

THE PROSPECT OF MUOGRAPHIC DETECTION USING PLASTIC SCINTILLATOR IN INDONESIA - A REVIEW

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Abstract

Muography technology has evolved over the past decade for various observational applications without using radioactive materials. Muography utilizes naturally occurring muons to penetrate objects with thick shielding and pass through kilometers of rock. Detectors are required to generate an image of an object obtained from muon captures. Various studies have created images of magma flow, thus enabling monitoring of active volcanoes, discovering hidden chambers within temple or pyramid structures, and so on. Plastic scintillation detectors are widely used in various muography applications due to their reliability and robustness in various challenging environments, ability to move flexibly, and cost-effectiveness. Muography can be applied in Indonesia, one of which is to monitor magma movement in volcanoes to provide early warning to the surrounding communities.

Keywords: Detector; Muon; Muography; Plastic scintillation detectors; Volcanoes monitoring

Introduction

Muons are naturally occurring charged particles produced by the interaction of cosmic rays with the Earth's atmosphere. These particles penetrate the Earth's surface at extremely high speeds (Mahon *et al.*, 2018). Although muons share similarities with electrons, they are about 207 times heavier (Leone *et al.*, 2021). At sea level, muons typically carry energies of 3-4 GeV and arrive at a rate of

approximately one particle per square centimeter per minute. Thanks to their high energy-about four orders of magnitude greater than that of conventional X-rays-they can penetrate dense materials and travel through kilometers of rock (Mahon *et al.*, 2018).

Muography is an imaging technique that takes advantage of these penetrating muons. By

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measuring the density of a target object, it enables the visualization of internal structures in large-scale objects (Cimmino, 2021). This non-destructive and non-radioactive method has gained recognition for its safety and effectiveness in applications where traditional imaging techniques are limited.

Over the years, muography has been widely applied in fields such as volcanology (Marteau *et al.*, 2012; Cârloganu *et al.*, 2013; Nishiyama *et al.*, 2014), tidal measurements (Tanaka *et al.*, 2021), cargo inspection at border crossings (Antonuccio *et al.*, 2016), nuclear storage monitoring (Park *et al.*, 2022), underground imaging through boreholes (Bonneville *et al.*, 2019), the scanning of archaeological heritage sites like pyramids and temples (Aguilar *et al.*, 2013; Melesio, 2014), etc.

The versatility of muography largely depends on the detectors used to measure and track muon interactions within a given object. Detector designs and capabilities vary based on the specific application, but recent advancements have significantly improved their reliability, durability, and energy efficiency (Bonomi *et al.*, 2020).

This article examines the potential of muography technology in Indonesia. It highlights the technology's diverse applications across various fields, including volcanology and archaeology. Additionally, it emphasizes its significance in addressing Indonesia's unique environmental and geophysical challenges.

Muography Principle

When a muon passes through an object, it decelerates and loses energy primarily due to atom excitation, ionization, and bremsstrahlung-radiation processes. While it may lose energy and be absorbed in dense materials, the muon can also be deflected or scattered from its straight-line trajectory due to multiple Coulomb scattering (Leo, 1994; Knoll, 1999). The extent of deflection and absorption is influenced by the muon's initial energy and the density and thickness of the object it traverses.

In this study, the term *muography* will refer to muon-based imaging techniques, specifically muon absorption radiography and muon scattering tomography (MST). In muography, the difference between the two techniques is that muon absorption radiography is suitable for gigantic objects, while MST is more effective for small to medium-sized objects. As seen in Figure 1, MST requires two detectors placed before and after the target object to reconstruct the muon path passing through it. This makes the technique unsuitable for large objects.

Meanwhile, muon absorption radiography only needs one detector placed after the object (IAEA, 2022).

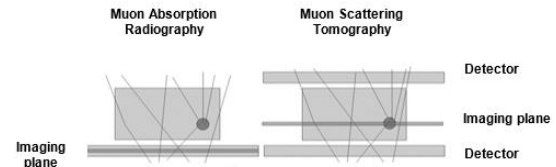


Figure 1. Schematic visualization of absorption radiography and scattering tomography and the corresponding detector geometries (Kaiser, 2018; IAEA, 2022)

Muon Absorption Radiography

In muon absorption radiography, the absorption of muons by matter is determined based on the attenuation of muon flux. The measured muon flux is then compared to the 'free sky' flux to produce a transmission rate. Since it is not possible to place a detector above large objects like a volcano, a free sky measurement is used as a substitute. Therefore, the effective muon transmission as a function of zenith (θ) and azimuth (φ) angles can be estimated by the following equation (Cimmino *et al.*, 2019; Saracino *et al.*, 2017a; 2019):

$$T_M(\theta, \varphi) = \frac{\Phi_T(\theta, \varphi)}{\Phi_{freesky}(\theta, \varphi)} \quad (1)$$

from the above equation, the transmission rate is a ratio between the muon flux that passes through a target $\Phi_T(\theta, \varphi)$ and the muon flux in the free sky $\Phi_{freesky}(\theta, \varphi)$.

Measured flux can be computed through the following equation (Baccani *et al.*, 2019):

$$\Phi_M(\theta, \varphi) = \frac{N(\theta, \varphi)}{t A_{eff}(\theta, \varphi)} \quad (2)$$

with $N(\theta, \varphi)$ as the number of detected tracks, and t as the acquisition time, and $A_{eff}(\theta, \varphi)$ as the detector's effective area.

