Chapter

Bacubirito: An Outstanding Cosmic Sample on Earth

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Abstract

The Bacubirito meteorite, although largely forgotten by the scientific community after its excavation in 1902, remains an incredible artifact and inspired generations of Mexican scientists. It is the fifth largest meteorite in the world and the longest with a length of 4.16 m. Using the Monte Carlo method, an innovative geometrical model and scanner, we have been the first to calculate the precise dimensions and mass (21 tons) of Bacubirito meteorite's complex structure. Moreover, we are advocating that it be added to the list of world heritage sites due to its scientific, cultural, and historical significance in Mexico and the world.

Keywords: Bacubirito, iron meteorites, anomalous meteorite, tridimensional model, volume, mass

1. Introduction

Meteorites have provided tremendous amounts of information about the planetary system and the cores of planets or star while fascinating societies for centuries. These pieces of asteroids or fragmented planets are composed of rock, iron, or a mixture of both. Iron meteorites were part of the nucleus of planetoids or asteroids, rock from the surface and the rock-iron from the intermediate zone. Mexico's large surface area contains a considerable number of valuable meteorites, and in the last 100 years, scientific research has evolved to study them. For instance, the Mexican Allende meteorite was used to calculate the age of our solar system [1].

The Bacubirito meteorite is a famous Mexican meteorite found in a small town named Camichín in the mountain range of Sinaloa in Northwestern Mexico, see **Figure 1**. The name comes from the closest town Bacubirito, and it has been the source of scientific research in Mexico for the last century. This enormous meteorite has an outstanding length of 4.16 m and a mass close to 20 tons.

We hope that the research presented here will also support our case for the meteorite's inclusion in the list of Heritage Sites in the United Nations Educational, Scientific, and Cultural Organization (UNESCO) and demonstrate its value to Mexican scientific research and the world's knowledge of meteorites. From our point of view, it meets the following criteria [2]:

> *"VII Containing extreme natural phenomena or areas of exceptional natural beauty or esthetic importance; VIII To be one of the representative examples of important historical stages of the history of the earth including testimonies of life, geological processes creating geological formations, or significant physiographic or geomorphic characteristics."*

Figure 1.
Map of México with the state of Sinaloa in detail. Culiacán the capital city of Sinaloa and the town of Bacubirito are shown as well. The meteorite is currently located in Culiacán.

Further arguments for its significance will appear in this chapter, and we will also discuss its impact on Mexican science in addition to the innovative method utilized to determine its mass.

2. Mexican scientific interest in meteorites

The magnitude of the surface of Mexico (1,964,375 km^2) allowed the discovery of a great number of meteorites. We can calculate the probability of meteorite impacts [3] on the Mexican territory with the cumulative distribution $N(d)$ of diameters of Earth-Crossing Asteroids (ECAs) derived by Poveda et al. in order to estimate the frequency of collisions of meteoroids with cars and aircraft. A meteorite with a 9-cm diameter strikes a car with an expected frequency of once every 5 years according to the available data for meteorite strikes. Mexico's large surface area also increases the frequency of meteorite strikes, although the correlation of meteorite impact and geographical location remains unclear. Even so, iron meteorites can have catastrophic effects on Earth. However, they were once the main source of metal for tools and weapons in ancient times [3], and in spite of the great amount of metallic metals in Mexico, there is no record of these tools in museums, perhaps taken during the Spanish conquest [2].

The early Mexican Scientific Community advocated the study and the catalog of meteorites and other geological features, and they successfully petitioned the government to protect and categorize them as a national heritage. For this reason, any of these objects appear in museums or public institutions. The field of geology and the mining industry promoted scientific development in Mexico in the nineteenth century. Scientists trained in these disciplines began to dedicate themselves to the study of the earth and established the procedures to protect, study, and catalog the meteorites.

