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This short report describes the interior survey of Temple 11 at the Copan archaeological site using cosmic ray imaging, which has been conducted with Prof. Seiichi Nakamura of Kanazawa University since 2018.

First, a brief explanation of cosmic ray imaging is explained. Cosmic rays are high-energy radiation that travels through space. Its main components are nuclei of proton and helium. When protons and other particles collide with the Earth's atmosphere, new particles are generated in the upper layers of the atmosphere. These particles include subatomic particles called muon, which have extremely high penetrating power due to their properties. Muons are falling at a rate of one per square centimeter per minute from all directions toward the earth's surface, and can penetrate materials up to several kilometers in length. These properties can be used to visualize structures above and below ground as with X-ray radiography.

So far, the authors have used cosmic ray imaging to visualize the interior of the Fukushima Daiichi Nuclear Power Plant and the Pyramid of Khufu (Fig.1). At the Fukushima Daiichi Nuclear Power Plant, the author succeeded in visualizing the core meltdown inside the nuclear reactor damaged by the Great East Japan Earthquake by observing from the structure next to the reactor building, called the turbine building. In the visualization of the interior of the Pyramid of Khufu, we discovered an unknown huge void in the center of the pyramid by observing from the Queen's Chamber in the pyramid [Morishima 2017]. Furthermore, by visualizing the upper part from what we call the descending corridor, we also discovered a corridor-like cavity behind the gabled structure called the Chevron on the north face of the pyramid. Thus, this technology has achieved results such

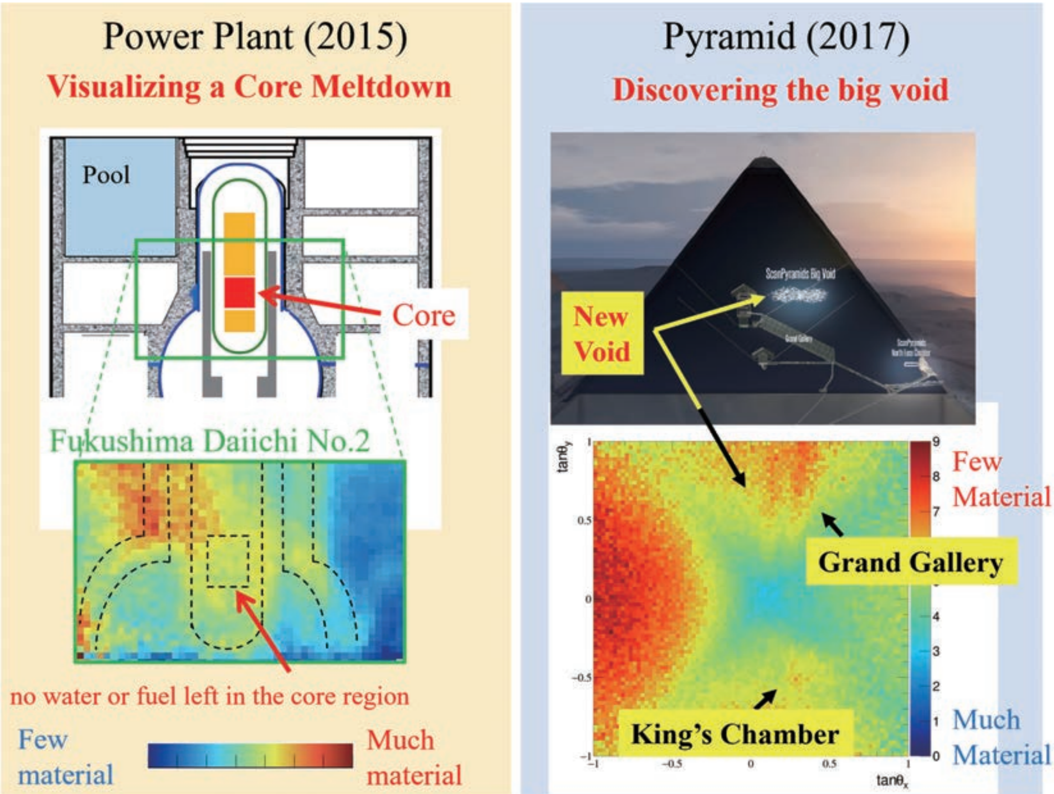

Figure 1 Examples of visualization by cosmic ray imaging. Left: Fukushima Daiichi Nuclear Power Plant Unit 2. Right: Pyramid of Khufu.