The following equation expresses the relative transmission equation, which is useful for identifying cavities (Cimmino *et al.*, 2019; Saracino *et al.*, 2017a, 2019):

$$R(\theta, \varphi) = \frac{T_M(\theta, \varphi)}{T_E(\theta, \varphi)} \quad (3)$$

Where $T_M(\theta, \varphi)$ is the measured transmission, and $T_E(\theta, \varphi)$ is the expected transmission. The

expected transmission is defined as the ratio of the muon flux obstructed by high-density material to the muon flux in the free sky. The relative transmission will have a value close to 1 if the muons passing through an object along the (θ, φ) direction do not encounter an empty space or density anomaly. However, if the muons pass through an empty space along the (θ, φ) direction, the measured transmission will be greater than the expected transmission, and the relative transmission will have a value greater than 1.

$$R(\theta, \varphi) > 1 \quad \text{If it passes through empty space} \quad (4)$$

and

$$R(\theta, \varphi) \sim 1 \quad \text{If it does not pass through empty space} \quad (5)$$

An evaluation with software simulation is required to obtain information about the density distribution of the target object.

The absorption of muons within a target volume is utilized to produce either a two-dimensional image of the object's density (Cimmino, 2021) or, with the use of multiple detectors, a three-dimensional absorption image (Kaiser, 2018). This capability makes the technique particularly effective for imaging large-scale structures.

One of the primary advantages of muon absorption radiography is its ability to penetrate thick and extensive objects, spanning several kilometers, without relying on radioactive sources. The density imaging that is produced by this technology is capable of identifying voids or high-density regions within massive structures. As a result, it is a perfect technique for applications such as monitoring magma in volcanoes or locating hidden chambers in pyramids and temples. Furthermore, its non-invasive nature makes it highly suitable for long-term observations, such as tracking magma movement in active volcanoes or preserving archaeological heritage without requiring direct contact or excavation.

Despite these benefits, muon absorption radiography has certain limitations. Its reliance on muon intensity measurements means it is less effective in detecting small anomalies or subtle density variations, which reduces its suitability for tasks requiring detailed imaging, such as inspecting hazardous materials in cargo containers. This limitation highlights the need for complementary techniques when precision imaging is essential.

Muon Scattering Tomography (MST)

In MST, when a muon passes through an object, it undergoes deflection or scattering by its atoms based on the multiple Coulomb scattering effect. By measuring the scattering angle of a muon after it passes through an object, the object's internal structure can be mapped based on the level of muon deflection. Multiple Coulomb scattering can be estimated using Molière theory (Bethe, 1953), with the scattering angle for small angles following a Gaussian distribution and for large angles following Rutherford's formula. The Gaussian approximation of the angular distribution for the small scattering angles can be calculated as follows (Lynch and Dahl, 1991):

$$\sigma_\theta = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{\frac{x}{X_0} \left[1 + 0.038 \ln \left(\frac{x z^2}{X_0 \beta^2} \right) \right]} \quad (6)$$

Where σ_θ is the scattering angle in the plane perpendicular to the particle motion, βc is particle velocity ($v = \beta c$, where c is the speed of light), p is muon momentum in MeV/c, z is particle charge (muons, $z = 1$), x is the path length of muons passing through the material in g/cm², X_0 is radiation length in g/cm². X_0 can be calculated using:

$$X_0 = 716.4 \text{ g/cm}^2 \frac{A}{Z(Z+1) \ln(287/\sqrt{Z})} \quad (7)$$

where A is the mass number, and Z is the atomic number of the element. From equations (6) and (7), it can be seen that the scattering angle correlates with Z . The X_0 value will decrease as the material's Z number increases. The following table shows the Z number and X_0 with the material. The various types of materials shown in Table 1, X_0 is obtained using equation (7).

Table 1. Atomic number and radiation lengths of materials (Patrignani *et al.*, 2016)

Material	Z#	Radiation Length, X_0 (g/cm ²)
Water (H ₂ O)	O: 8, H: 1	36.08
Polyethylene		44.77
Shielding Concrete		26.57
Aluminum (Al)	13	24.01
Iron (Fe)	26	13.84
Copper (Cu)	29	12.86
Tungsten (W)	74	6.76
Lead (Pb)	82	6.37
Uranium (U)	92	6.00

The degree of muon scattering is determined by the density and composition of the material it traverses. Denser materials, which typically have a higher atomic number (Z), such as heavy metals and other high-density substances, cause greater scattering of muons. In contrast, materials with lower density result in less scattering to allow for differentiation between regions of varying density within an object.

Nuclear materials generally exhibit high Z values (as shown in Table 1), which facilitates their identification based on scattering characteristics. When muons pass through an object from multiple angles, the resulting scattering data provides a wealth of information about the material's internal composition. This data can then be analyzed using advanced computational algorithms to reconstruct a three-dimensional image of the object's internal structure with high precision.

Some advantages of MST include its suitability for non-invasive inspections requiring high sensitivity in high-density objects, allowing it to detect high-density materials better than absorption radiography. This technique enables the detection of small details in large objects because changes in the muon scattering angle can provide information about high-density materials, such as heavy metals or hazardous substances. This is especially useful for applications like cargo inspection at border crossings.

