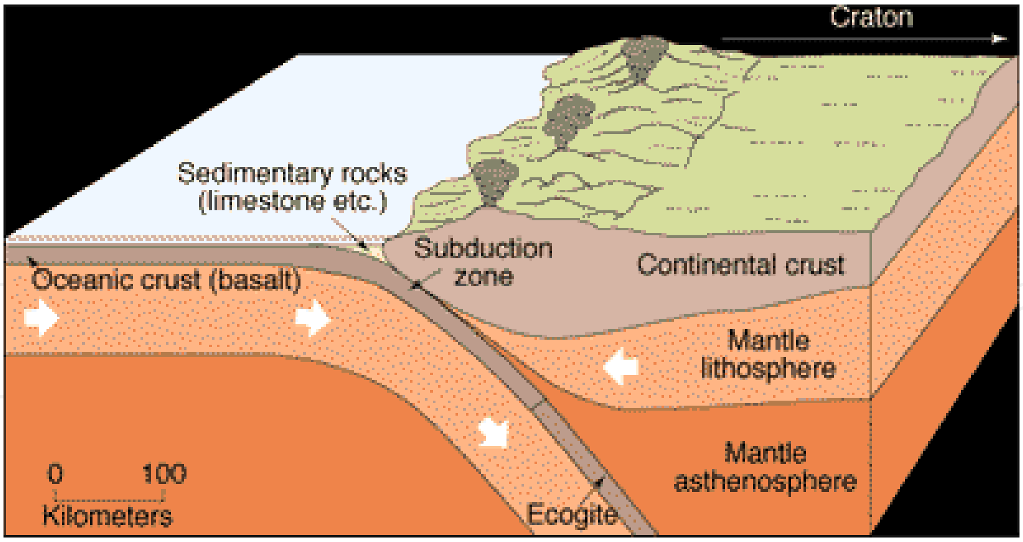

Figure 14. Diamonds can be formed by subduction [50]

5.2. Sapphires

Sapphires are commonly hosted in dykes, volcanic necks and lava flows which are composed by alkali basalts. Many sapphires have been found in Changle of Shandong, Liuhe of Jiangsu and Muling of Heilongjiang in China. Sapphires are also formed in basalts in Kanchanaburi and Banca in Thailand, Pailin in Cambodia and Anaky in Australia [51].

5.3. Garnets

Garnets are a group of silicate minerals that have been used since the Bronze Age as gemstones and abrasives. Garnets possess similar physical properties and crystal forms but different chemical compositions. The different species are pyrope, almandine, spessartine, grossular (varieties of which are hessonite or cinnamon-stone and tsavorite), uvarovite and andradite [52].In these species, only the pyrop has a relationship with the volcanic activities. They are mainly produced in kimberlite, basalt and mantle xenoliths. A famous pyrop, Bohemian garnet in the Czech Republic, is known to be associated with maar diatreme volcanoes of the Czech Republic.

In the abyssal lherzolite inclusions of the basalts, there are olivine, pyroxene, garnet, spinel and other minerals which have fine crystals and bright colours. They have been widely used as gems. This type of inclusion can be easily found in the countries which have volcanoes [51].

5.4. Opal and others

Australia is the opal capital of the world. Opals are often host in fractures, voids and primary stomata of the volcanic rocks (basalts, andesites, rhyolites and tuffs). Besides Australia, opals have been found in the Czech Republic, Mexico, Honduras and other countries. The compositions and formations of the agate and chalcedony are similar to opal, but their distributions are much wider than opal. A lot of agates and chalcedonies have been produced in India, China, Brazil, the United States, Russia, Madagascar, Ireland, Namibia and Egypt [51].

Opal, agate and chalcedony are semi-precious stones that come under the category of quartz. These stones are characterized by fine granular texture and bright colours. They are processed and marketed in different shapes and sizes [53].

Gems with a variety of colours and textures can be formed by the aragonites that fill in the stomata of the basalts and andesites. The basalt of the Penghu Islands in China is rich in this precious gem. This type of gem has been produced in Spain, Italy, Austria, Chile, the United States and other countries [51].

5.5. Obsidian

Obsidian is a naturally occurring volcanic glass formed as an extrusive igneous rock. It is produced when felsic lava extruded from a volcano cools rapidly with minimum crystal growth. Obsidian is commonly found within the margins of rhyolitic lava flows known as obsidian flows, where the chemical composition (high silica content) induces a high viscosity and polymerization degree of the lava. Obsidian can be found in locations which have experienced rhyolitic eruptions. It can be found in Argentina, Armenia, Azerbaijan, Canada, Chile, Greece, El Salvador, Guatemala, Iceland, Italy, Japan, Kenya, Mexico, New Zealand, Peru, Scotland and the United States [54]. Anatolian sources of obsidian are known to have been the material used in the Levant in modern-day Iraqi Kurdistan from a time beginning sometime about 12,500 BC [55]. In Ubaid in the 5th millennium BC, blades were manufactured from obsidian mined in what is now Turkey [56]. Now obsidian has been used for blades in surgery. Obsidian is also used for ornamental purposes and as a gemstone. It possesses the property of presenting a different appearance according to the manner in which it is cut: when cut in one direction it is jet black, in another it is glistening grey. Plinths for audio turntables have been made of obsidian since the 1970s [54].

