

## ARTICLE

## Morphology of Khorgo Volcano Crater in the Khangai Mountains in Central Mongolia

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ARTICLE INFO: Received: 31 Jan, 2020; Accepted: 18 May, 2020

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**Abstract:** Cenozoic basalt, which is widespread in Mongolia, has been attracting the attention of Central Asian researchers since the beginning of the last century.

This study identified the geomorphological shape of the Khorgo volcano. The main purpose of the study is to determine the origin and morphological form of Khorgo volcano, a key representative of Cenozoic volcanism. In general, there are several types of morphological forms associated with lava overflow, and it is important to determine which types are the most common and also to establish a link between them. Geomorphological studies in this area have not been conducted in Mongolia. Spatial improvement and morphometric methods satellite imagery had identified Khorgo volcanic faults.

Khangai magmatism had thinned its crust to 45 km during the Tariat-Chuluut volcanic activity. It can be concluded that this was due to the thinning of the continental crust in the Khangai Mountains because of mantle plume. During this time, tectonic faults were formed, which had broken through the earth's crust. Part of this fault was formed in the vicinity of Khorgo Mountain from northwest to southeast, and lava flowed with the basic composition, which led to the formation of the current morphological form of Khorgo volcano. The lava flow was less than 45% silica and potassium-dominated, which blocked the Suman River valley and formed the present-day Terkhiin Tsagaan Lake. The morphometric analysis compared the morphology of a typical volcano, which showed that the mouth of the crater of the Khorgo volcano has a slope slanting about 45 degrees, it is about 100 meters in depth, with a diameter of about 500 meters. By comparing the basalt composition of the Khorgo volcano and its morphometric characteristics with other standard volcanoes, it has been determined that it is in the form of a lava dome.

**Keywords:** Basalt; Khorgo volcano; Fault; Lava dome; Geomorphological shape;

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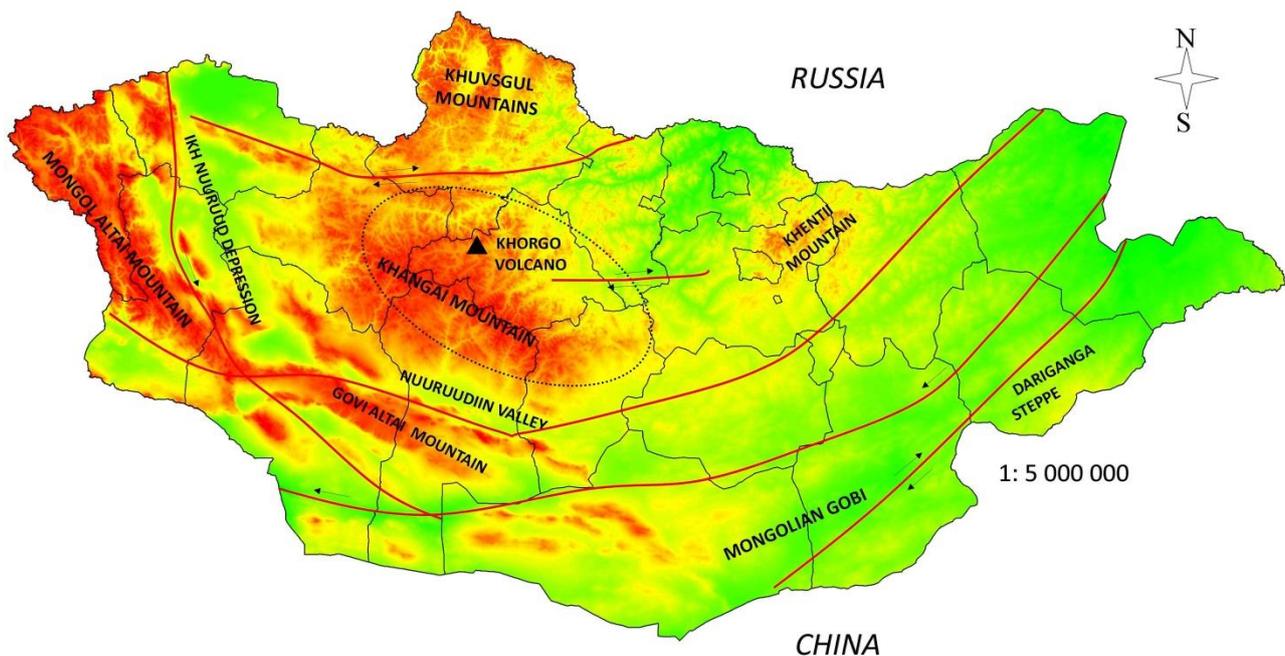
## INTRODUCTION

The Khangai Region in Central Mongolia is a mountainous area covering about 200,000 sq. km. with numerous peaks over 3,500 meters and is one of the important 'domed' structure within the basement blocks of Mongolia [1].

The Khangai region consists mainly of intensively deformed Carboniferous-Devonian and minor Permian-Triassic sedimentary rocks, which were deposited on basement blocks and intruded by huge bodies of granite and granodiorite plutons [2] appertaining to Late Paleozoic to Early Mesozoic periods. The geological interpretation of the isotopic data implies that blocks of the consolidated Precambrian crust were over thrustured onto younger crustal complexes of sea basins

between these blocks during the accretionary-collision formation [3] of the fold belts.

Numerous high potassium alkaline basaltic provinces of the Late Cenozoic Era, which are covered by unconsolidated Quaternary sediments, are distributed throughout the Khangai Region. Therefore, the stress from the India-Asian collision from the southwest (Altai transgressional belt) and Lake Baikal extensional structures from the north, are playing an important role in neotectonics faulting and perhaps Cenozoic magmatic activation in the Khangai dome [4-5]. There are a number of NE and NW-trending normal faults within the Khangai mountains region (Fig.1).



