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Discovery of the Baijifeng impact structure in Tonghua, Jilin, China

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ABSTRACT

An impact structure 1400 m in diameter, formed by a bolide impact, has been discovered on Baijifeng Mountain in Tonghua City in Northeast China's Jilin province. The impact structure takes the form of a cirque-shaped depression on the top of the mountain and is located in a basement mainly composed of Proterozoic sandstone and Jurassic granite. A large number of rock fragments composed mainly of sandstone, with a small amount of granite, are distributed on the top of Baijifeng Mountain. Planar deformation features (PDFs) have been found in quartz in the rock and mineral clasts collected from the surface inside the depression. The forms of the PDFs indexed in the quartz include among others, $\{10\bar{1}3\}$, $\{10\bar{1}2\}$, and $\{10\bar{1}1\}$. The presence of these PDFs provides diagnostic evidence for shock metamorphism and the impact origin of the structure. The impact event took place after the Jurassic Period and probably much later.

I. BACKGROUND

Terrestrial impact structures are formed by hypervelocity impacts of asteroids or other celestial objects crashing onto the Earth's surface. The number of impact structures discovered per unit land area in China is far below the world average, and to date, only two impact structures have been confirmed in China.[1,2] Recently, a geological phenomenon on Baijifeng Mountain in the Baijifeng National Forest Park in Tonghua City, in Northeast China's Jilin Province, has attracted our attention. There are a large number of rock fragments on the top of Baijifeng Mountain, formerly known as "basalt."[3] The mountain reaches 700 m in height. The formation and origin of these rock fragments remained a mystery for a long time.[3] These stones of unknown origin are commonly called "Celestial Stone" by the local people.[4] We set out to find out the real story behind this accumulation of rock fragments. Our investigation has revealed for the first time the presence of an impact structure on Baijifeng Mountain.

II. GEOGRAPHIC AND GEOLOGIC SETTING

Tonghua City is located in the southern foothills of Changbai Mountain. This is a middle–low mountainous area, with an altitude of 600–1589 m above sea level, and is widely covered by mixed coniferous and deciduous broad-leaved forest. The region has a typical temperate continental monsoon climate, with hot summers and cold winters. Baijifeng Mountain is situated 25 km southeast of the center of Tonghua City, and covers an area of about 15 km^2. The northwest slope of Baijifeng Mountain is in the Baijifeng National Forest Park, while its southeast slope is under the jurisdiction of Tonghua County.

In tectonic terms, the Tonghua area is located in the Paleo-Proterozoic Liao-Ji Orogenic Belt in the northeastern margin of the North China Craton.[5] The basement is made up of Archean–Proterozoic strata, which are partially covered by Paleozoic strata and Mesozoic–Cenozoic volcano-sedimentary rocks.[6] A large amount of Proterozoic and Mesozoic granitoids occur in this region. The main lithologies in Baijifeng National Forest Park are Proterozoic strata and Jurassic granite.[6]

III. IMPACT STRUCTURE

Baijifeng Mountain has a double peak. One of the peaks, with an elevation of 1318 m, is called "Front Baijifeng" and the other, with an elevation of 1300 m, is called "Rear Baijifeng." The distance