5.6. Gold deposit

Gold deposits attract the constant attention of every country around the world. People have found that the formation of gold deposits has a close relationship with volcanic activities in terms of time and space. Hu et al. studied the classification of gold deposits relevant to volcano, sub-volcano, intrusion and hydrotermalism. He introduced classification methods of gold deposits according to the volcanic internal ore-controlling structures [57]: 1) gold deposits from bedrock, such as the super large gold bearing porphyry copper deposits in Bingham in the United States and Chuquicamata in Chile; 2) gold deposits from the contact zone between bedrock and volcanic caprock, such as the gold ore in Tuanjiegou, Heilongjiang, China; 3) gold deposits from the volcanic edifice of the caprock of volcanic rock series, such as Conrad in Kazakhstan; 4) gold deposits from hot spring accumulation near volcanic craters, such as Round Mountain in Nevada, California, the United States.

Jiang et al. [58] undertook an in-depth study on volcanism and gold deposits, and claimed that volcanism is one of the optimal geologic conditions for the formation of gold deposits. They classified gold deposits into three categories [58]. The first category is volcanic sediment deposits in tensioned structures which were formed by submarine volcanism. The second category is plutonic volcanic gold deposits formed due to plate activities and collisions during the orogenic and post-orogenic period. They are classified into three sub-categories: 1) gold deposits in intrusive rocks or contact zones including the vein deposits in intrusive rocks and porphyric gold deposits, e.g., Barrick (gold reserves: ~420t), Lihir Island (gold reserves: ~500t) and other huge sub-volcanic porphyry gold deposits in Papua New Guinea, which were formed along with the intrusive magmatism in the Cenozoic island-arc volcanic rock zone subducted by the Western Pacific Plate; 2) gold deposits from continental volcanic rocks; they are mainly developed in the Circum-Pacific Island Arc and related to Middle Cenozoic volcanic activities; 3) metasomatism and filling gold deposits related to plutonic volcanic magmatism, e.g., the Carlin type gold deposits in Nevada, the United States [58] and the Munmtau gold deposit belt in Uzbekistan [59]. The third category is the placer gold deposits formed due to weathering and sedimentation under hypergene conditions.

5.7. Diatomite

Diatomite is a naturally occurring, soft, siliceous sedimentary rock that is easily crumbled into a fine white to off-white powder. It has a particle size ranging from less than 1 micrometre to more than 1 millimetre, but typically 10 to 200 micrometres. Diatomite is formed by the accumulation of the amorphous silica (opal, $SiO_2\,nH_2O$) remains of dead diatoms (microscopic single-celled algae) in lacustrine or marine sediments [60]. So diatomite can be found in exposed maar crater lakes. Where there are maar crater lakes, there are diatomite (e.g., Germany, China, Hungary, Slovakia and so on). It is used as a filtration aid, mild abrasive, mechanical insecticide, absorbent for liquids, matting agent for coatings, reinforcing filler in plastics and rubber, anti-block in plastic films, porous support for chemical catalysts, cat litter, an activator in blood clotting studies and a stabilizing component of dynamite. As it is heat-resistant, it can also be used as a thermal insulator [60].

Most of these deposits are related to calc-alkali volcanic rock, mainly andesite. Some of these deposits are replacement and vein deposits. Stratiform lead and zinc deposits are found at Nong Phai and Song Thoin Kanchanaburi in middle Ordovician limestone. The zinc deposits at Pha Daeng, Mae Sot is the largest zinc deposit in Thailand. The ore are zinc carbonate and zinc silicate in the supergene enrichment in the Jurassic Kamawkala limestone near the Thai-Myanmar border.

6. Volcanic landscapes

Volcanoes are nature's sculptors, making numerous beautiful scenic spots and natural landscapes, which are not only tourist attractions but also ideal places for scientific research. Many famous landscapes and tourist attraction are also volcanic areas, and all of them are colourful and charming. Many of the world's geoparks and natural heritage sites are related to volcanoes.

Heritage is our legacy from the past, what we live with today, and what we pass on to future generations. The United Nations Educational, Scientific and Cultural Organization (UNESCO) seeks to encourage the identification, protection and preservation of cultural and natural heritage around the world considered to be of outstanding value to humanity. This is embodied in an international treaty called the Convention concerning the Protection of the World Cultural and Natural Heritage, adopted by UNESCO in 1972 [61]. The World Heritage List includes 936 sites forming part of the cultural and natural heritage which the World Heritage Committee considers as having outstanding universal value [61].These include 725 cultural, 183 natural and 28 mixed properties in 153 states. Some of them are closely related to volcanic activities and the unique geological landscape and ecological systems in these places illustrate the charm of volcanic activities for humans.

A geopark is defined by UNESCO in its International Network of Geoparks' program as "a territory encompassing one or more sites of scientific importance, not only for geological reasons but also by virtue of its archaeological, ecological or cultural value" [62]. A global geopark is a unified area with geological heritage of international significance and where that heritage is being used to promote the sustainable development of the local communities that live there [63]. The key heritage sites within a geopark should be protected under local, regional or national legislation as appropriate.