**Figure 1. The geographic location of Khorgo volcano in Central Mongolia. Simplified digital elevation map shows the position of major faults of Mongolia**

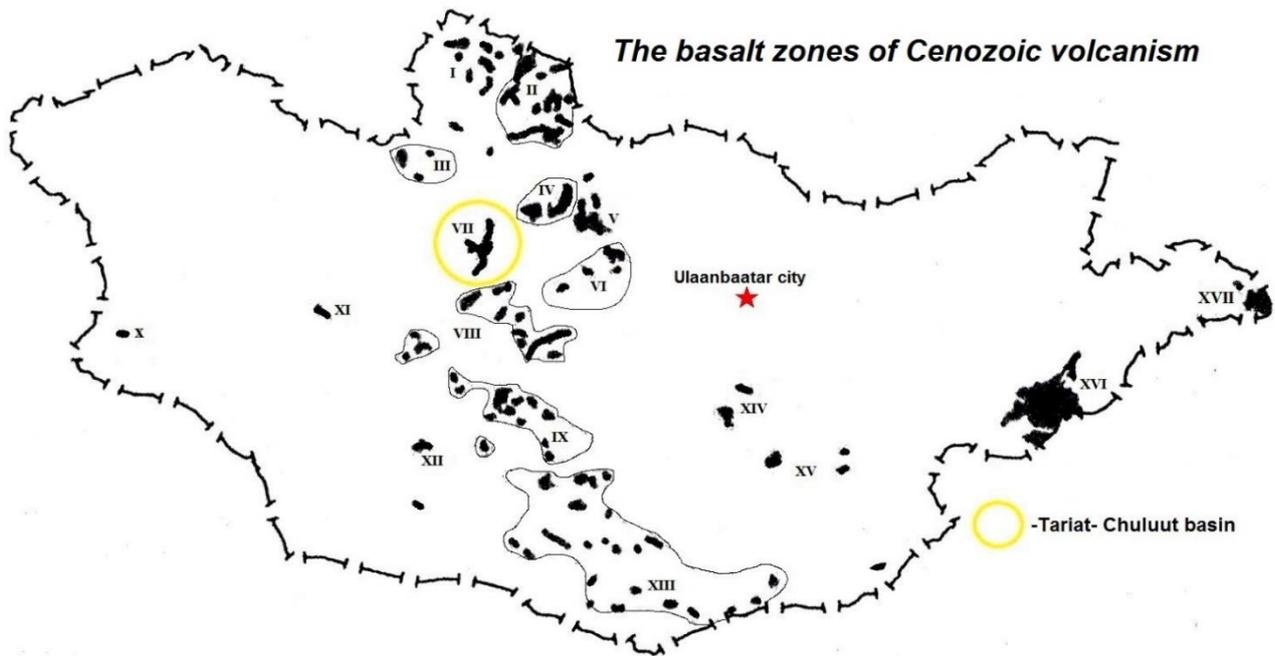
Khangai doming began in the middle Oligocene Era and was contemporary with alkaline volcanism throughout the Khangai Mountains. The total amount of surface uplift is about 3 km, with the most active phase of uplift between 3-4 Ma and the present day. The young, normal fault systems in the Khangai are perhaps a response to crustal uplift and doming

in the range. In addition, the faults with the clearest evidence for Holocene activity within the Khangai occur at relatively high elevations, suggesting that these areas are extending most actively [3]. This activity is related to the peculiar position of Mongolia, situated between the extensional structure of the Baikal rift system and the transgressional mountain belt of

Central Asia (the collision zone between India and Asia [6-7]).

*Late Cenozoic Volcanic fields in the Khangai Region.* Based on the geochronological study of volcanic basalt, 17

zones are distinct [8]. The Khangai Range includes basalt zone of the Khangai center, Tariat-Chuluut, Hanuin, Orkhon-Selenge and Ugii Nuur lakes. The Khorgo volcano is located in the Tariat-Chuluut zone (Fig. 2).



**Figure 2. The basalt zones of Cenozoic volcanism (Marinov, 1973; Genshaft and Saltykovskii, 1979; 2000)**

The Khangai mountain system is one of the largest elements of the Inner Asian mountain belt. Its Late Cenozoic history was marked by numerous volcanic eruptions, which produced morphologically different lava flows that resulted in the forming of several basaltic fields, such as Orkhon-Selenge, Tariat-Chuluut, Khanui and Ugii Nuur (Fig. 2).

Late Cenozoic volcanism occurred in the region as eruptions of highly mobile sub-alkaline basalt and basanite lavas, which spread over tens of kilometers as horizontal lava fields or extended valley flows. Based on existing geochronological data, several stages of volcanic activity with different structural positions and morphology of lava flows are

recognized during the last 10 Ma [9]. The Late Miocene–Pliocene stage (10–2 Ma) was characterized by several volcanic episodes [10–11]. They also occurred at the lower reaches of the Chuluut River near the eastern termination of the Tariat Graben and produced a large (24 Ч 15 km) lava plateau in this area [12]. The Pleistocene–Holocene stage (<1.25 Ma) is reflected in the development of valley lava flows or “lavarivers.”

*The Khorgo Volcano.* The Khorgo Lake volcano is a dormant volcano located on the eastern shore of Terkhiin Tsagaan Lake in the Tariat volcanic field (N48°11’11”, E99°51’25”, 2240 m a.s.l.) in Tariat soum in Arkhangai aimag (Province) of Mongolia.



**Figure 3. a. The Khorgo Volcano b. Crater of the Khorgo Volcano, Aerial photo by D. Davaadorj, 2019**

The crater walls are nearly vertical at the top (Fig. 3). A loose fan of pumice-like cinder is formed near the eastern and northeastern base of the cone with the inclusion of volcanic bombs as large as 1 m across. A lateral crater that has cut into the southwestern edge of the Khorgo volcanic cone is partially filled with lava. A few large bombs have rolled down into the lateral crater from the slope of the central

volcanic cone. Near the lateral crater is a lava dome, some of which has propagated onto the crater slope [13]. The central slope, the lateral crater, and the lava dome had a common feeding conduit striking north–northeast. The Khorgo lava flows are highly porous and have an irregular blocky surface produced by flowing volatile-rich lava breaking through and collapsing its top (Fig. 4a).



**Figure 4.a. Outcrop of the porous basalt b. Fresh basalt samples with numerous olivine phenocrysts and olivine bearing xenoliths from Khorgo Volcano**

The Khorgo lava flow has phonolithic tephrite to alkali basalt-basanite composition and contains olivine-bearing mantle xenoliths and metacysts of anorthoclase (Fig. 4b). The erupted Khorgo volcano lavas form a natural dam on the Suman River, causing the formation of the Terkhiin Tsagaan Lake.