Two mining engineers [4], Antonio Del Castillo (1820–1895) and Mariano Santiago de Jesús de la Bárcena y Ramos (Mariano Barcenas for future reference) (1842–1899) featured prominently in the initial study of meteorites in Mexico and guaranteed legal protection for these objects while advancing research in the field. Castillo, an outstanding academic, created schools and institutes about geology and geography (*Escuela Practica de Minas* and *Consejo de Minería y obras Publicas and Colegio de Mineria*). He also wrote the *Catalogue descriptif des météorites du Mexique de 1889* (a 200-page work discussing meteorites in Mexico), and he published his excavations of Chihuahua's meteorites (displayed in the entrance of the National School of Engineers in 1893). Although Castillo describes the Bacubirito meteorite in this work, he did excavate or visit it, and thus, he relied on an estimation to calculate its mass. Moreover, he was a member of the federal congress, and in a letter sent on May 7, 1889, he proposed legislation to protect all Mexican celestial objects, including meteorites, from private ownership and prohibited their destruction, exportation, alienation, and required their conservation. Thus, Bacubirito is the property of the Republic of Mexico and cannot be exported or sold, the current constitution of Mexico still contains this legislation. Moreover, he influenced the interest of other scientists to study meteorites, particularly in his former students.

Mariano Barcenas was one of the most internationally well-known Mexican scientists and one of the most prominent students of Del Castillo. He combined an outstanding academic career with a successful public life as an entrepreneur and politician. In the congress of the Academy of Natural Sciences in Philadelphia in 1876 [5], he made the Bacubirito meteorite internationally known. Barcenas studied this meteorite by means of a sample that the governor of the state, Eustaquio Buelna-Perez from 1871 to 1875. Afterward, he obtained the composition of the meteorite and gave a mass estimation, though not precisely, since no other information was available without excavation. Despite the interest around meteorite, it remained buried for many more years, mainly due to the difficulty in arriving to the Camichin.

Professor Henry Augustus Ward (1834–1906), from the Rochester Academy of Science of New York and meteorite collector, excavated the meteorite in 1902 in Mexico [6, 7]. He describes in detail the hard work to arrive to Bacubirito and how the 20 individuals were required to unearth this enormous celestial piece, see **Figure 2**. He also reported the object's dimensions: 13 feet, 1-inch length (3.96 m), 6 feet, 2 inches wide (1.8 m), and 5 feet, 4 inches in depth (1.52 m) and mass of 50 tons. He estimated the object's mass assuming a cubic shape (although the meteorite is highly irregularly shaped). Despite of the affection that Camichin's population had for the meteorite, it was moved to Constitution Civic Center in Culiacan (see **Figure 3**), the capital of the state of Sinaloa in 1959, a 245.5-km route, in order to facilitate the object's study.

Figure 2.
Unearthing of the specimen in 1902 by local individual.

Figure 3.
Photograph of the former location of the meteorite in the constitution Civic Park (Parque Civico Constitución) in 1959.

Figure 4.
Photograph of the meteorite in Culiacan in 2018 [8].

Professor Vagn Fabritius Buchwald (1929–current) from the Department of Mechanical Engineering in the Technical University of Denmark visited the meteorite in 1978. He evaluated the physical properties of Bacubirito meteorite and determined its volume and mass. He described the width, which varied between 100 and 185 cm and a depth between 30 and 75 cm. The intricate shape and ear-like curve made it difficult to calculate the exact volume. However, he used a photographical method to arrive at a volume of 2.80 m^3 ± 10%, corresponding to a weight of 22 tons: a good approximation with the tools available at the time. In 1993, the meteorite was relocated to its current position in Science Center of Sinaloa in Culiacan (**Figure 4**).

A new generation of scientist in Mexico is analyzing and promoting Bacubirito meteorite [8, 9]. They have obtained new measurements that place it as the longest in the world (4.1 m). They have also promoted it in the State Congress of Sinaloa in 2018 and declared that the meteorite should be considered a cultural and historical patrimony of the state. This was achieved with the support of Dr. Victor Antonio Corrales-Burgueño (1954–today), a congressman and former Head Dean of the Autonomous University of Sinaloa (UAS). Thus, with this legislation, we hope to have the meteorite declared to Human Heritage, so that it will be included in this esteemed list and take place as an "exceptional and universal value."