However, MST also has some limitations, including the need for more data for high accuracy, which results in relatively longer detection and image processing times. MST also requires complex data processing software and has limitations regarding the thickness of objects that can be analyzed. Excessive thickness can reduce the number of remaining muons available for analysis so that the image generated is less accurate.

Detectors for Muography

Although muon interactions with objects occur naturally, a detector is essential to measure and record these interactions effectively. The primary function of a muon detector is to convert the energy deposited by muons into an electric signal for analysis. This conversion enables the accurate detection and imaging of internal structures in various applications of muography.

Over the years, several types of muon detectors have been developed to meet the growing demands of muography applications. These include ECC (Emulsion Cloud Chamber) emulsion detector

(Nishiyama *et al.*, 2017, 2019; Tioukov *et al.*, 2019), Cherenkov detector (Catalano *et al.*, 2016), plastic scintillator (Tanaka *et al.*, 2010; Anghel *et al.*, 2015; Baccani *et al.*, 2019; Bonneville *et al.*, 2019; Lo Presti *et al.*, 2020), scintillator arrays (Lesparre *et al.*, 2017), Close cathode chamber (CCC) detector (Oláh *et al.*, 2018a), and Multi-wire Proportional Chamber (MWPC) detector (Oláh *et al.*, 2019). The continual development of highly responsive and accurate detectors remains a critical requirement for advancing muography technologies.

Muon detectors designed for absorption-based muography often encounter harsh and challenging environmental conditions. To perform reliably, these detectors must demonstrate stability in varying environmental settings while maintaining minimal power consumption. Moreover, ease of transport and installation is vital, particularly when accessing remote or difficult-to-reach locations for field applications. To meet these criteria, specialized front-end electronics and data acquisition systems are often necessary (Bonomi *et al.*, 2020).

The durability of muography detectors is another key consideration, as they must operate effectively over long periods with minimal need for direct human intervention. Different muographic applications may require specific detector shapes, sizes, and configurations to achieve optimal performance (Bonechi *et al.*, 2020). Therefore, the choice of a suitable detector depends on factors such as available space, infrastructure constraints, and the specific objectives of the muographic study (Leone *et al.*, 2021).

Nuclear Emulsion Detector

Nuclear emulsion (NEF) is a unique photographic film that detects minimal ionizing particles like cosmic ray muons. This emulsion film is exceptionally lightweight and does not require electricity and maintenance, making it suitable for mountainous areas (Tanaka *et al.*, 2007; Tioukov *et al.*, 2019). This nuclear emulsion film can provide information in the form of a 3D image with sub-micrometer accuracy (Nakamura *et al.*, 2006; Morishima, 2015; Nishio *et al.*, 2015; Morishima *et al.*, 2017). The film is usually replaced every two months (Morishima *et al.*, 2017). After use, this NEF is processed using photographic development in a darkroom, and then it needs to be read by an automated nuclear scanning system (Hamada *et al.*, 2012; Morishima *et al.*, 2013; Yoshimoto *et al.*, 2017).

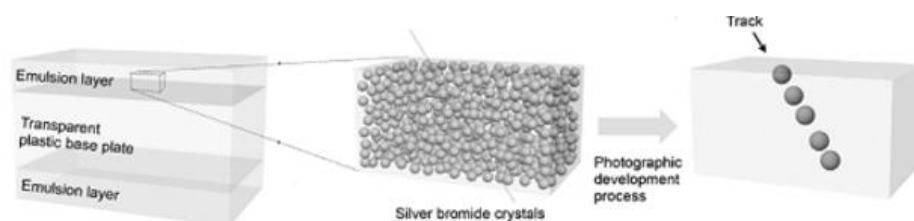


Figure 2. Schematic view of a nuclear emulsion film (Morishima *et al.*, 2017)

NEF can be made from an arrangement of silver bromide crystals dispersed in a thick, sensitive emulsion layer and adhered to both sides of a transparent plastic base, as seen in Figure 2 (Morishima, 2015; Morishima *et al.*, 2017). Each film will then be packed in an aluminum laminated vacuum package. This is done to prevent damage from light exposure, to control humidity (30% relative humidity, RH), and to avoid dust contamination (Morishima *et al.*, 2013; Tioukov *et al.*, 2019).

The charged particles passing through the emulsion layer leave their traces in the form of a 3D trajectory, which is recorded, and the results can be determined after undergoing the chemical development process. Typically, the film can last for 2-3 months in a 25°C environment by adjusting the volume occupancy of silver bromide crystals by 35% (Morishima *et al.*, 2017). The reconstruction of muon tracks involves identifying coincidences between the two-layered films based on signal selection criteria, and subsequently, these identified coincidences are tallied as detected muons (Morishima *et al.*, 2013).

Gaseous Detector

In muography, gaseous detectors are known for their durability and capability to operate outdoors for extended periods (Morishima *et al.*, 2017), providing excellent spatial resolution and real-time detection capabilities (Procureur and Attié, 2019). Despite these advantages, they are less practical than other alternatives due to their larger size (Morishima *et al.*, 2017), and the costly electronic systems required for operation. Additionally, gaseous detectors often exhibit less stable performance under variable outdoor conditions (Procureur and Attié, 2019), and are more complex to operate and maintain in field environments compared to scintillation detectors (Bonomi *et al.*, 2020).