There are several types of geomorphological forms associated with lava

overflow, hence the choice of Khorgo volcano is related to the fact that Khorgo volcano is a novel study that has never been done before in our country. The purpose of determining the geomorphological shape in relation to the origin of the volcano is to consolidate the theoretical results, to determine the line of lava overflow, to map the direction and consequences of the

lava flow, and to determine the geomorphological shape.

*The Terkhiin Tsagaan Lake.* The freshwater Terkhiin Tsagaan Lake is located near the Khorgo volcano (N48°10'15'', E99°43'20'', 2060 m a.s.l.) [14-15]. The area of the lake is 61.4 km<sup>2</sup>, with a length of 16 km, a maximum width of 4.5 km, an average depth of about 6 m and a maximum depth of 19.3 m [15]. Upon formation of the volcano, the valley of the Terkh River was dammed by lava flows [16-19]. The lake water outflows via the Suman River. The flow of basalt was pushed into Suman River which is believed to be the origin of the Terkhiin Tsagaan Lake. Studies conducted on the Terkhiin Tsagaan Lake sediments have dated organic matter overlying the lavas to between 8.7 and 7.7 Ka using C<sup>14</sup> techniques [20]. Also, the lacustrine sediments

of the Terkhiin Tsagaan Lake provide a record back to ca. 8780-year B.P. The basin is filled with approximately 3.5–6 m of lacustrine sediment [18]. A C14 isotopic survey of the essence taken from a depth of 6-10 meter of the lake indicates that it's age is approximately 7.0 Ka [21]. The bottom sediment of the Terkhiin Tsagaan Lake is composed of dark gray mass or fine laminated organic rich mud, in the upper part and medium level there are coarse grained sandy layers, and in the lower part are rare basalt pebbles. The thin gravel-sand layer separates these deposits from the underlying basalt lava bedrock. On the satellite image below (Fig. 5), lava flow from Khorgo volcano is marked as a yellow arrow, the area covered by lava is within the boundary marked in red, and the height result (Lava Plato) is shown as well.



**Figure 5.** Google earth map of basalt flow, which created the Terkhiin Tsagaan Lake by Terkh River's flow lava-dammed lake

**MATERIALS AND METHODS**

Geological and geomorphological features of the area. The results of previous studies of the Khorgo volcano, Tariat-Chuluut basin and Khangai magmatism were used and

the results were interpreted on the topographic maps of 1:100 000 scale and Satellite mapping (0.67m) using ArcGIS 10.3, ENVI 5.3 and other computer software.

**Morphometric method**

Tectonic movements cause linear deformation of the land surface [23]. This is the main sign of fault on the topographic map [7,

24-25]. The morphometric method was applied using topography mapping. For defining the fault of the Khorgo volcano, we used a topographic map of a scale of 1:100 000.

*Table 1. Criteria for morphometric analysis determination in the topographic map (Modified after Filosofov, 1967; Bold, 1987; Florinsky, 1996)*

No	Criteria of morphometric analysis	The Khorgo Volcano
1	Create close, straight linear structures between the topographic map isogips (Counter map).	+
2	High-altitude distortion occurs between contours of the topographic map, with repetitions following one straight line	+
3	Create a rectangular or kind of linear shape on any part of the surface	+
4	The formation of anomalies in the topographic map, the anomalies repeated along a single line	+

This symptom originated [26-28] on the east side of the Khorgo volcano. Based on the fault characteristics of Khorgo volcano, the faults was drawn on the topographic maps. The morphometric parameters of Khorgo volcano have shown many deviations and fault lines. Morphometric method, which is used for identifying tectonic fault on a scale at 1:100 000 on topographic maps, was used to identify the location of tectonic fault by making comparisons with satellite and aerial photo images.

**Spatial improvement method of Remote Sensing**

A Digital Globe Satellite map of 0.67 m resolution was obtained with remote sensing directional filter method and each pixel was changed by every other pixel in spatial development. In order to do so, it was required to choose various windows called a kernel. Those windows run along the image's row and

column and whenever it reaches a particular pixel, it defines the kernel's central value by using values of other pixels also contained in it. This is the instructive method to improve artificial and natural objectives by changing each pixel's radiometric values [29-30].

Sobel operator: When the weight at the central pixels, for both Prewitt templates, is doubled, it gives the famous Sobel edge-detection operator which, again, consists of two masks to determine the edge in vector form. The Sobel operator was the most popular edge-detection operator until the development of edge-detection technique with a theoretical basis. It proved to be popular in as much, on the overall, it gave a better performance than other contemporaneous edge-detection operators, such as the Prewitt operator [31].

The SOBEL function returns an approximation to the Sobel edge enhancement operator for satellite images,

$$G_{jk} = /G_x/ + /G_y/ \tag{1}$$

$$G_X = F_{j+1, k+1} + 2F_{j+1, k} + F_{j+1, k-1} - (F_{j-1, k+1} + 2F_{j-1, k} + F_{j-1, k-1}) \tag{2}$$

$$G_Y = F_{j-1, k-1} + 2F_{j, k-1} + F_{j+1, k-1} - (F_{j-1, k+1} + 2F_{j, k+1} + F_{j+1, k+1}) \tag{3}$$

Where (j, k) are the coordinates of each pixel  $F_{jk}$  in the satellite images.

This is equivalent to a convolution using the following masks:

$$\begin{matrix}
 & 1 & 2 & 1 & & -1 & 0 & 1 \\
 Y \text{ mask} = & 0 & 0 & 0 & X \text{ mask} = & -2 & 0 & 2 \\
 & -1 & -2 & -1 & & -1 & 0 & 1
 \end{matrix} \quad (4)$$

All of the edge points in the result are set to zero. We used the Image Analysis toolbox of ArcMap 10.3 versions for horizontal and vertical Sobel filter. In order to determine 4 directional line objects of satellite images, we calculated the summaries of both images (x and y directional images), which indicate line edges with the highest value as white.

The Khorgo volcano's fault was drawn by using Digital Globe satellite's high resolution

(0.67 m) space image and Convolution and Morphology menu's Directional Filter command of ENVI 5.3 Remote Sensing software. This process was completed by field measurements as well as identifying fault lengths and locations, and subsequently, the fault lines were mapped and validated through remote sensing methods.