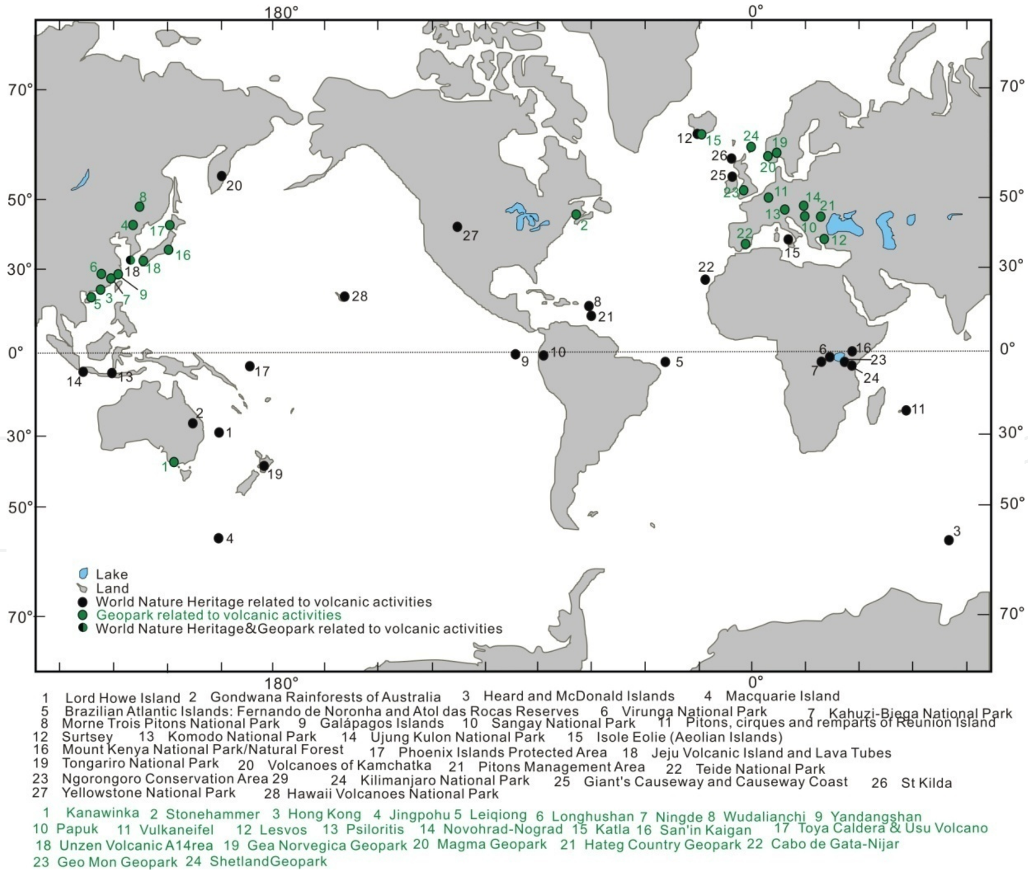

Figure 15. Location of the world nature heritage sites and geoparks which are related to volcanic activities

We will now introduce some typical heritage sites and geoparks which are associated with volcanic activities (Table 6, Table 7).

Country	World Nature Heritage Sites	
Australia	Lord Howe Island Group	Located in the South Pacific, 700 km north-east of Sydney, the property is included administratively in New South Wales. Lord Howe Island is the eroded remnant of a large shield volcano which erupted from the sea floor intermittently for about 500,000 years in the late Miocene (6.5-7 million years ago). The entire island group has remarkable volcanic exposures not known elsewhere.
	Gondwana Rainforests of Australia	The outstanding geological features displayed around shield volcanic craters and the high numbers of rare and threatened rainforest species are of international significance for science and conservation.
	Heard and McDonald Islands	Located in the Southern Ocean, approximately 1,700 km from the Antarctic continent and 4,100 km south-west of Perth. As the only volcanically active sub-Antarctic islands they 'open a window into the Earth', thus providing the opportunity to observe ongoing geomorphic processes and glacial dynamics.
	Macquarie Island	Macquarie Island is an oceanic island in the Southern Ocean, lying 1,500 km south-east of Tasmania and approximately halfway between Australia and the Antarctic continent. It is the only island in the world composed entirely of oceanic crust and rocks from the Earth's mantle deep below the surface.
Brazil	Brazilian Atlantic Islands: Fernando de Noronha and Atol das Rocas Reserves	The Fernando de Noronha Archipelago and Rocas Atoll represent the peaks of a large submarine mountain system of volcanic origin, which rises from the ocean floor some 4,000 m in depth. The Fernando de Noronha volcano is estimated to be between 1.8 million and 12.3 million years old.
Democratic Republic of the Congo	Virunga National Park	Virunga National Park is notable for its chain of active volcanoes and the greatest diversity of habitats of any park in Africa. Features include hot springs in the Rwindi plains and the Virunga Massif volcanoes, such as Nyamulagira (3,068 m) and Nyiragongo (3,470 m), are still active, which alone account for two-fifths of the historical volcanic eruptions on the African continent. They are especially notable because of their highly fluid alkaline lavas. The activity of Nyiragongo is globally significant for its demonstration of lava lake volcanism, with a quasi-permanent lava lake at the bottom of its crater, periodic draining of which has been catastrophic to the local communities.
	Kahuzi-Biega National Park	A vast area of primary tropical forest dominated by two spectacular extinct volcanoes, Kahuzi and Biega, the park has a diverse and abundant fauna.