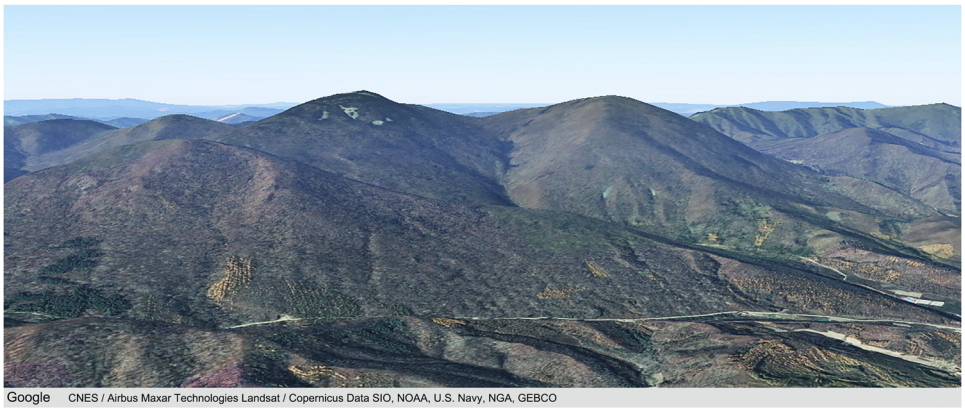

FIG. 1. The Baijifeng impact structure on the top of Baijifeng Mountain. The impact structure is a cirque-shaped depression with a diameter of about 1400 m and a height difference of 418 m. The two peaks surrounding this depression are Front Baijifeng on the left side and Rear Baijifeng on the right side. The panoramic view of the impact structure was taken from the southeast. Image: Google CNES / Airbus Maxar Technologies Landsat / Copernicus Data SIO, NOAA, U.S. Navy, NGA, GEBCO.

between the peaks is about 1400 m. On the basis of a terrain analysis, a cirque-shaped depression has been recognized on the top of Baijifeng Mountain (Fig. 1). Front Baijifeng is located on the southwest edge of the depression and Rear Baijifeng on the northeast edge. The elevation along the southwest–northwest–northeast edge of the depression is 1160–1318 m, and that along the southeast edge is 900 m. The center of the depression is at an elevation of 1080 m. The depression has a cirque-like shape, with one side of the three-sided ring wall facing a downhill slope. The latitude and longitude of the depression are 41°33′07″N and 126°06′40″E, respectively.

An aerial view of the depression landform reveals a near-circular structure with a rim-to-rim diameter of 1400 m. On Earth, impact structures less than 4 km in diameter in crystalline rocks and 2 km in sedimentary rocks commonly take the forms of simple craters (i.e., bowl-shaped depressions).[7] If the cirque-shaped depression on Baijifeng Mountain was formed by a bolide impact, then it can be classified as a simple crater. During the impact cratering, a large amount of rock would have been excavated and ejected to form this new geological structure. The collision would have greatly changed the original terrain of the target, forming two new peaks, namely, Front Baijifeng and Rear Baijifeng (Fig. 1). The morphological characteristics of the cirque-shaped impact structure that was produced should have a close correlation with the original topography of the mountain. The mechanism of impact cratering for this cirque-shaped depression will be discussed later.

The cirque-shaped depression occurs mainly in the Neo-Proterozoic strata, with only a small part in the northwest occurring in the Jurassic granite. A thick accumulation layer of impact-ejected rock fragments with sharp edges and corners covers a large area of Baijifeng Mountain, especially on Front Baijifeng and Rear Baijifeng [Fig. 2(a)]. These rock fragments range up to several meters in size. There are tens of thousands of square meters of rock fragments on the top and the upper parts of the mountain without vegetation cover. The vegetation-covered areas in and around the depression are also extensively covered with similar rock fragments. The major lithology of the rock fragments is sandstone, with a small amount of granite. No basalt has been found. The granite fragments are fresh or weakly weathered. A comparative investigation has shown that the granite area near the depression is generally covered by a weathered granite layer with a thickness up to 5 m. Therefore, the degree of weathering of impact-produced rock fragments on Baijifeng Mountain is relatively low. This demonstrates that the Baijifeng impact structure is well preserved.