## RESULTS AND DISCUSSION

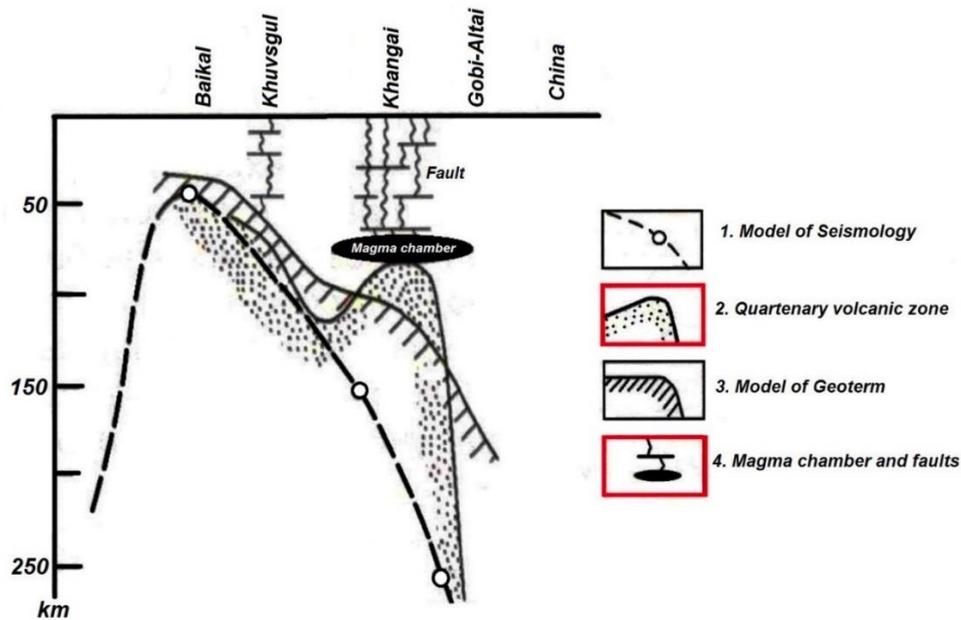
### Components of lava and origin of Khorgo volcano

There are following models of the origin of Cenozoic magmatism: 1. Mantle plume and hot spot [1-2]; 2. The mantle plume and hot spot situated between the extensional structure of the Baikal rift system [9, 32]; 3. Collision between India and Asia during the Oligocene Period and combined effect of second activation of mantle plume [12, 33]; 4. Kindle resulted in continent's plate collision [34].

There is not enough evidence regarding the Plateau of Mongolia, which has however gone through tremendous expansion, and most models link magmatism with plume. Although lesser expansions coincide with magmatism in some areas, the thin feature is not considered as a sufficient evidence as a reason for magmatism

[35]. According to Kepezhinskas (1979) the content of SiO<sub>2</sub> accounts for 45-50% of magmatism in the Khorgo volcano.

Some scientists agree on the tectonic origin of the Khorgo volcano. They measured the volcano of Tariat-Chuluut and the thickness of the basin crust was around 45 km during its active period [37-39]. Harris (2009), basing on his xenolith research, proved that Tariat's websterite with garnet and lherzolite with garnet, were formed under P=18-20 kbar pressure at T=1070-1090°C, and linked the Khangai dome and magmatism to inland's weakening due to deep mantle plume [40]. Genshaft and Saltykovsky (1979 & 2000) made the following depth structure model map [41-42] of Mongolian crust (Fig. 6).