Gaseous detectors encompass various types designed for specific applications in muography. Examples include Close Cathode Chambers (CCC)

for borehole-based muography (Varga *et al.*, 2013), Glass Resistive Plate Chambers and multi-wire proportional chambers (MWPC) for muon imaging of volcano (Carloganu *et al.*, 2013; Oláh *et al.*, 2019), MWPC for borehole-based muography (Oláh *et al.*, 2018a; Oláh *et al.*, 2018b). Another advanced variation is the micro-pattern gaseous detector, such as Micromegas, which offers improved precision and versatility for muon detection (Bouteille *et al.*, 2016).

The working principle of gaseous detectors involves muons traversing a gas-filled volume, leaving behind an ionized trail as they interact with the gas molecules. An applied electric field collects the resulting electrons and ions, allowing the detection process to proceed. Standard configurations often feature a cylindrical design with a thin wire anode to gather the electrons produced during ionization (Bonechi *et al.*, 2020). Real-time analysis is then performed to determine the muon track parameters, enabling immediate reconstruction of the particle's trajectory (Morishima *et al.*, 2017).

Cherenkov Detector

Cherenkov-based detector was used in the muography experiment due to its higher spatial resolution and ability to disregard the background (Catalano *et al.*, 2016). Cherenkov radiation occurs when charged particles, like muons, move through a dielectric medium at a speed (v) exceeding the medium's speed of light. The Cherenkov detector operates in the visible and ultraviolet regions of the electromagnetic spectrum. Imaging Atmospheric Cherenkov Telescopes (IACT) was used for performing muography of giant objects using multiple telescopes such as VERITAS (Weekes *et al.*, 2002), MAGIC (Tridon *et al.*, 2010), H.E.S.S. (Benbow, 2005). Cherenkov Telescope Array (CTA) then became the next generation of IACT (Actis *et al.*, 2011). IACT and CTA consisted of an optical system comprising highly reflective mirrors concentrating Cherenkov light onto a multi-pixel camera with rapid read-out electronics.

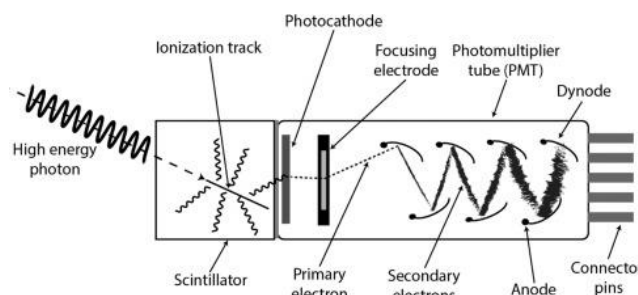


Figure 3. Part of scintillation detector (Kerlin and Upadhyaya, 2016)

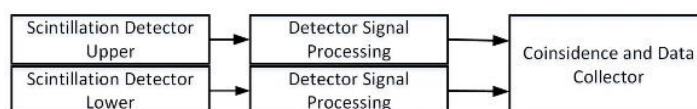


Figure 4. Schematic diagram of muography detector simplification

Scintillation Detector

There are various optimal criteria for a muon scintillator detector, which encompass (1) achieving high luminance efficiency, (2) exhibiting a short decay time, (3) absence of afterglow emissions, (4) possessing a short attenuation length, and (5) cost-effective (Yamashina *et al.*, 2010). The scintillation detectors need a power supply, which can be provided by the photovoltaic panel (Gibert *et al.*, 2010).

The scintillation detector, as illustrated in Figure 3, comprises two essential components. The first is the scintillator, which acts as the medium for photon ionization by converting the energy deposited by muons into visible light. The second component is the photomultiplier tube (PMT), which amplifies and converts the emitted photon light into measurable electrical signals for further analysis.

The schematic diagram in Figure 4 above explains the sequence of processes for detecting muons, which minimally involves using two scintillation detectors stacked on each other. The output signals from the detectors are processed by a signal processor to obtain the digital signal. Then, the output digital signals are synchronized with coincidences to obtain the single count value of the muon number.

Scintillation detectors are classified into two main types based on their material composition: organic materials, such as liquid and plastic scintillators, and inorganic materials, such as crystals. Plastic scintillators are widely used as muography detectors due to their robustness, which allows them to function effectively in harsh environments (Bonechi *et al.*, 2020). They offer

additional advantages, including ease of machining, a flexible structural design, stable performance, and adaptability for various applications (Procureur, 2018; Yang *et al.*, 2022). In muography, plastic scintillators are typically configured in a telescope structure, where multiple scintillator planes are aligned to detect and trace the trajectory of muons passing through the target object. This arrangement enhances angular resolution and enables accurate reconstruction of internal density distributions in large-scale structures.

The telescope structure is adopted in muon absorption imaging, utilizing multiple parallel-arranged scintillator planes capable of measuring the angular distribution of muons behind the target area and generating images using the back-projection method (Bonomi *et al.*, 2020). This configuration enables the generation of detailed images using the back-projection method, which reconstructs the internal density distribution based on the detected muon trajectories. A key performance parameter in this structure is the angular resolution, which is influenced by the spatial resolution of the scintillator planes relative to the maximum distance between them. Additionally, the aperture, determined by the area of the scintillator planes over their separation distance, plays a critical role in ensuring the accuracy and precision of the imaging results (Yang *et al.*, 2022).