One of the strongest arguments to promote this initiative is the studies that we have achieve to measure the weight of this metal giant. As we have seen in its description, its size has made this difficult to establish with accuracy. Notwithstanding, advances in techniques and methods have enabled us to establish the final weight of this specimen. In the following section, we explain this in detail.

3. Geometrical model of Bacubirito to assess its mass

As stated formerly, the meteorite has suffered classification changes in size over time and is considered anomalous in density, which may be due to a lack of detailed investigations. Back in 1975, Buchwald indicated that only a few studies existed on the meteorite, and little has been done 40 years later. There have only been rough estimates of properties, such as its mass, dimensions, and densities, as noted from the large mass variations reported. Moreover, for most of the estimations, uncertainties have not been provided. Accurate measures of geometrical parameters, the mass, and statistics of the regmaglypts were determined from the elaboration of a three-dimensional model of Bacubirito.

The importance of studying this meteorite can be understood in terms of the role it plays on the entry dynamics of the object. If we consider the theoretical prediction for speed given by Regan and Anandakrishnan [10], two important variables appear namely the drag coefficient C_d and cross-sectional area A that are determined by its geometry. Another important dynamic variable that can be investigated is the mass using the ablation model in Revelle [11], and from the two parameters just mentioned, an estimate of the object mass can be obtained before entry. Finally, given that the meteorite shape is nonspherical and assuming that it

Figure 5.
Perspectives of the Bacubirito meteorite.

was not greatly modified during entrance, we can use our geometrical model and study the drag force for an asymmetrical object as in Leith [12]. However, these studies are beyond the scope of the present investigation, and for this research, we will limit ourselves with the model acquisition and parameters previously cited.

The Bacubirito meteorite has a rather complex shape (see **Figure 5**) and large weight (**Tables 1** and **2**), and thus, determining the surface shape of Bacubirito can be used to infer important information about its passage through the atmosphere and learn more about the meteorite itself. The geometric model can also provide reliable classification for meteorites, and comparisons between this and other recovered pieces contain additional details [9]. This model allowed us to calculate some of its important features: geometric parameters, mass, and statistics of regmaglypts. First, we generated the model, and we defined and calculated the geometric features. An analysis of reported densities to obtain a precise mass estimate was performed. Then, we reported the size and depth of the regmaglypts, and finally, we obtained a precise geometrical model of the meteorite.

Under these restrictions, we have chosen to use a portable scanner to determine the model. This instrument allows for a vastly accurate estimation of the relative positions of surface points on a rigid object and is highly suited from a practical perspective—the outdoor location of the meteorite and its resting on a high position are benefits in this case. This device has been used in civil engineering applications, where detailed, precise and three-dimensional representations are required. Being a highly characterized instrument, it allows us to reduce the uncertainty of our results.

The scanner used was the Leica Nova MS50. This equipment radiates and collects a laser beam, which can either directly interact with the object to measure it or by means of a prism. The direct operation mode is mostly employed since it offers a higher resolution and precision to acquire the 3-d points. According to an extensive characterization from the manufacturer (see Leica Nova MS50 Datasheet), it has an angular accuracy of =1″ in horizontal and vertical angular measurements, a

Meteorite	Country	Dimensions [m × m × m]	Mass [tons]
Hoba	Africa	2.7 × 2.7 × 0.9	60
Campo del Cielo (El Chaco)	Argentina	–	31
Cape York (Ahnighito)	Greenland	3.25 × 2.1 × 1.6	30.88
Cape York (Agpalilik)	Greenland	2.1 × 2.0 × 1.5	20.14
Bacubirito	México	4.1 × 1.8 × 0.2*	19.43±0.51*

*Revised table from Buchwald [13]. *Our measurement.*

Table 1.
List of the largest meteorites of the world.

Author	Year	Mass [tons]
Ward	1902	50
Angerman	1903	25
Merrill	1929	20
La Paz	1973	27
Buchwald	1975	22 ± 10%
Sanchez-Rubio	2001	19

Table 2.
Reported Bacubirito meteorite mass estimates until year 2001 (see Refs.).

linear precision of l = 2–3 mm + 2 ppm, and collects up to 1000 pts./s. The scanner can measure objects up 1 km away. Our measurements, however, were conducted at distances of about 15 m (see **Figure 2**). We placed the scanner in five different positions around the meteorite in order to reach every spot on its surface. For the inaccessible regions, a prism was employed. We finished with a model of 1,812,875 points on the meteorite's surface.