Country	World Nature Heritage Sites	
Dominica	Morne Trois Pitons National Park	Luxuriant natural tropical forest blends with scenic volcanic features of great scientific interest in this national park centred on the 1,342-m-high volcano known as Morne Trois Pitons. With its precipitous slopes and deeply incised valleys, 50 fumaroles, hot springs, three freshwater lakes, a 'boiling lake' and five volcanoes, located on the park's nearly 7,000 ha.
Ecuador	Galápagos Islands	The islands were formed by volcanic processes and most represent the summit of a volcano, some of which rise over 3,000 m from the Pacific floor. Ongoing seismic and volcanic activities reflect the processes that formed the islands. The larger islands typically comprise one or more gently sloping shield volcano, culminating in collapsed craters or calderas. Other noteworthy landscape features include crater lakes, fumaroles, lava tubes, sulphur fields and a great variety of lava and other ejects such as pumice, ash and tuff.
	Sangay National Park	The site is situated in the Cordillera Oriental region of the Andes in central Ecuador. The park is dominated by three volcanoes, Tungurahua (5,016 m) and El Altar (5,139 m) to the north-west and Sangay (5,230 m) in the central section of the park.
France	Pitons, cirques and remparts of Reunion Island	The Pitons, cirques and remparts of Reunion Island site covers more than 100,000 ha or 40 % of La Réunion, an island comprising two adjoining volcanic massifs located in the south-west of the Indian Ocean. Dominated by two towering volcanic peaks, massive walls and three cliff-rimmed cirques, the property includes a great variety of rugged terrain and impressive escarpments, forested gorges and basins creating a visually striking landscape.
Iceland	Surtsey	Surtsey is a new island formed by volcanic eruptions in 1963-1967. It has been legally protected from its birth and provides the world with a pristine natural laboratory. There is a recent tendency to promote Surtsey Island as a geopark.
Indonesia	Komodo National Park	The generally steep and rugged topography reflects the position of the national park within the active volcanic 'shatter belt' between Australia and the Sunda shelf. These volcanic islands are inhabited by a population of around 5,700 giant lizards, whose appearance and aggressive behaviour have led to them being called 'Komodo dragons'. They exist nowhere else in the world.
	Ujung Kulon National Park	This national park, located in the extreme south-western tip of Java on the Sunda shelf, includes the Ujung Kulon peninsula and several offshore islands and encompasses the natural reserve of Krakatoa. In addition to its natural beauty and geological interest – particularly for the study of inland volcanoes – it contains the largest remaining area of lowland rainforests in the Java plain.

Country	World Nature Heritage Sites	
Italy	Isole Eolie (Aeolian Islands)	The Aeolian Islands provide an outstanding record of volcanic island-building and destruction, and ongoing volcanic phenomena. Studied since at least the 18th century, the islands have provided the science of vulcanology with examples of two types of eruption (Vulcanian and Strombolian).
Kenya	Mount Kenya National Park/Natural Forest	At 5,199 m, Mount Kenya is the second-highest peak in Africa. It is an ancient extinct volcano, during whose period of activity (3.1-2.6 million years ago) it is thought to have risen to 6,500 m.
Kiribati	Phoenix Islands Protected Area	The Phoenix Island Protected Area (PIPA) is a 408,250 sq.km expanse of marine and terrestrial habitats in the Southern Pacific Ocean. PIPA conserves one of the world's largest intact oceanic coral archipelago ecosystems, together with 14 known underwater sea mounts (presumed to be extinct volcanoes) and other deep-sea habitats.
Korea, Republic of	Jeju Volcanic Island and Lava Tubes	Jeju Volcanic Island and Lava Tubes together comprise three sites that make up 18,846 ha. It includes Geomunoreum, regarded as the finest lava tube system of caves anywhere, with its multicoloured carbonate roofs and floors, and dark-coloured lava walls; the fortress-like Seongsan Ilchulbong tuff cone, rising out of the ocean, a dramatic landscape; and Mount Halla, the highest in Korea, with its waterfalls, multi-shaped rock formations, and lake-filled crater.
New Zealand	Tongariro National Park	Tongariro National Park is situated on the central North Island volcanic plateau. The park's volcanoes, which are outstanding scenic features of the island, contain a complete range of volcanic features. The mountains at the heart of the park have cultural and religious significance for the Maori people and symbolize the spiritual links between this community and its environment.
Russian Federation	Volcanoes of Kamchatka	This is one of the most outstanding volcanic regions in the world, with a high density of active volcanoes, a variety of types, and a wide range of related features.
Saint Lucia	Pitons Management Area	Dominating the mountainous landscape of St Lucia are the Pitons, two steep-sided volcanic spires rising side by side from the sea. The Pitons are part of a volcanic complex, known to geologists as the Soufriere Volcanic Centre which is the remnant of one (or more) huge collapsed stratovolcano. The Pitons occur with a variety of other volcanic features including cumulo-domes, explosion craters, pyroclastic deposits (pumice and ash) and lava flows
Spain	Teide National Park	Teide National Park, dominated by the 3,781 m Teide-Pico Viejo stratovolcano, represents a rich and diverse assemblage of volcanic features and landscapes concentrated in a spectacular setting. Mount Teide is a striking volcanic landscape dominated by the jagged Las