When muon energy emissions interact with a scintillation detector, the deposited energy is converted into visible light signals through the scintillation process. These light signals are subsequently captured by a photosensor, which converts them into electronic signals for further

analysis. Traditionally, photomultiplier tubes (PMTs) were used as photosensors; however, Silicon Photomultipliers (SiPMs) have emerged as a widely preferred alternative due to their lower cost, reduced power consumption, and compact design. SiPMs offer improved energy efficiency and reliability, making them particularly suitable for modern muography applications where portability and long-term operation are essential. (Bonomi *et al.*, 2020; Bonechi *et al.*, 2020).

In a plastic scintillator, muons interact with the atoms of the scintillator material as they pass through, resulting in energy loss and Coulomb scattering (Saracino *et al.*, 2017b; Procureur, 2018). The absorbed energy excites the scintillator molecules, which subsequently release this energy in the form of photons. These emitted photons are collected by photosensors, such as (SiPMs) or (PMTs), which convert the optical signals into corresponding voltage signals for further processing. This efficient conversion process is critical for detecting and analyzing muon trajectories in muography applications (Procureur, 2018).

The scintillator for muography is mainly made of organic material, such as polystyrene or polyvinyltoluene, and is doped with primary dopant and secondary dopant as a wavelength shifter. For example, Anghel *et al.* (2015) used 1% by weight of PPO as the primary dopant and 0.03% by weight of POPOP as a secondary dopant (Anghel *et al.*, 2015). Plastic scintillators used in the muography have several parameters, as shown in Table 2.

Table 2. Parameter of the plastic scintillator used in the muography experiment (Yang *et al.*, 2022)

Properties	Value
Base	Polyvinyltoluene
Dopant	POPOP
	p-Terophenyl
Atomic ratio (H: C)	11:10
Density (g/cm ³)	1.05
Refractive index	1.58
Light output (% anthracene)	55
Light yield (pe/MeV)	11000
Emission peak (nm)	405
Attenuation length (cm)	190
Slow/ fast yield	0.27
Fast decay time (ns)	2.1
Slow decay time (ns)	14.2

The size of the plastic scintillator can vary, depending on the needs. For muography purposes, plastic scintillators are made up to 1 m long or up to 6 m long and can be produced using an extrusion method with heating at its melting point (220-230°C) and molded into required shapes. The edges of the bars are sanded with fine sandpaper and polished with a transparent adhesive. Scintillator bars can also be coated with a 250 µm thick titanium dioxide (TiO₂) layer, which helps to reflect ultraviolet (UV) rays and the blue glow produced by radiation ionization (Anghel *et al.*, 2015).

The scintillator's shape for muography is either square, rectangular, or triangular bars, adjusted to obtain a position-sensitive detection layer to produce fewer read-out channels. Scintillators can be arranged with various detection layer configurations. Each bar is optically shielded so that particles passing through it will produce a light signal and reconstruct coordinates.

A scintillator telescope typically comprises two or more double layers of plastic scintillator bars, which are arranged to trace particles across multiple projections (Saracino *et al.*, 2017b; Baccani *et al.*, 2018). The configuration of the plastic scintillator bars can be adapted to suit the specific requirements of the experiment as it allows for flexibility in design and functionality. The number of bars in the array is carefully adjusted based on the size of the coverage area to ensure optimal detection efficiency and spatial resolution. This adaptability makes scintillator telescopes highly effective for a wide range of muography applications, from large-scale imaging to localized density measurements.

Plastic scintillator bars can be arranged sideways, as illustrated in Figure 5(a), using square or rectangular bars with dimensions tailored to match the surface area of the target being tested. In this configuration, muon particles interacting with the detector may strike either a single bar or two adjacent bars simultaneously. This arrangement provides a straightforward and efficient method for detecting muon trajectories by offering reliable spatial resolution while maintaining structural simplicity. Such configurations are particularly advantageous for applications requiring large-area coverage with minimal complexity in design and implementation.

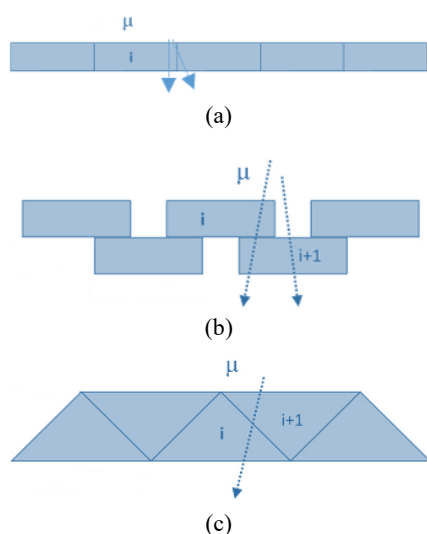


Figure 5. Configuration of scintillator bars (a) rectangular bars arranged sideways (Bonechi *et al.*, 2020); (b) rectangular bars arranged overlapping sideways (Baccani *et al.*, 2018; Baccani *et al.*, 2019); (c) triangular bars stacked on top of each other (Anastasio *et al.*, 2013; G. Baccani *et al.*, 2018; Baccani *et al.*, 2019)

The MIMA project (Baccani *et al.*, 2018; Baccani *et al.*, 2019) utilized rectangular bar scintillators overlapping sideways, as seen in Figure 5(b). This arrangement yields better spatial resolution than the above setup with the same number of read-out channels but employs a more complex coordinate reconstruction algorithm. This arrangement can identify two events: a muon hitting a single bar and a muon hitting two adjacent bars. This arrangement defines three different regions for each of its bars.