Before proceeding to computing the geometric parameters, we propose a Monte Carlo simulation to obtain even more precise positions and evaluate the uncertainty of our results from the single series of measurements. A classical reference to the Monte Carlo method and its applications in many areas is found in Rubinstein and Kroese [14]. With this goal in mind, we first develop a simple probabilistic model and later explain its practical implementation. We start assuming that the uncertainties in our measured positions are random, namely, that our calibrated instrument presents negligible systematic deviations as supported by the small parts per million on its linear accuracy. Furthermore, both distance and angle measurements present systematic-free errors that follow a Gaussian distribution. Now, the propagation error in position due to the angular uncertainty is negligible (≪1 mm) for our short separation distances and angular precision, and we conclude that this will follow a Gaussian distribution. From this discussion, the deviation $\overrightarrow{\delta r_i}$ of a measured position with respect to the instrument $\vec{r_i}$ can be written as $\overrightarrow{\delta r_i} = \overrightarrow{\lambda r_i}$, with $\vec{r_i}$ a unit vector (see **Figure 6**), where the λ parameter k is the random variable in the Monte Carlo simulation with a Gaussian distribution centered at zero and σ = 6 mm/2. This information is valid for both the characterization provided by the manufacturer (see datasheet) and the measurement technique in which the instrument was positioned in different locations with uncertainties lower than 4 mm.

The application of the method consists of taking the ith position measurement $\vec{r_i}$ and then, a particular value for λ is generated based on the distribution described above. We then add $\overrightarrow{\delta r_i}$ and repeat the process for each of the measurements. These amounts are obtained from one experiment from which the desired parameters can be extracted. The experiment is repeated many times for a simulation and is averaged over the intermediate results leading to a convergence.

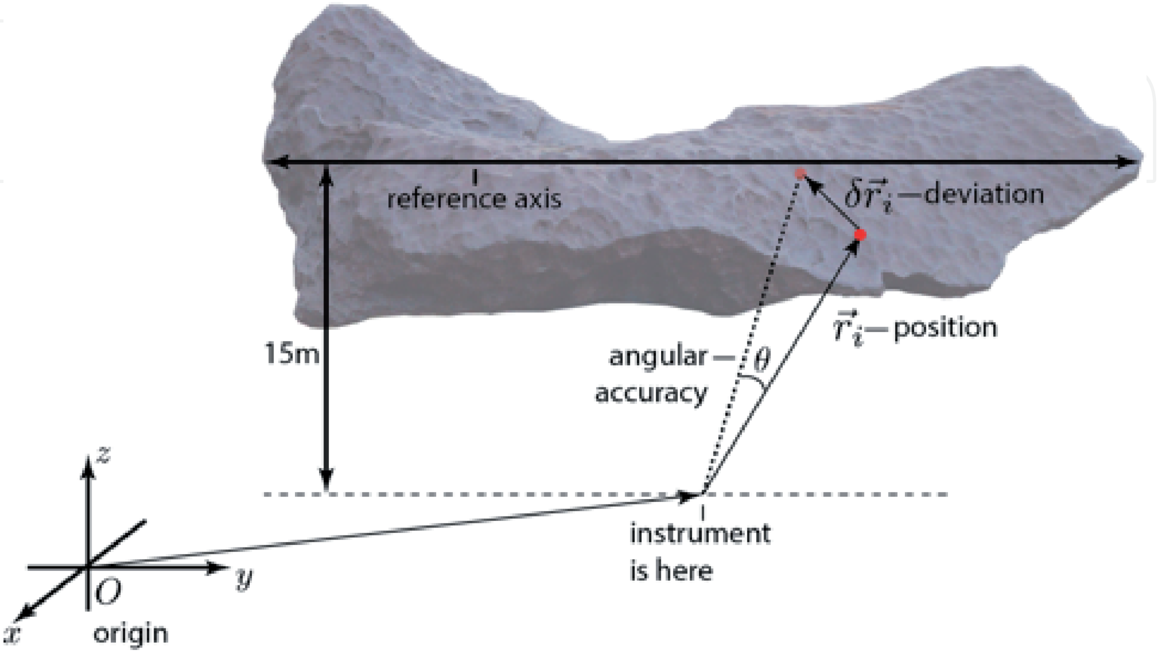

Figure 6.
Angular and linear deviations of the surface points due to intrinsic measurements uncertainty.