Country		World Nature Heritage Sites
		Cañadas escarpment and a central volcano that makes Tenerife the third tallest volcanic structure in the world. Teide National Park is an exceptional example of a relatively old, slow moving, geologically complex and mature volcanic system.
Tanzania, United Republic of	Ngorongoro Conservation Area	The Ngorongoro Conservation Area spans vast expanses of highland plains, savannah, savannah woodlands and forests. It includes the spectacular Ngorongoro Crater, the world's largest caldera. Ngorongoro Crater is one of the largest inactive unbroken calderas in the world which is unflooded. It has a mean diameter of 16-19 km, a crater floor of 26,400 ha, and a rim soaring to 400-610 m above the crater floor. The formation of the crater and other highlands are associated with the massive rifting which occurred to the west of the Gregory Rift Valley.
	Kilimanjaro National Park	Mount Kilimanjaro is one of the largest volcanoes in the world. It has three main volcanic peaks, Kibo, Mawenzi and Shira. With its snow-capped peak and glaciers, it is the highest mountain in Africa.
United Kingdom of Great Britain and Northern Ireland	Giant's Causeway and Causeway Coast	The Giant's Causeway lies at the foot of the basalt cliffs along the sea coast on the edge of the Antrim plateau in Northern Ireland. It is made up of some 40,000 massive black basalt columns sticking out of the sea. The Causeway Coast has an unparalleled display of geological formations representing volcanic activity during the early Tertiary period some 50-60 million years ago. The most characteristic and unique feature of the site is the exposure of a large number of regular polygonal columns of basalt in perfect horizontal sections forming a pavement. Tertiary lavas of the Antrim Plateau, covering some 3,800 km^2, represent the largest remaining lava plateau in Europe. The coastline is composed of a series of bays and headlands consisting of resistant lavas. The average height of the cliffs is 100 m, and has a stepped appearance due to the succession of five or six lava flows through geological time.
	St Kilda	This volcanic archipelago, with its spectacular landscapes, is situated off the coast of the Hebrides and comprises the islands of Hirta, Dun, Soay and Boreray. It has some of the highest cliffs in Europe, which have large colonies of rare and endangered species of birds, especially puffins and gannets.
United States of America	Yellowstone National Park	Yellowstone National Park, established in 1872, covers 9,000 km2 of a vast natural forest of the southern Rocky Mountains in the North American west. The park has a globally unparalleled assemblage of surficial geothermal activity, thousands of hot springs, mudpots and fumaroles, and more than half of the world's active geysers. The world's largest recognized caldera (45km by 75km – 27 miles by 45 miles) is contained within the park. It boasts an impressive array of geothermal phenomena,

Country		**World Nature Heritage Sites**
		with more than 3,000 geysers, lava formations, fumaroles, hot springs and waterfalls, lakes and canyons. The park is part of the most seismically active region of the Rocky Mountains, a volcanic 'hot spot'. The latest eruptive cycle formed a caldera 45 km wide and 75 km long, when the active magma chambers erupted and collapsed. The crystallizing magma is the source of heat for hydrothermal features such as geysers, hot springs, mud pots and fumaroles.
	Hawaii Volcanoes National Park	Lies in the south-east part of the island of Hawaii (Big Island), the easternmost island of the State of Hawaii, and includes the summit and south-east slope of Mauna Loa and the summit and south-western, southern, and south-eastern slopes of the Kilauea Volcano. Mauna Loa and Kilauea are two of the world's most active and accessible volcanoes where ongoing geological processes are easily observed. This property serves as an excellent example of island building through volcanic processes. It represents the most recent activity in the continuing process of the geologic origin and change of the Hawaiian Archipelago.

Table 6. World nature heritage sites which are related to volcanic activities [61]

Country		Geopark
Australia	Kanawinka Geopark	The Kanawinka Geopark is located in south-eastern Australia. The area covers 26,910 square kilometres, seven local government areas with 58 protected geosites within Australia's most extensive volcanic province. The surface geology of Kanawinka is a striking contrast of sweeping plains and spectacular cones which are largely the product of volcanic activity. The Blue Lake is one of the most significant volcanic sites within the Kanawinka Global Geopark. Mount Elephant is considered as "one of the highest and one of the major scoria cones in the largest homogenous volcanic plains on earth". The Geopark displays geological history and the nature of volcanoes in the region.
Canada	Stonehammer Geopark	Stonehammer Geopark is located in Southern New Brunswick on the East Coast of Canada. The Geopark encompasses 2500 square kilometres and extends from Lepreau Falls to Norton and from the Fundy Trail to the Kingston Peninsula. The landscape of the Stonehammer Geopark has been created by the collision of continents, the closing and opening of oceans, volcanoes, earthquakes, ice ages and climate change. It shows a billion years of Earth's history.
China	Hong Kong Geopark	Situated in close proximity to Hong Kong's world-famous financial and business centre, Hong Kong Global Geopark of China is lauded as a unique "geopark in the city". Hong Kong Geopark's major geo-attractions include