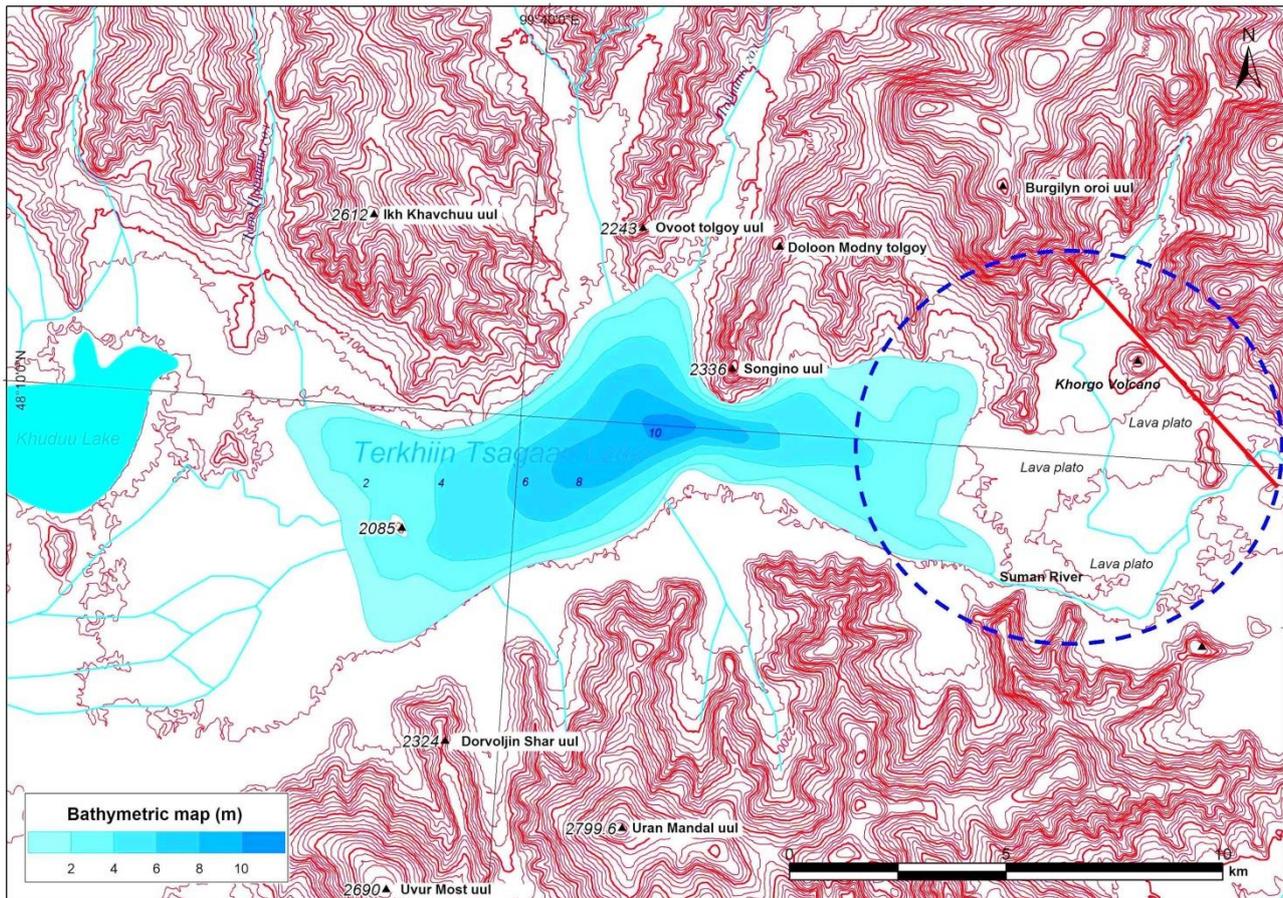


**Figure 6. Structure of the deep crust in Mongolia (Genshaft and Saltykovsky, 1979; 2000)**

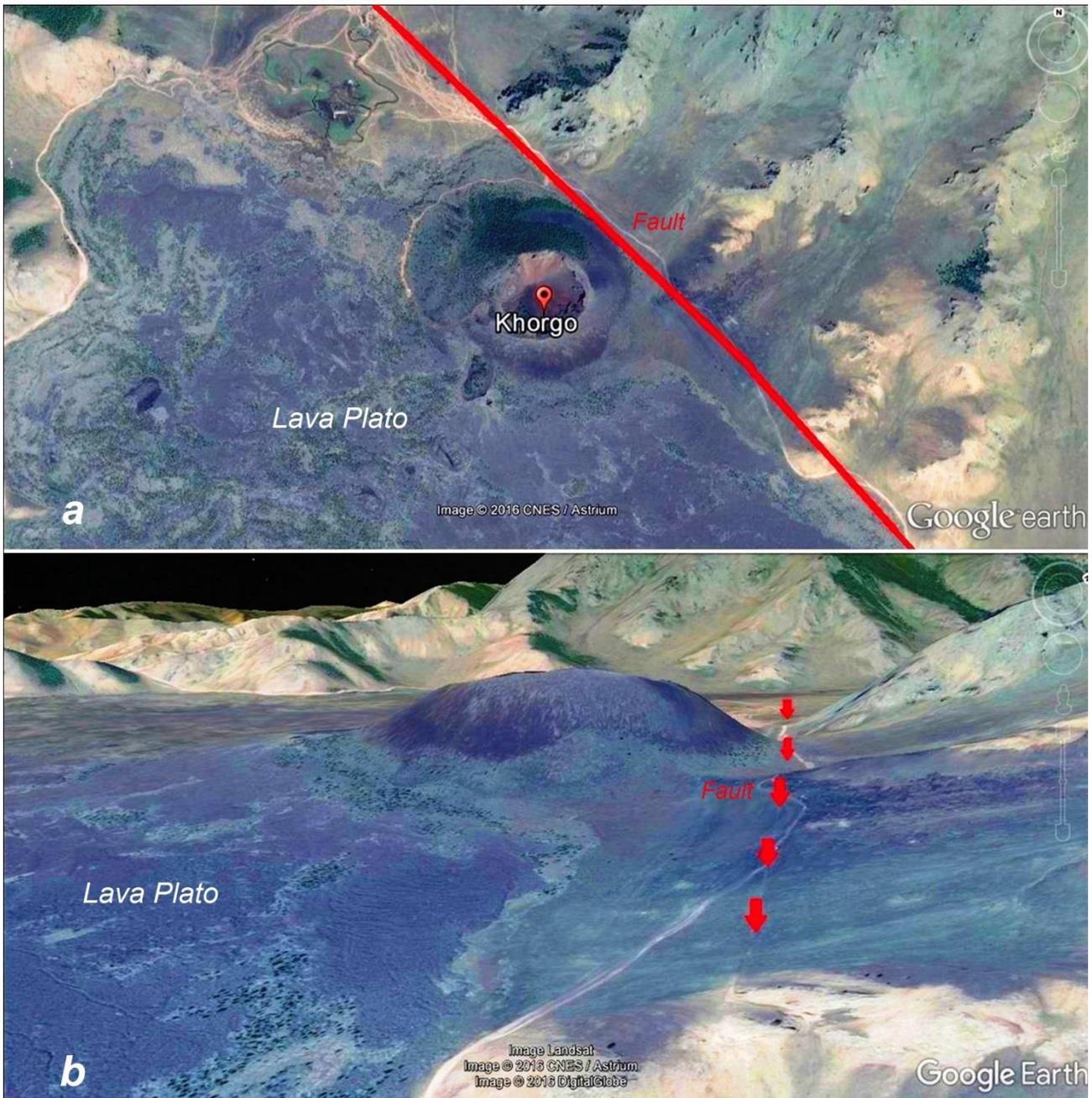
The Khentii elevation is at 80 km, and the Dariganga area is 110 km [43, 45]. On the Khangai elevation level, there are several hot flows and also water springs that follow the Khangai ridge, for example [36]. According to the study and the deep crust structure, Khangai ridge's thin crusts are one of the biggest reasons for Quaternary Era volcano's overflow following the fault line. Zhelubovsky (1945) had maintained that the Tariat-Chuluut basin active volcano in volcanic area has a structure of lava flowing along the fault line [44].

Deep fault is marked as earth surface's morphologic elements and various magma stones [6-7, 45].