Finally, we start determining Bacubirito's dimensions. We define its length as the separation between the two farthest-apart points and fix an axis onto these points. We next define the width as the distance between the two farthest-away points that are both perpendicular to the axis and lie on a plane containing the axis. Similarly, the thickness is defined as the largest distance between the two points that define a line orthogonal to that plane and that pass through the axis. A sketch is shown in **Figure 7**.

In the next step of experiment, we estimate the meteorite volume by combining the Monte Carlo simulation with Gauss' Theorem. A Monte Carlo experiment is first employed. Gauss' Theorem is then used to estimate the volume enclosed by the simulated surface defined by a Delaunay triangulation. Thus, we obtained the associated volumes for each simulation run.

We continued with the analysis of the meteorite's densities reported so far and its mass determination. The percentages of its chemical elements are shown in **Table 3** (see Ref. [9]). Those values were measured in different samples from Bacubirito. On average, the measurements should be an approximation of the full meteorite's concentrations and densities. We obtained the average density of 7.7250 ± 0.2061 g/cm^3 from the mentioned table and with the aid of the volume calculated the mass.

The diameter and depth of the regmaglypts were the next determined quantities using the model. We defined a regmaglypt's diameter as that of the best-fit circle for the corresponding pit mouths. The depth is the difference between the bottom and the top. In order to characterize the distribution of regmaglypts, three zones around the meteorite were selected for presenting contrasting structures as shown in **Table 1**. The diversity in structures was assessed statistically using the Kolmogorov-Smirnov test for a thorough and rigorous treatment of the technique. To this end,

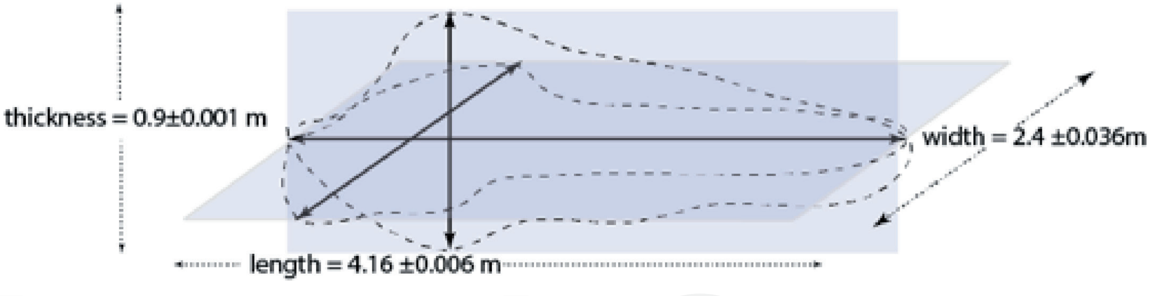

Figure 7.
Sketch of the Bacubirito meteorite and its dimensions.

(see Refs.)	Year	Chemical elements of the meteorite [%]							ρ [g/cm^3]
		Fe	Ni	Co	P	Ga*	Ge*	Ir*	
Hildehrand	1905		9.4	0.98	0.18				7.58[a]
Moore & Lewis	1968		9.78	0.76	0.16	17.7	31.9	4.9	7.97
Scott	1973		9.62			17.7	31.9	4.9	7.62
Wasson, pers. comm.	1968		9.62			17.7	31.9	4.9	7.62
La Paz	1973	88.94	6.98	0.21	0.15				7.64
Average ± std. dev.									7.7250 ± 0.2061

[a]*Quantity determined by Cohen according to La Paz (La Paz 1973).*
**Gallium, Germanium and Iridium are presented in a ppm scale.*

Table 3.
Reports of elements concentrations for the Bacubirito meteorite.