Country		Geopark
		well-outcropped acidic volcanic hexagonal rock columns, of which the average diameter is 1.2 metres and which are distributed over a land-and-sea area of 100 square kilometres. The Geopark also has comprehensive sedimentary rock formations formed about 400 to 55 million years ago. In addition, It is integrated with diverse ecological resources and historical relics, all combining to form the unique natural landscape of Hong Kong Geopark.
China	Jingpohu Geopark	The Jingpohu Geopark is located in the upper-middle reaches of the Mudanjiang River, Northeast China's Heilongjiang Province. Jingpo lake covers an area of 79 square kilometres with a total water volume of 1.62 billion cubic meters. It is the largest lava barrier lake in China, and the second largest in the world. About 1 million years ago, Lava as a result of volcanic eruption blocked the river bed of the Mudanjiang River forming a lava dam. As a result, the incipient Jingpo Lake began to take shape. In the late Glacial Period, larger volcanic eruptions helped build a more voluminous lava dam. Hence the Jingpo Lake as we see it today. The granite rocks after experiencing various earth movements are in the shape of cliffs which are called a "geological corridor" by visitors. The Diaoshuilou Waterfall is the only large collapsed-lava waterfall of China which is also rarely seen in the world.
China	Leiqiong Geopark	Leiqiong Global Geopark is located in the southern margin of Chinese Mainland, straddling Qiongzhou Strait. More than 100 volcanoes are densely distributed across the Geopark. These include examples of nearly all volcanic types. Judging from the number, variety and completeness of the volcanoes, the park is considered topmost among the Quaternary volcanic belts of China. Two districts of Leiqiong Geopark feature several 'maar' craters – broad, low-relief craters caused by groundwater coming into contact with hot lava. The Geopark is extremely rich in volcanic landscapes and lava structures, such as different kinds of lava flows and tunnels. The territory of the park spans Haikou City and Zhanjiang City, which are famous cultural centres. Also, the Geopark is positioned in an ecological transition area characterized by a rich diversity of flora and fauna.
	Longhushan Geopark	Located in China's Jiangxi Province, Longhushan Geopark holds geological, geomorphological, human and natural ecological landscapes. The major landform in the park is the Danxia landform and others but minor are volcanic landforms.
	Ningde Geopark	Ningde Geopark is located in the southeastern part of the Eurasian Plate, belonging to the continental marginal active zone adjacent to the Pacific Ocean. Ningde Geopark is an integration of various landforms such as miarolite landform, volcanic landform, erosion riverbed landform, and

Country		Geopark
		erosion coastal landform. The occurrence of many landforms in a geopark suggests that the area has a complicated geological history. At the same time, the park landform landscape also has the very high ornamental value.
	Wudalianchi Geopark [66] (Figure 16)	Wudalianchi Geopark is located in the north central Heilongjiang Province, China. Wudalianchi World Geopark is such a precious legacy left by the volcanic actions in the Quaternary period. Fourteen young and old volcanoes, the world's top volcanic resources, stand in the 1,060 km^2 geopark, with their eruption ages ranging from 2.07 million years prehistory to 280 years before now. They are the world's best-conserved volcanic landforms with the most varieties and most typical forms. The 14 volcano cones that sprung from the ground add beauty to the mountains and rivers, composing a remarkable picture; the micro-topographic landscapes in various forms such as lava platform, lava sea, lava cascade, lava postern, lava stalactite, lava Vortex, trunk lava, flower-like lava, fumarolic cone and disc, lapilli and volcanic bomb are named "Natural Museum of Volcano" and "An Open Textbook on Volcano". The five connected lakes, like a string of beads, are formed by the latest volcanic magma filling the ancient Baihe valley, thus named Wudalianchi (five connected lakes). The mineral water here is renowned as "The World's Three Cold Springs" together with Vichy mineral water of France and Ciscaucasia mineral water of Russia.
	Yandangshan National Geopark	Yandangshan National Geopark is located in Zhejiang Province in China, which covers an area of 294.6 square kilometres. The Mount Yandang Shan is a natural park based on its geological landform of Cretaceous volcanic rhyolite. The geoheritage in the Park is referred to as a typical example of the formation and evolvement mode of reviviscent caldera on the edge of Asian Plates in late Mesozoic. From the Geoheritage, we can see the complete geo-evolving process of the eruption, subsiding and reviviscent apophysis of volcanoes. The Geoheritage provides a permanent sample for studying the volcanoes in Mesozoic.
Croatia	Papuk Geopark	Papuk Geopark is located in Slavonia, in eastern Croatia. Mount Papuk has a "stormy" geological history going as far back as the Precambrian with metamorphic rocks that date back as far as the Precambrian, more than 540 million years ago. More recent geological features result from mountain building with Mesozoic sediments 260 and 65 million years old, including carbonate rocks, mostly dolomites, as well as the Cretaceous volcanic sedimentary complex of Rupnica. The Rupnica geosite is famous due to a characteristic exposure of the columnar jointing developed in the albite rhyolite volcanic rock.