The following configuration involves using triangular bars stacked on top of each other, as in the MU-RAY project (Anastasio, 2013) (see Figure 5(c)). Incident particles will always hit two adjacent bars. This configuration allows spatial resolution to be achieved in an order of 3 mm. This resolution is better than that captured by the configuration in the overlapping sideways using the same number of read-out channels. In this configuration, the number of photons captured will increase proportionally with the increase in signal-to-noise ratio and spatial resolution obtained using large-area SiPMs directly connected to the scintillator.

Table 3. Summary of muography applications

Detector type	Active surface	Angular resolution	Method	Applied field	Ref.
Plastic scintillator	1-4 m ²	~ 0.1 to > 10 mrad	AM	Volcanology	(Tanaka <i>et al.</i> , 2009; Gibert <i>et al.</i> , 2010; Tanaka <i>et al.</i> , 2010; Carbone <i>et al.</i> , 2014; Tanaka <i>et al.</i> , 2014; Ambrosino <i>et al.</i> , 2015; Rosas-Carbajal <i>et al.</i> , 2017; Saracino <i>et al.</i> , 2017; Baccani <i>et al.</i> , 2018; Baccani <i>et al.</i> , 2019; Lo Presti <i>et al.</i> , 2020)
				Archaeological	(Hanazato, <i>et al.</i> , 2014; Okamoto, 2014; Hanazato <i>et al.</i> , 2017; Kouzes <i>et al.</i> , 2022)
				Mining	(Bryman <i>et al.</i> , 2014; Bryman <i>et al.</i> , 2015; Borselli <i>et al.</i> , 2022)
				Oceanografi	(Tanaka <i>et al.</i> , 2021)
			MST	Security	(Anghel <i>et al.</i> , 2015 ; Antonuccio <i>et al.</i> , 2016; Park <i>et al.</i> , 2022)
Gaseous detectors	1 to > 10 m ²	~ 0.1 to ~ 10 mrad	AM	Volcanology	(Carloganu <i>et al.</i> , 2013; Oláh <i>et al.</i> , 2018a; Oláh <i>et al.</i> , 2019; Procureur and Attié, 2019)
			AM	Geology	(Tanaka <i>et al.</i> , 2020)
			MST	Security	(Durham <i>et al.</i> , 2018; Bonomi <i>et al.</i> , 2022; Lorenzon <i>et al.</i> , 2023)
Nuclear Emulsions	< 1 m ²	< 10 mrad	AM	Volcanology	(Nishiyama <i>et al.</i> , 2014; Tioukov <i>et al.</i> , 2019)
			AM	Geology	(Nishiyama <i>et al.</i> , 2017, 2019)
			AM	Civil	(Kitagawa <i>et al.</i> , 2023)
			AM	Safety	(Morishima <i>et al.</i> , 2017)

Legend:

AM = Absorption muography

MST = Muon scattering tomography

The photons produced from interactions within the scintillator can be further optimized using wavelength shifting (WLS) fibers, which enhance light collection efficiency. These fibers absorb the emitted photons and re-emit them at a higher wavelength, reducing attenuation losses during transmission. The re-emitted photons are then directed to photosensors, such as (PMTs) or (SiPMs), for efficient detection and signal conversion. This technique improves the overall light yield and enhances the performance of the scintillation detector, particularly in applications requiring precise and reliable muon detection (Yang *et al.*, 2022).

Information about muon detectors are summarized in Table 3.

Muon Detection in Indonesia

Researchers have been developing and researching muon detection in Indonesia for the last decade. In 2014, Hanazato *et al.* used muography to survey the structure of the Prambanan Temple, which the Central Java Earthquake damaged in 2006 (Hanazato *et al.*, 2014). After the earthquake, all temple buildings in the Prambanan complex were restored except Candi Siva. Candi Siva is Prambanan's oldest and highest temple building, and the condition of the inside structure could not be detected. Muography was used to project the inner structure of Candi Siva, including the size and location of its hidden room, and was carried out for 5 months (Hanazato *et al.*, 2014; Hanazato *et al.*, 2017). The detection method of Candi Siva's inner structure used plastic scintillators as scintillating detectors assembled with PMTs and connected to an electronic support system and laptop. This instrument was put on the corner of the base floor with an active detection area of 1764 cm² with an angular interval of 70 mrad. The research concluded that the inner structure of Candi Siva was safe from structural damage (Hanazato *et al.*, 2017).

In the other research, the simple way to develop a muon detector was using a CMOS sensor from a webcam and was used to substitute scintillator and PMT since it was much simpler and cheaper (Nurawan *et al.*, 2018; Riveli, 2018). In this research, the photon energy of visible light was detected by a photodetector, which was installed inside a CMOS sensor, thus creating a photoelectric effect. Free electrons from this occurrence generated electricity from the USB hub to the PC. The software processed the muon images and gave information, including intensity and frequency.