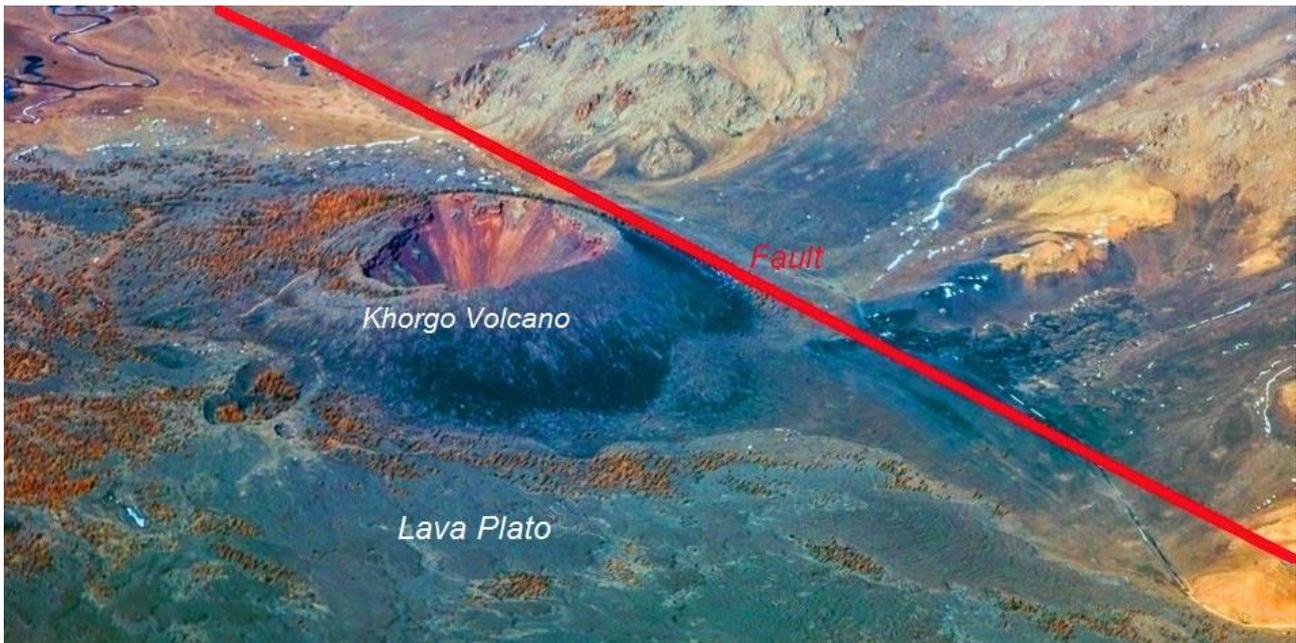
The location of volcanic craters near Khorgo volcano almost in one line proves the existence of tectonic fault [46]. Faults would occur in the Khorgo volcano topographic map because they formed abrupt changes on the surface. Considering the comparative topographic maps of fault, lava base overflowed from north western to south eastern along the northeast behind the Khorgo volcano (Fig. 7).



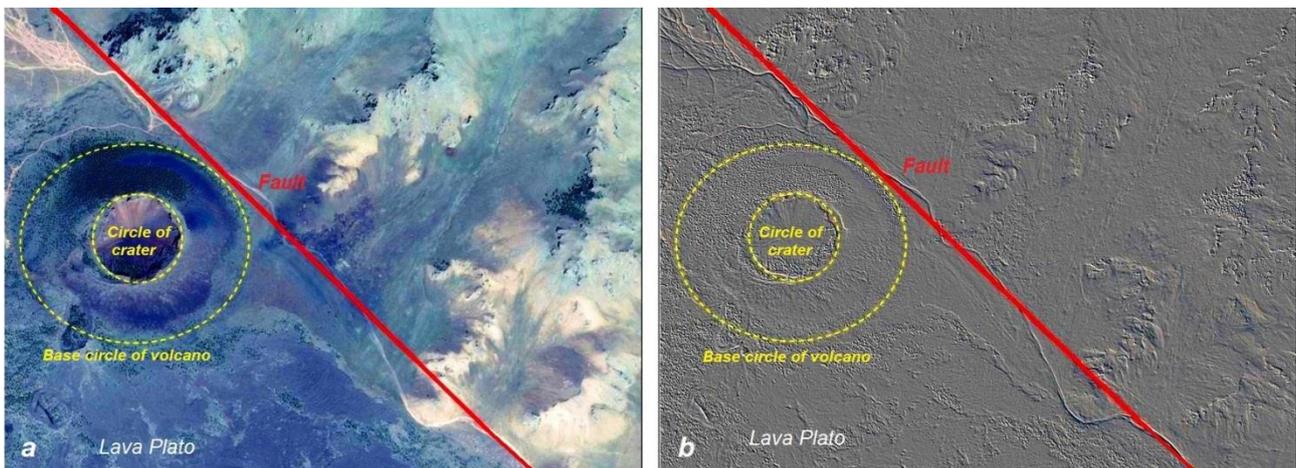
**Figure 7.** The fault of Khorgo (red line of blue dotted focus circle) was drawn on a scale of 1:100 000 topographic maps by the morphometric method



**Figure 8. The fault as shown in a Google Earth satellite image comparison a. 2D satellite image b. 3D satellite image, Khorgo volcano**



**Figure 9.** The fault of Khorgo volcano (red line), Aerial photo by Ch. Batzaya, 2016



**Figure 10.** The fault of Khorgo volcano (red line) a. Digital Globe satellite (0.67m) image  
 b. Image using ENVI 5.3 Remote Sensing programme

The red line shows the existence of fault starting from northwest to southeast in the northern part of Khorgo volcano. Newly identified parts of fault on the surface are known to be around 10 km, while the estimated length could be roughly 20 km. The exact fault line length was indicated by ENVI 5.3 Remote Sensing programme. The Directional filter command in Convolution and Morphology menu proved the existence of fault line.

**Background of Khorgo volcano’s origin**

The volcanic surface age in the Tariat-Chuluut basin hasn’t been estimated yet.

Okinova (1940), and Selivyanov (1967, 1972) noted that basalt rocks are from Neogene, early stage of the Quaternary Era, while Murzaev (1952) maintained that the Tariat-Chuluut basin belongs to the earlier period of the Quaternary Era. Kozhevnikov (1970) and other scientists proved that it is from the middle and later stages of the Quaternary Era [18, 36, 42, 46]. The sediment of the volcano overflowed through different periods of times in the beginning of the Late Pleistocene or Oligocene Eras to the late periods of the Quaternary Era due to the difference between various habits. The proof is that lava overflow filled some of the river

basins during the earlier stage of Quaternary Era and basalt's rocky sheets belong to the Miocene and Pliocene's earlier periods that resulted in the Khangai depression, and the dumping outer surface proves that basalt of this

volcano belongs to the Pliocene's late period to the earlier period of the Quaternary Era. The extinction period of volcano with its outer surface creation is estimated by comparing it with younger terraces [18-19].