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Figure 2 Temple 11 at Copan Ruins

as the discovery of two unknown structures inside the Pyramid of Khufu in Egypt by cosmic ray imaging.

The Copan archaeological site survey conducted in 2018 and 2019 is the first study to be applied in earnest to the Mayan archaeological site survey. During the Copan site survey, several nuclear emulsion plates [Morishima 2022] were installed in the tunnels inside Temple 11 (Fig.2). Nuclear emulsion plates are photographic film-type radiation detectors (Fig.3). By photo-developing and fixing the radiation trajectories recorded in the nuclear emulsion plates, it is possible to analyze three-dimensional trajectories with submicron precision. After development, the nuclear emulsion plates are analyzed using an optical microscope to take advantage of their resolution. For the analysis of nuclear emulsion plates, an automated nuclear emulsion scanning system called Hyper Track Selector (HTS) developed at Nagoya University based on an optical microscope is used to digitize the cosmic-ray muon tracks recorded on the nuclear emulsion plates. Using the databased track information, an internal image of the target was obtained by cosmic rays transmitted through Temple 11.

The detectors installed inside Temple 11 are shown in Figure 4 and 5. The nuclear emulsion plate is fixed between aluminum plates facing in the direction to be visualized. The compactness of the detector, which requires no power source, makes it very suitable for measurements inside the archaeological site. After a measurement period of one to two months, the detector was collected and brought back to Japan to be developed. The nuclear emulsion plates were then read by the HTS to produce a cosmic ray image. An example of a cosmic ray image obtained from nuclear emulsion plates placed inside the tunnel of Temple 11 is shown in Figure 6. This image shows the directional distribution of cosmic rays, with the center of the image perpendicular to the nuclear emulsion plate. The vertical and horizontal axes indicate tanθ, where 1 corresponds to 45 degrees. The red color indicates the direction in which more cosmic rays were detected, and the blue color indicates the opposite, that fewer were detected. The non-uniformity of the directional distribution of cosmic rays indicates the density distribution of the material comprising Temple 11 integrated in each direction from the location of the detector.

The obtained image of the cosmic rays clearly identified a structure containing a passageway in the upper part of Temple 11 (Fig.7). When viewed from the center of the site, the upper passage-like structure was recognized as a depression of about 2 meters in relation to the walls on both sides of the structure, so that more cosmic rays were visualized as coming from the area of that passage than from the surrounding area. Thus, using the known structure, we were able to confirm the extent to which a structure of about 2 meters could be visualized. Next, the central region of Temple 11 was examined to see if there were any regions where more cosmic rays came from compared to the