Country	Geopark	
Germany	Vulkaneifel Geopark	Located in the middle of Central Europe, at the northwestern part of the 'Rheinish Slate Mountains', the rolling Eifel highlands are a hilly landscape with deep, glacially carved valleys cut into old Devonian sediments (360-415 million years old). Volcanoes dot the landscape, with 350 known eruption centres, and give the area its name – Vulkaneifel. In some craters, bogs and lakes have formed while others remain dry. Known as 'maar' craters, these bodies reveal a nearly uninterrupted stack of sediments dating back to 150,000 years ago that provides data for the reconstruction of past climate, vegetation and ecology. Similarly, fossils found in 43 million years old sediments of Eckfeld Maar are of worldwide importance, since they contained an archetypal horse and the oldest known honey bee. The Vulkaneifel has attracted geo-scientists for 200 years and many international research projects have been conducted here.
Greece	Lesvos Petrified Forest Global Geopark	Located in the western part of the Greek island of Lesvos, north-east Aegean Sea, the Lesvos Petrified Forest Geopark features rare and impressive fossilised tree-trunks. Formed some 15 to 20 million years ago, due to intense volcanic activity, the trees were covered by lava, ashes and other materials that were spewed into the atmosphere. The Lesvos Petrified Forest Global Geopark brings visitors to an ancient forest preserved by a massive volcanic eruption 20 million years ago.
	Psiloritis Geopark	Psiloritis Monts rose up through the sea a few million years ago when the African continent encroached on Europe. Psiloritis Geopark is characterized by its superb geodiversity. This is reflected by a great variety of volcanic, sedimentary and metamorphic rocks aging from Permian to Pleistocene (300 to 1 million year ago), outstanding folds and faults, fascinating caves and deep gorges with rich biodiversity.
Hungary-Slovakia	Novohrad-Nograd	Novohrad-Nograd Geopark lies at the border of Hungary and Slovakia. Being transnational, the Geopark's name comes from the Slovak and Hungarian names of the very county, where the Novohrad - Nograd Geopark is located. The geology of the Geopark includes diverse past volcanic events and a geological history dating back the last 30 million years from the birth of the Pannonian basin. Within a small area, the Geopark contains a wide spectrum of volcanic sites of spectacular sights, and several landscape protection areas and other territories. The area is also recognized as an important centre for the Palóc ethnic group's folk art and living traditions. Recently people pay more attention to the Maar diatreme volcanism and Miocene andesite volcanism in the region.
Iceland	Katla Geopark	The Katla Geopark is named after the volcano Katla that has for centuries had great impact on Icelandic nature and people living in the area. Katla is one of the largest central volcanoes in Iceland, covered by the glacier Mýrdalsjökull. Katla Geopark is located in the southern part of Iceland. The

Country	Geopark	
		Geopark consists of three municipalities: Skaftárhreppur, furthest east; Mýrdalshreppur, in the middle; and Rangárþing eystra, in the west. The volcanic activity of Eyjafjallajökull, Katla, Grímsvötn, Lakagígar and Eldgjá and its widespread effect on the landscape in the area provide the geological basis for the Geopark. Apart from the ice-capped volcanoes and lava streams, sandur plains with their black beaches and rootless vents (pseudocraters) are prominent features in the landscape.
Japan	San'in Kaigan Geopark	The San'in Kaigan Geopark is located in the west of Japan and stretches from the eastern Kyogamisaki Cape, Kyoto to the western Hakuto Kaigan Coast, Tottori. The San'in Kaigan Geopark is home to a diversity of geological sites related to the formation of the Sea of Japan, including granite outcrops formed when Japan was part of the Asian continent (70 million years ago), as well as sedimentary and volcanic rocks accumulated when Japan rifted away from Asia (25 to 15 million years ago) to form the Sea of Japan, a geological process still on-going today. It also contains geographical features, such as ria type coasts, sand dunes, sandbars, volcanoes and valleys. Thanks to such diversity, the Geopark is home to rare plants like Pseudolysimachion ornatum and Ranunculus nipponicus, as well as Ciconia boyciana (Oriental White Storks) - a symbol of biodiversity.
Japan	Toya Caldera and Usu Volcano Global Geopark	The Toya Caldera and Usu Volcano Global Geopark is located in Hokkaido, northern Japan and displays a unique showcase of active volcanism on the Pacific Rim. This is a unique region which has a wealth of characteristic geological relics in a relatively compact area, from the 110,000-year-old Toya Caldera to the 20,000 to 10,000-year-old Nakajima domes and a strato-volcano Usu, as well as the recent history of eruptions. The recent eruptive stage of Usu volcano started in 1663, and repeated nine times, creating lava domes, such as "Showa-Shinzan" that was born in a wheat field during 1943-1945. There are also precious fauna and flora living in the conserved thick forest and abundant water resources.
	Unzen Volcanic Area Global Geopark	Unzen volcano gives us a lot of gifts: outstanding landscapes, hot springs, spring water, fertile agricultural soil, and so on. On the other hand, Unzen volcano erupts repeatedly and causes serious disasters. In 1792, about 15,000 people were killed by the tsunami derived from the strong earthquakes due to sector collapse of an old lava dome, one of the worst volcanic disasters in Japan. In 1991-1995, a part of lava dome at the summit of the mountain collapsed. The pyroclastic surges containing giant hot ash clouds took 44 lives. Many buildings, houses, and school were also completely burned or buried by the flows and many residents lost their property. The burned school building and destroyed houses of the last eruption have been preserved just as they were. Now, these facilities are