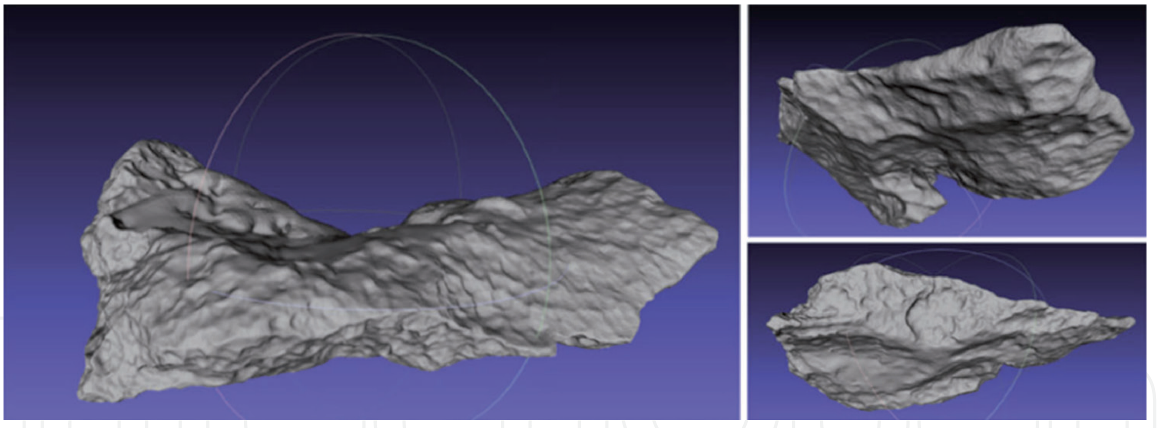

Figure 8.
Renders of the Bacubirito meteorite model.

we retrieved diameters and depths for each region from the model and took each as a random variable. The null hypothesis that any two of the regions originate from a same distribution for either variable was then evaluated.

3.1 Results and discussion

Renders of our tridimensional model are given in **Figure 8** and can be observed in a high level of detail. A precise retrieval of any geometrical parameters and its derivatives is also possible. We focus in this section on the dimensions, mass, and statistics of the regmaglypts.

The basic defining parameters of Bacubirito are the dimensions and their uncertainties depicted in the last column of **Table 4**. Contrasting differences are observed with respect to one of the first studies performed by Ward and the latest one by Buchwald. While estimates of geometric parameters of Bacubirito have been reported previously, different studies exhibited noticeable changes. We made the formal definition for consistency among studies and determine them precisely from the model. Therefore, we can confirm the old claim that Bacubirito is the longest meteorite in the world, with a total length of 4.130 ± 0.005 m (see **Table 4**).

The previous estimate of volume was based on photographs by Buchwald [13] resulting in 2.8 ± 10% m^3. This was very good approximation considering the prevalent instrumentation and data analysis techniques of the time. The volume calculated from a number of simulations through the Monte Carlo method is:

$$V = 2.5151 \pm 0.0005 \text{ m}^3 \tag{1}$$

This represents a novel rigorous calculation of the volume of the meteorite. The remaining two parameters give the reader the idea of the aspect ratio of the body and its importance among meteorites in the world.

Dimensions	Ward [m]	Buchwald [m]	This work [m]
Width	1.88	1.00–1.85	2.053 ± 0.005
Thickness	1.63	0.30–0.75	0.911 ± 0.005
Length	3.99	4.25	4.130 ± 0.005

Table 4.
Geometrical parameters of the Bacubirito meteorite.

We emphasize that the density of points considered here (a total of 1,812,875) reflects an upper bound for an instrument with uncertainties in the millimeter range. An increase in the number of points would result in separation distances along the meteorite surface in the range of μm, which is well beyond the maximum precision of the device.

The mass is calculated from averaging the densities in **Table 3** and our volume estimation.

$$m = 19.429 \pm 0.51 \text{ tons} \tag{2}$$

We obtained a mass uncertainty of around 3%, and this was consistent with the estimations made by Buchwald and Sanchez-Rubio et al. [15]. Furthermore, we can note that these densities represent the main uncertainty, and hence, we recommend improving their estimation.