IV. SHOCK METAMORPHISM

Hypervelocity collisions between celestial bodies and the Earth may result in shock metamorphism of target rocks. Considering the complexity of Earth's geologic processes, shock metamorphism often provides critical evidence for identifying terrestrial impact structures.[7] The formation of planar deformation features (PDFs) in quartz corresponds to shock pressures of 10–35 GPa.[7,8] Owing to this broad pressure range, the presence of PDFs in quartz has been widely accepted as diagnostic evidence for shock metamorphism and terrestrial impact structures.[7,8] The basement rocks of Baijifeng Mountain are composed mainly of sandstone and granite, in which quartz is one of the most common rock-forming minerals. If the cirque-shaped depression was formed by a bolide impact, then PDFs should be detectable in quartz in these rocks. To investigate the origin of the depression, samples of rock and mineral clasts were collected from the surface inside the depression. The samples were made into polished thin sections to search for PDFs in quartz.

The collected samples were found to be mixed substances with different degrees of shock metamorphism. Preliminary investigation of the first 50 thin sections identified more than 30 quartz grains with PDFs. The PDFs in the quartz displayed one or more sets of lamella-like textures [Fig. 2(b)]. These lamellar sets were straight. The thickness of individual PDF lamellae ranged from 1 to 2 μm, and the spacing between individual planes ranged from 1 to 10 μm. One to three sets of PDFs were observed in quartz single crystals [Figs. 2(b) and 2(c)]. The PDFs in the quartz occurred in planes corresponding to specific rational crystallographic orientations. The forms of the PDFs indexed in the quartz included, among others, $\{10\bar{1}3\}$, $\{10\bar{1}2\}$, and $\{10\bar{1}1\}$, with the most abundant being $\{10\bar{1}3\}$. The discovery of PDFs in the quartz from the cirque-shaped