Country	Geopark	
		the main geosites of the Geopark and have been utilized widely for local disaster prevention educational programs in Japan. The theme of Unzen Volcanic Area Global Geopark is "the coexistence of an active volcano and human beings".
Korea	Jeju Geopark	See Table 6.
Norway	Gea Norvegica Geopark	Gea Norvegica Geopark is located in southeastern Norway, in the counties of Vestfold and Telemark. The story told in this geopark is a 1.5 billion year-long journey, from old mountain chains, the tropical sea, strange volcanoes, rifting of a continent and a glaciated surface -and how we all depend on this geological diversity and natural resources.
	Magma Geopark	Magma Geopark is situated in southwest Norway. The story began as early as 1.5 billion years ago when red-hot magma and sky-high mountains characterized the region. Through millions of years, glaciers helped to form today's characteristic landscape. Although the magma has cooled down and solidified and the mountains have been worn away, the area offers a glimpse into the roots of an ancient mountain chain. Here is a rock type called anorthosite that is more common on the moon than on Earth.
Romania	Hateg Country Geopark	The Hateg Country Geopark is located in the central part of Romania, in a very fertile region surrounded by mountains. The region is world famous for its dwarf dinosaurs from the end of Cretaceous, 65 million years ago. Also well documented at the Geopark are the volcanic rocks-tuffs, lavas and craters that mark eruptions that took place during the age of the dinosaurs.
Spain	Cabo de Gata-Nijar Global Geopark	The Geopark's geodiversity derives from ancient Miocene volcanic substrata emplaced between 16 and 8 million years ago. In fact, the Geopark represents the most extensive and complex calco-alcaline fossil volcanism in the Iberian Peninsula. Visitors can walk through an open air geological museum with lava flows, volcanic domes, calderas, columnar joints, and fossilized sand beaches with tropical fossil reefs. This semi-arid climate and poor soil supports a surprising richness of plant species which ranks among the most diverse in Europe.
United Kingdom	Geo Mon Geopark (Wales)	The beautiful Isle of Anglesey lies off the west coast of Wales, UK. The island is renowned for its diverse tectonic geology. Brilliantly coloured Precambrian (about 800 Ma) 'pillow' lavas (erupted on the deep ocean floor with a characteristic shape) and deep ocean sediments are exposed at the western end whilst on the north coast is the world type locality for melange containing blocks of limestone with 800 million year old fossils. The remarkable folds and faults of South Stack date from the Cambrian period (520 Ma). Carboniferous limestones deposited about 350 Ma,

Country		Geopark
		crowded with fossil coral and shells show how ancient ice ages, sea level changes and plate movements affected the world long ago.
	Shetland Geopark	This tiny windswept archipelago has played host to tropical seas, volcanoes, deserts, ice ages and ancient rivers. The islands can boast the best section through the flank of a volcano in the UK, the best exposure of one of Europe's major tectonic faults, and are one of the best places in the world to see a compact vertical section through ancient oceanic crust.

Table 7. Global Geoparks which are related to volcanic activities [64, 65]

Figure 16. Landscape of Wudalianchi, China

There are many other volcanic landscapes around the world besides the heritage sites and geoparks which have not been listed in Table 6 and Table 7. Take the Llancanello Volcanic Field in Argentina as an example, together with the nearby Payun Matru Field, there are at least 800 scoria cones and voluminous lava fields that cover an extensive area behind the Andean volcanic arc, six volcanoes show evidence of explosive eruptions involving magma-water interaction. Tuff rings and tuff cones can also be seen in this field. The diversity of volcanic landforms is so well-preserved that some people are promoting it as a geopark. Changbai Mountain volcano area (Figure 17) in northeast China is also a famous resort around the world. In Changbai Mountain, the forest is boundless, waterfalls are plentiful, the mountain peaks poke into the clouds and steamy hot springs flow along the canyons. Tianchi is embraced by a group of peaks. It is a paradise for scientific research because of rich biological resources, forest resources, mineral resources and typical volcanic geomorphologic landscape. We believe that all volcanic heritage sites should be protected under local, regional or national legislation as appropriate.

Figure 17. Landscape of Changbai Mountain, China

7. Conclusion

Volcanoes have provided us with material and spiritual wealth. The land resources enlarge our habitats; geothermal activity is a clean and regenerative energy source; hot springs and mineral springs are beneficial to our health; volcanic materials had become new and popular materials of the 21st century; gemstones and mineral resources are symbols of wealth; volcano landscapes provide us with an opportunity to experience the rich and extraordinary natural world of the volcanic zones. It is said that volcanoes have had a far-reaching impact upon our lives and participated in the progress of our society. So we should protect volcanic resources, exploit them reasonably and appreciate all the gifts which volcanoes give us.

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