Finally, an important feature of iron meteorites is their regmaglypts (**Figure 9**). Those meteorite traits provide important information related to its fall. For example, according to Lin and Qun [16], larger pits correspond to zones where the surface vector is more aligned with the meteorite velocity vector. The statistics of the regmaglypts are depicted in **Table 5**, which demonstrates different areas on the meteorite that exhibit contrasting average diameters and depths. To confirm those differences, a Kolmogorov-Smirnov test shows a p value of <0.01 among the regions. Consequently, each region has a characteristic structure and implies different origins.

These data obtained from Bacubirito distinguish it from other meteorites in the world in length and size and for previous generations of scholars presented a significant challenge.

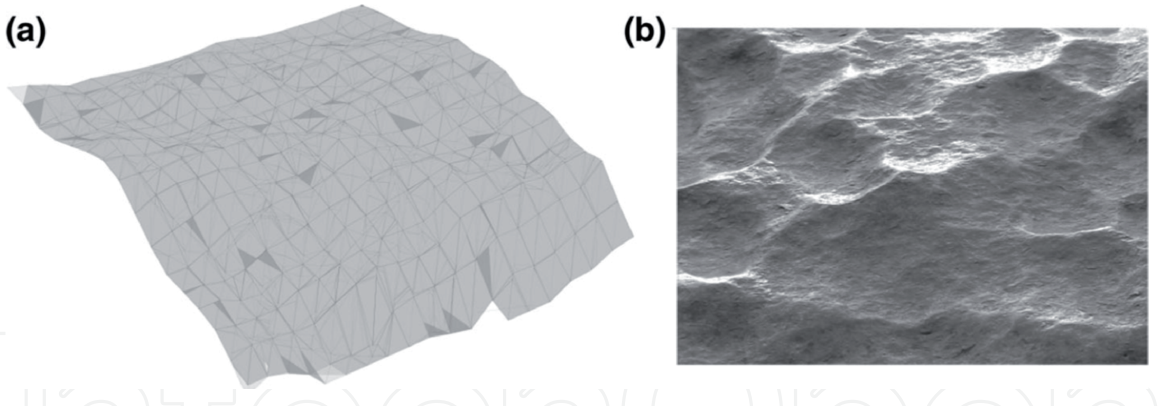

Figure 9.
(a) Render and (b) photography of Bacubirito.

Region	Diameter [cm]	Depth [cm]
Front	8.0 ± 2.3	1.0 ± 0.3
Rear	12.6 ± 2.6	1.4 ± 0.3
Below	10.9 ± 2.6	2.2 ± 0.4

Table 5.
Diameter and depth of the meteorite's regmaglypts.

4. Conclusions

In this work, we obtained a geometrical model that determined the mass of the Bacubirito meteorite and its other geometrical features. Our results are listed as follows:

1. The mass has a value of 19.43 ± 0.51 tons. The results are both the geometric dimensions and mass. These were achieved through state-of-the-art analysis techniques and equipment, considerable improvement on previous estimations.

2. The volume of the meteorite is 2.5151 ± 0.0005 m^3. We utilized the Monte Carlo method to simulate a series of measurements for a tridimensional rigid object in order to reduce time and expenses related to the repetition of in-field measurements.

3. The maximum length of the Bacubirito is 4.130 ± 0.005 m—the longest known in the world, and we also obtained estimations of the meteorite's main dimensions.

4. The depth and width of the regmaglypts of three regions were retrieved. The regions were found to exhibit different structures. The zone labeled as below is most likely to have been exposed directly to the atmosphere in the ablation altitudes.

The study also supports our proposal to include the Bacubirito meteorite on the list of the World Heritage Sites for its tremendous impact on culture, science, history, and geological studies. In addition to the impressive physical characteristics, mass, and length of the meteorite, the early Mexican scientific community developed through its research of the object and developed a series of legislative initiatives to conserve celestial objects. Moreover, local residents of Bacubirito and Sinaloa believe that the object represents national heritage and is a source of local pride.

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