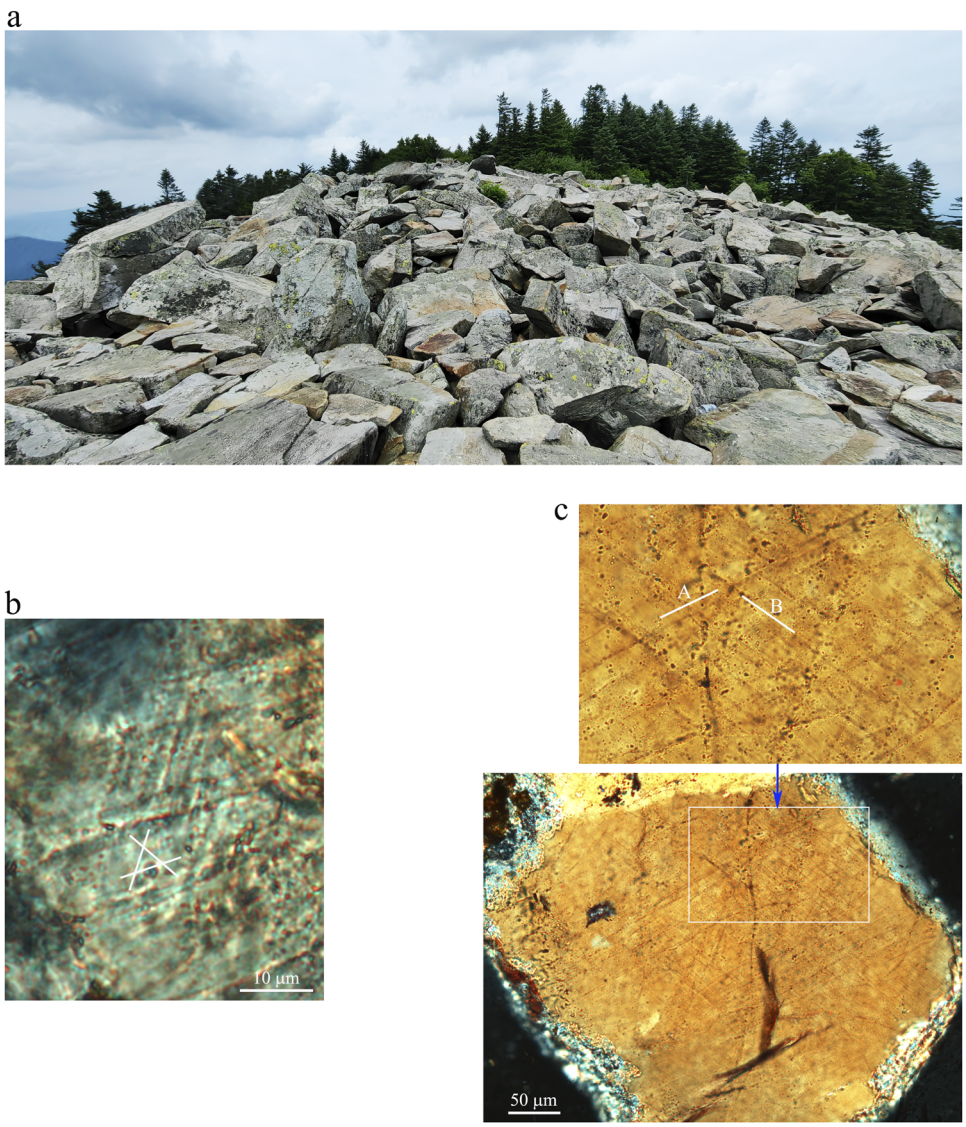

FIG. 2. Impact-ejected rock fragments and evidence of shock metamorphism. (a) Sandstone fragments with sharp edges and corners on the top of Front Baijifeng. (b) Optical microscope image of a quartz grain with three sets of PDFs (highlighted by three solid white lines) with cross-polarized light illumination. (c) Optical microscope image of a quartz grain with two sets of PDFs indexed as $\{10\bar{1}3\}$ (A) and $\{10\bar{1}1\}$ (B) with cross-polarized light illumination.

depression in Baijifeng Mountain provides unambiguous evidence of shock metamorphism, and supports an impact origin of the cirque-shaped depression.

V. AGE OF IMPACT EVENT

The granite of Baijifeng Mountain was formed in the Jurassic Period, with an age of 150–172 Ma.[6,9] Therefore, the Baijifeng impact structure must have been generated after the formation of this granite. In the case of simple terrestrial craters, the layers of rock debris at the uplifted crater rim are easily eroded and are present only in the youngest and best-preserved structures.[7] The good preservation of the impact-generated rock fragments on Baijifeng Mountain indicates a young impact structure.

The granite fragments exposed on the surface of the Baijifeng impact structure are relatively fresh or only weakly weathered. Here, we would like to compare the Baijifeng impact structure with the Yilan impact crater in Harbin, Heilongjiang Province, China. Both the Harbin and Tonghua regions have a temperate continental monsoon climate, and both impact structures are located in forest areas. The Yilan impact crater was formed in a granite basement 0.049 Ma ago.[2] The granite fragments accumulated on the rim of the

Yilan impact crater have been strongly weathered.[2] According to the degree of weathering of the impact-produced granite fragments, the age of the Baijifeng impact structure should not be far from that of the Yilan impact structure. The exact age of the Baijifeng impact event needs further investigation.

VI. CONCLUSION

The cirque-shaped depression with a diameter of about 1400 m on Baijifeng Mountain, Tonghua City, has been confirmed to be an impact structure. This impact structure is located in a basement composed mainly of Neo-Proterozoic sandstones and Jurassic granites. The formation of the impact structure corresponds to a bolide crashing into the top of a high mountain. The presence of PDFs in quartz provides diagnostic evidence for the impact origin of the geological structure. The impact event took place after the Jurassic Period and probably much later. The Baijifeng cirque-shaped depression is a well-preserved impact structure with unique morphological characteristics, and its location at the top of a high mountain creates spectacular natural scenery.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Ming Chen: Investigation (equal); Writing – original draft (equal). **Yang Lu**: Investigation (equal). **Jiahao Ning**: Investigation (equal). **Wenge Yang**: Investigation (equal); Writing – review & editing (equal). **Jinfu Shu**: Investigation (equal). **Ho-kwang Mao**: Investigation (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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