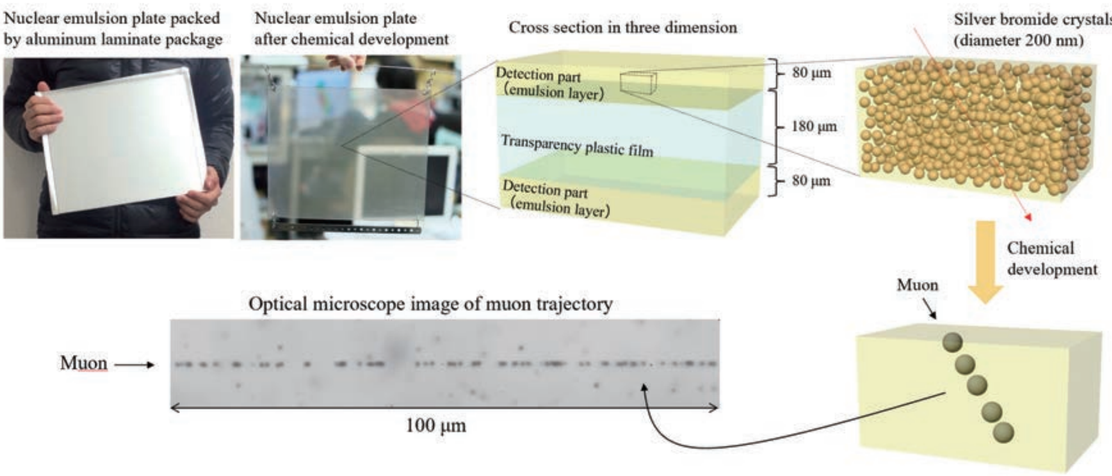

Figure 3 Nuclear emulsion plate. A latent image is generated and recorded on a 200 nm silver bromide crystal in the path of the charged particles in radiation. By developing the latent image into silver particle, muon tracks are fixed in the nuclear emulsion plate. The trajectory can be measured by observation with a optical microscope.

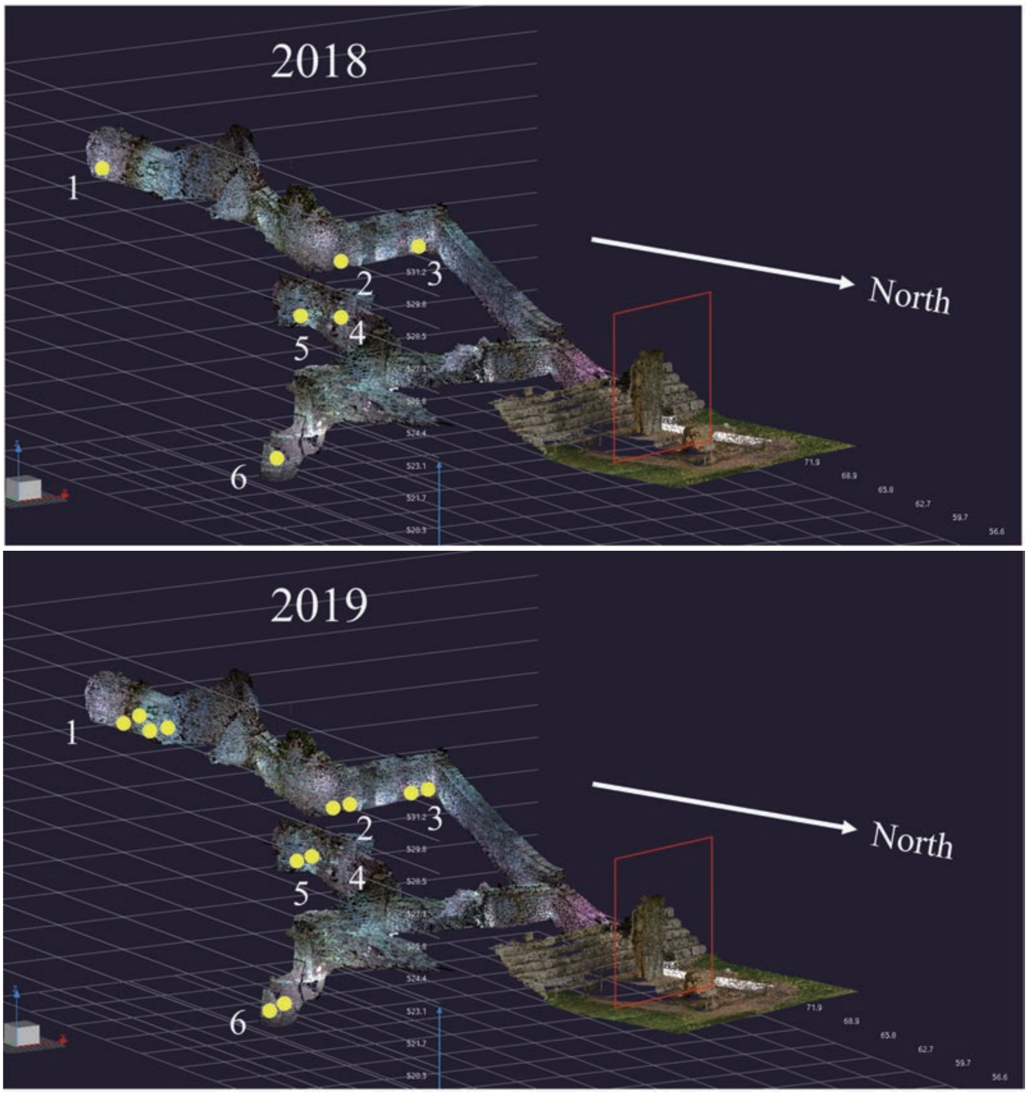

Figure 4 Inner tunnel of Temple 11 pyramid and location of detectors in 2018 and 2019.