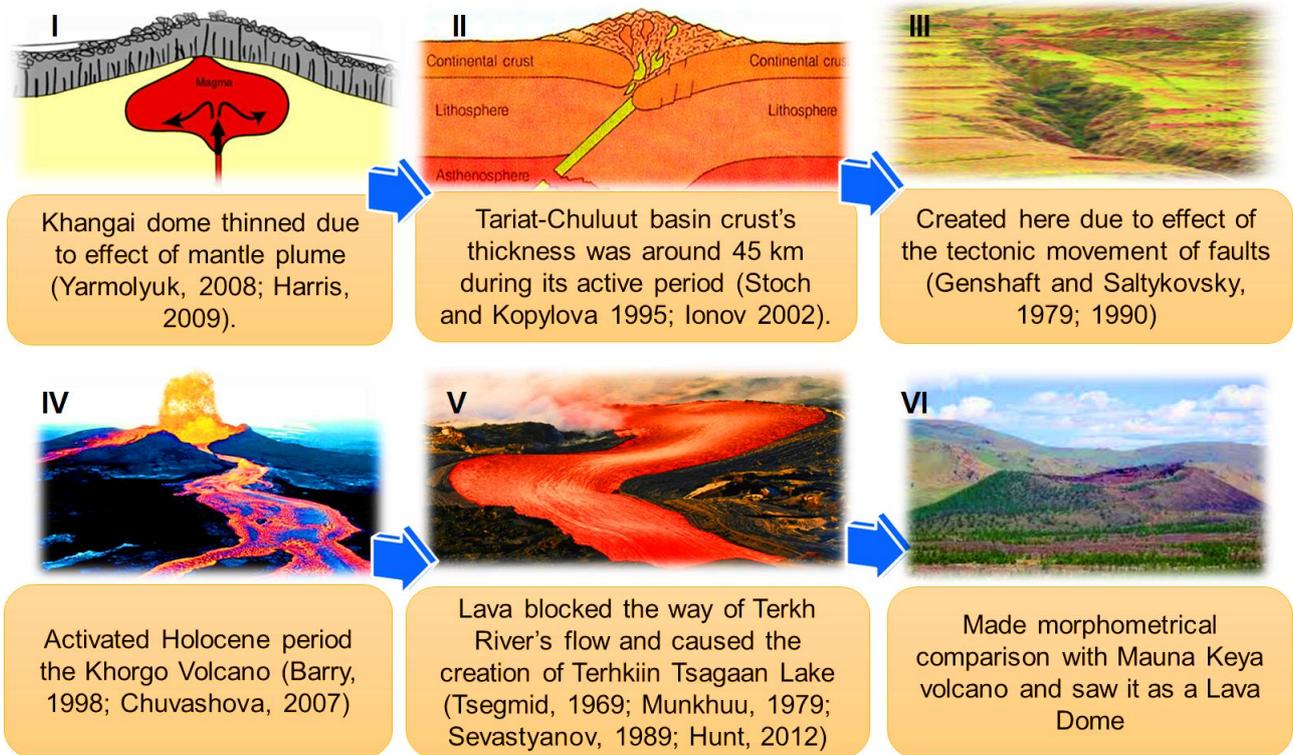


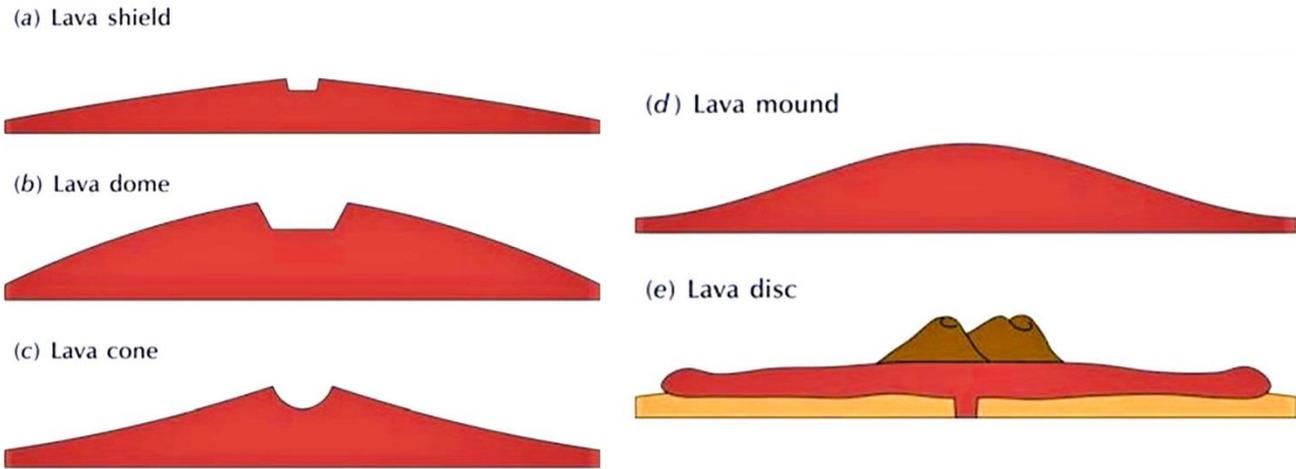
Figure 11. Scheme of the Khorgo volcano's origin

**The geomorphological shape of Khorgo volcano**

The shape of Khorgo volcano was determined by comparing Mauna Kea's volcanic morphometric results, such as chemical compound of basalt, topography, photographic and satellite images. The direction of overflowed magma that belongs to the Quaternary Era was estimated or identified along the fault, using satellite image.