To the best of the author's knowledge, there has been no extensive scientific discussion on muon

detection research in Indonesia apart from the studies mentioned above. Existing literature remains limited, with only a few documented applications, such as the structural imaging of Prambanan Temple. This highlights a significant research gap and emphasizes the need for further investigations into the potential applications of muon detection technology across various scientific and industrial fields in Indonesia.

Prospect of Muography in Indonesia

Muography is likely to be applied in Indonesia for various purposes, some of which are outlined below.

Volcanology

Indonesia is home to 127 volcanoes, with 77 classified as active, including prominent examples such as Mount Merapi, Mount Semeru, Mount Galunggung, and Mount Anak Krakatau (Gunawan *et al.*, 2019). This concentration of active volcanoes underscores the country's considerable risk of volcanic disasters. According to the National Disaster Management Agency (BNPB), Indonesia experienced four volcanic eruptions in 2023, one eruption each in 2021 and 2022, and seven eruptions in both 2019 and 2020 (BNPB, 2024). These eruptions have resulted in significant human casualties, extensive damage to infrastructure, and substantial economic losses. Given the frequency and severity of volcanic activity, enhancing and developing effective volcanic disaster mitigation strategies is of paramount importance to safeguard communities and reduce potential impacts.

One of the volcanic mitigation measures in Indonesia is implementing a volcano monitoring system, which includes monitoring seismic activity, temperature, surface deformation, and remote sensing using satellites (Alvarado *et al.*, 2007). In volcano monitoring, the Indonesian Center for Volcanology and Geological Hazard Mitigation (CVGHM) collaborates with the U.S. Volcano Disaster Assistance Program (VDAP), funded by the U.S. Agency for International Development (USAID) and the U.S. Geological Survey (USGS) (Lowenstern *et al.*, 2020) in the form of geological mapping, seismic monitoring, aerial monitoring, and volcanic gas observations. The equipment used for volcano monitoring in Indonesia to detect early signs of eruptions includes satellite remote sensing (Pallister *et al.*, 2019) and ground-based monitoring systems such as seismometers (Indrastuti *et al.*, 2019), Global Positioning System (GPS) (Hotta *et al.*, 2019), tiltmeters (Andreastuti *et al.*, 2019), Electronic Distance Measurement (EDM)

(Nandaka *et al.*, 2019), Differential Optical Absorption Spectroscopy (DOAS) for SO_2 measurements (Primulyana *et al.*, 2019) and so on.

All of those volcano monitoring systems generally rely on ground-based (visual) monitoring that requires direct contact with the ground surface. Currently, there is still no magma movement monitoring from within. Muography offers an internal monitoring technique that can reveal magma flow and internal structural changes within the volcano. Muography technology can be used to measure magma levels and monitor the activity of active volcanoes. With the implementation of muography technology, magma movement can be easily observed because the empty areas in the vent have a lower density than magma and surrounding rocks (Leone *et al.*, 2021).

The application of muography in volcanology has several advantages, including its ability to be applied to volcanoes for long-term monitoring so that it can predict the volcanic hazard through imaging the density variation of the magma in the vent area in real-time. In the volcano's muography imaging, space in the vent has the least density than the magma and surrounding rocks, thus making the magma movement easy to observe (Leone *et al.*, 2021). Aside from that, the axisymmetric structure of the volcano makes it possible to assume that the density variations of muon particles are only localized in the crater area (Yamashina *et al.*, 2010). Muography can construct images of the magma column's movement before and after the volcanic eruption (Tanaka *et al.*, 2014). The abundant natural source of muons makes muography a technique that always has resources. Muography also enables detailed observation of the internal structure from outside the volcano without requiring direct contact with the ground surface, and it can map the internal structure over a wide area. An example of muography application on a volcano can be seen in Figure 6.

In addition to these advantages, muography has some limitations. It has a lower resolution than satellite remote sensing, GPS, or others. Muography also requires a long operational time to obtain accurate data due to fluctuations in muon flux, which can interfere with imaging results and require recalibration for accuracy. Muography equipment is composed of expensive specialized detection devices that may need to be more readily available in Indonesia. High rainfall and humidity can affect the sensitivity and accuracy of muography equipment and damage sensitive electronic components. This reduces the effectiveness of muography compared to weather-resistant techniques like remote sensing or other geophysical methods.

Future research could focus on developing durable muography equipment for long-term monitoring in volcanic areas. Research institutions in Indonesia need to establish collaborations with international universities or research organizations to accelerate the development of muography technology. With the application of muography technology in Indonesia, volcanic eruption disasters can be well predicted, thus maximizing volcanic disaster mitigation and minimizing the number of casualties.

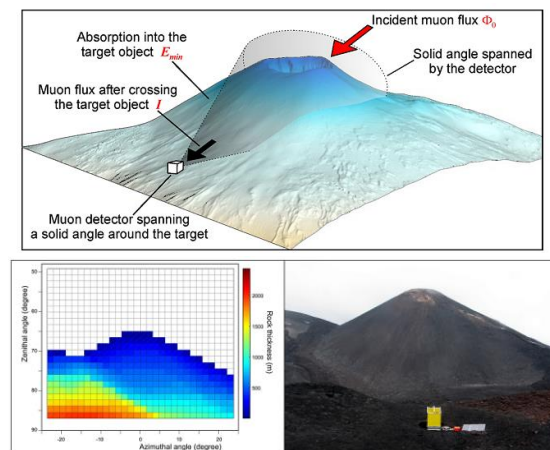


Figure 6. Muography for volcanoes imaging. Top: detector set up for muography in a volcano. Bottom: image reconstruction result (Carbone *et al.*, 2014)