Figure 5 Aluminum plate detectors installed in the tunnel of Temple 11 Pyramid in 2018 and 2019.

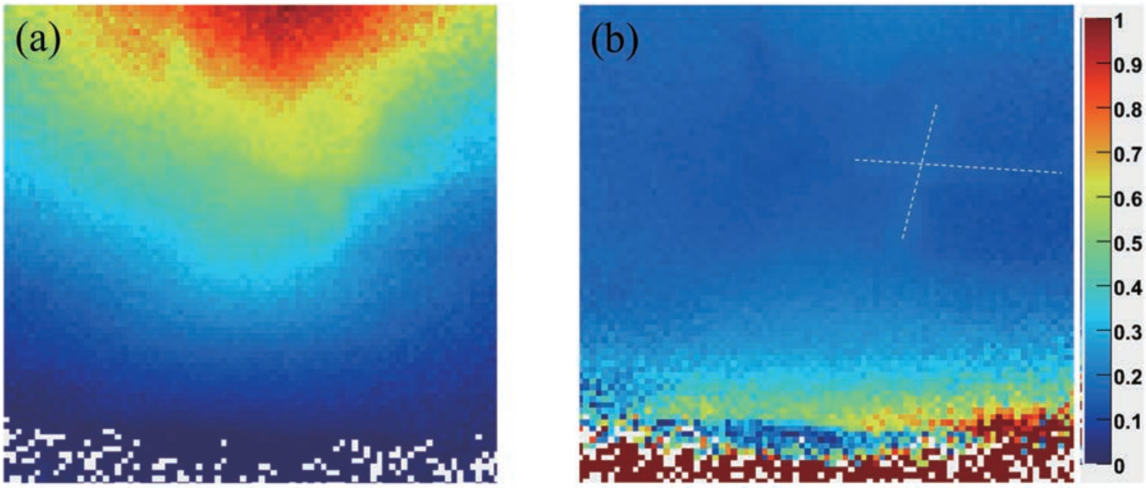

Figure 6 Cosmic ray image obtained from Detector 1 of Temple 11 installed in 2018. (a) Distribution of cosmic ray muon flux, (b) Distribution of transmission rate obtained from cosmic ray muon flux. The structure of the passage was confirmed along the dotted line.

Figure 7 Structure of the upper passageway of Temple 11

surrounding area, but as in the above, no structure was identified that could be recognized as a cavity of about 2 meters. Based on these results, a cavity of about 2 meters in length left in a hollow state was not detected within the confirmed region, but the possibility remains that the space was not detected because it had collapsed, a point that requires attention in the cosmic ray survey. The cosmic ray imaging cannot distinguish between a cavity that did not exist at the time of construction and a cavity that collapsed and filled in later, so it can only be detected as a clear image if it remains as a cavity.

During the measurement of Temple 11, some technical problems arose due to the tuff which is the main stone material that make up the Copan archaeological site. Specifically, the trajectory of radiation from the tuff was recorded on the nuclear emulsion plate during the measurement, and this affected the analysis of cosmic ray muons, which we wanted to capture as a signal, as noise. As a countermeasure, we shortened the observation period from 60 days for the first observation to 44 days for the second observation. Such measures are necessary when observing sites composed of sedimentary rocks of volcanic origin such as tuff, so care must be taken in future measurements. On the other hand, for sites composed of limestone, such as the Egyptian pyramids, long-term observations over a period of several months are possible. For example, among Maya sites, the Tikal archaeological site is composed of limestone, and therefore, cosmic ray imaging under better conditions is considered possible.

In the future, we expect that cosmic ray imaging will be actively applied not only to the additional survey of the Copan archaeological site targeted in this study, but also to other Maya sites such as the Tikal archaeological site, and that interesting new findings will be obtained as Maya archaeology.

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