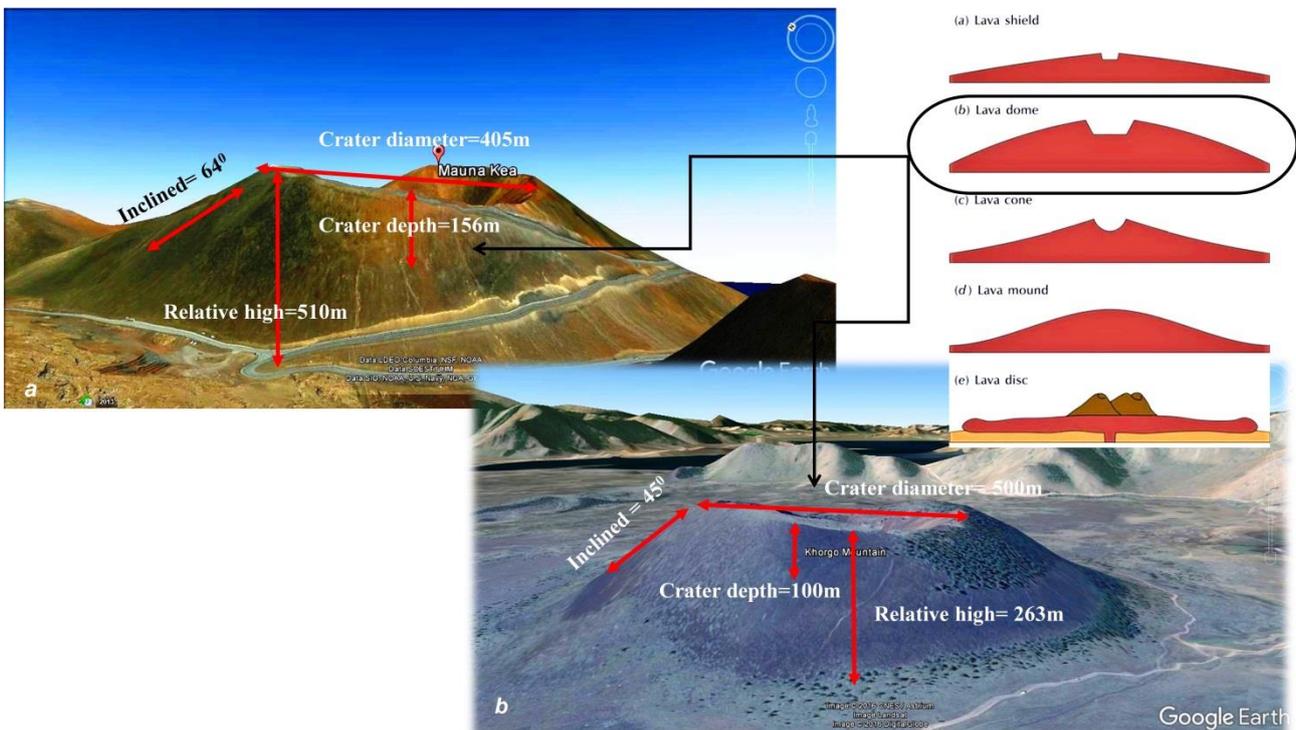
Several types of basic-lava volcanoes have been identified: lava shields, lava domes,

lava cones, lava mounds, and lava discs [47-48]. Classic examples of lava shields are found on the Hawaiian Islands. Mauna Loa and Mauna Kea rise nearly 9 km from the Pacific floor. Lava domes are smaller than, and often occur on, lava shields. Individual peaks on Hawaii, such as Mauna Kea, are lava domes. Lava cones are even smaller (Fig. 12). Mount Hamilton, Victoria, Australia, is an example. Lava mounds bear no signs of craters. Lava discs are aberrant forms, examples of which are found in Victoria, Australia [47].



**Figure 12. Geomorphological types of basic-lava volcanoes (Ollier et al., 1969; Holland, 2011; Huggett, 2016)**

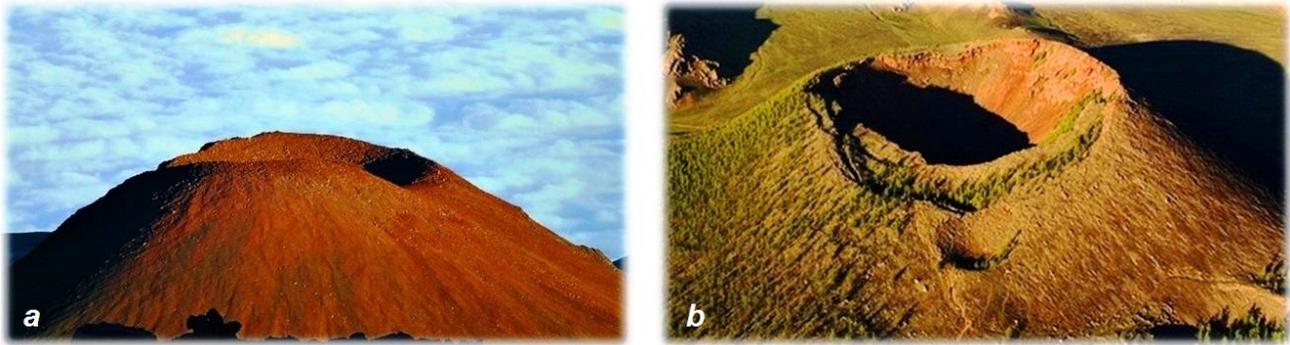
The following (Fig. 13) shows the comparisons of Khorgo and Mauna Kea volcanoes with their morphometric results.



**Figure 13. The geomorphological shape created from basalt lava. Comparative images of Mauna Kea and Khorgo volcanoes**

With regard to the definition of the above and the tectonic relation of origina, the morphological shape of the Khorgo volcano is distinguished as lava dome. The edge of the Khorgo craters is approximatey 45 degrees

steep, 100 meters deep, and has 500 meters of round-shaped diameters. The edge of Mauna Kea craters is around 64 degrees steep, 156 meters deep, 405 meters round shaped diameters, according to the image above.



**Figure 14. Aerial images of Lava Dome a. Mauna Kea Volcano, Hawaiian Island, USA; b. Khorgo volcano, Khangai Mountain, Central Mongolia**

There are around 400 volcanic craters in Mongolia. There are more than 200 volcano craters in Dariganga, in the extreme east of the country. Other volcanic craters are located in the Khangai, Khuvsugul, Orkhon-Selenge and

Bayankhongor volcanic basins [17-18, 36, 45]. It is also possible to determine the geomorphological shape of volcanoes in Mongolia according to their origin.

**CONCLUSIONS**

This significance of this study becomes more important as it determines the geomorphological shape of the Khorgo volcano in relation to its origin.

The location of the volcanic crater around Tariat is almost in a straight line, which is directly related to tectonic faults. In this study, we identified Khorgo volcanic faults using remote sensing spatial enhancement and geomorphological morphometric methods.

The thickness of the crust during the Tariat volcanic activity is 45 km, and the tectonic movement in the crust is due to the intensity of magmatic fissures. The base lava overflowing from the Khorgo volcano formed a

large lava platform, closing the river valley and forming the Terkhiin Tsagaan Lake.

By comparing the basalt composition of the Khorgo volcano and its morphometric characteristics with other resembling volcanoes, it was determined that it is a form of lava dome.

Furthermore, it is possible to classify geomorphological forms by determining the shape of volcanoes in Mongolia according to their origin.

**Acknowledgements**

Financial support for this study was kindly provided by the Young Scientist Grant (P2018-3568) in the National University of Mongolia.

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