Archaeological Heritage

Indonesia has relatively high seismic activity, often experiencing earthquakes with an intensity of more than 20 events per year (BNPB, 2024). The temples in Indonesia are historical relics over 1000 years old, so many of their stones have cracks or even decayed. Large structures like Prambanan Temple and Borobudur Temple are highly vulnerable to earthquake damage due to the age of their constituent rocks, which have been around for thousands of years. In Indonesia, the Indonesia Heritage Agency (IHA), under the Directorate General of Culture, oversees the management of temples and heritage sites. The maintenance and upkeep of temple structures are conducted by monitoring the structural stability of the temples, using crack meters, robotic total stations, geodetic GPS, digital inclinometers, and others.

By imaging their internal structure, muography can be applied to determine the condition inside these rock sites to facilitate maintenance. Using this technology, the internal structure of temples can be monitored to detect shifts, cracks, or structural weaknesses that are not visible from the outside without excavating or exposing stone floors or other components. This is highly beneficial for identifying temple buildings that need reinforcement to withstand earthquakes. The 3D imaging from muography can provide a more detailed picture of the internal structure of a temple, aiding in conservation or restoration planning, as the data produced is quite detailed.

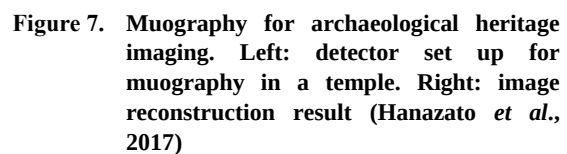


Figure 7. Muography for archaeological heritage imaging. Left: detector set up for muography in a temple. Right: image reconstruction result (Hanazato *et al.*, 2017)

Cargo Inspection

X-ray scanner technology has been widely used in the past decade in ports as a non-invasive inspection technology capable of detecting density differences in cargo materials, which are then turned into images (Molder *et al.*, 2009). X-ray radiography can construct an image from the object inside a cargo container by detecting the differences in its object's density. Generally, pulsed X-ray linacs are used to generate high-energy X-rays so that they can penetrate deep inside the cargo

container. Several X-ray scanners are used across various ports in Indonesia, including the HCVM model X-ray container scanner and the Hi-co X-ray scanner. The Hi-co X-ray scanner has limitations, such as its inability to scan light-sensitive imported goods or items containing radioactive sources.

The gamma-ray detection system usually uses high activity of Cobalt-60 or Cesium-137 sources. It can produce higher-resolution images than the X-ray system, yet it cannot be turned off (Isnaini *et al.*, 2021). Radiation portal monitors (RPMs) detect radioactive materials using gamma rays or neutron detectors. This technology uses large detectors and is highly efficient (Livesay *et al.*, 2014; Gilbert *et al.*, 2015). In this technology, if radioactive material is shielded by sufficiently thick shielding (dense material with high Z), then the RPM may be unable to detect it.

In addition to RPMs, there is also the Vehicle and Cargo Inspection System (VACIS) Gamma Ray Container Scanner, which uses gamma rays. There are two types of VACIS: portal VACIS gamma ray and mobile VACIS gamma ray. Portal VACIS is placed in customs areas, especially at busy ports where export and import goods are unloaded from ships. At the same time, a mobile VACIS gamma ray is mounted on a vehicle equipped with container scanning equipment.

In Indonesia, x-ray scanners are used to scan imported goods, whereas gamma-ray scanners are used to scan exported goods. This is because gamma-ray scanners provide more accurate detection than x-ray scanners (Febrica, 2023). However, x-ray scanner technology has drawbacks because the generated photons cannot penetrate far into the cargo contents (container cargo) (Gomes *et al.*, 2013). X-ray scanners are often turned off when it rains (to prevent them from getting wet), allowing container trucks to pass through freely without inspection (Pamadi and Sari, 2022). Furthermore, using X-ray and gamma-ray scanners requires caution because they result in high radiation doses that harm the human body (Bendahan, 2017).

Muography is one of the passive detection techniques that can be applied to observe the cargo container. Among the cargo inspection technologies mentioned, muography is also suitable for application in Indonesia since it can see through dense and thick materials; this technology allows for in-depth inspection without opening the container. It can detect hidden objects or hazardous materials inside containers, such as nuclear materials or contraband, and does not damage or alter the contents inside. So that this technology can be applied in Indonesia, especially for special cases that do not require a short detection time.

Muography, unlike other methods, does not use radioactive sources that could be hazardous for operators or the surrounding environment, as it only utilizes muons from natural cosmic rays. Muography can produce high-resolution images using detector units, making it easier to identify the structure of objects or materials within the container. Additionally, muography covers a wide area, making it suitable for large containers or dense materials that are difficult to inspect with X-rays or another more limited method.

In addition to the advantages of using muography, there are some drawbacks. For example, scanning with muography generally takes longer than an X-ray or gamma scanner. This is because muography relies on muons, so the imaging process can be affected by fluctuations in muon particles, which can impact the consistency of the results and slow down the scanning time. This becomes a challenge, especially for inspections at ports or locations with high container traffic that require quick scanning. In addition, muography technology is more effective for materials with significant density differences. For materials with similar densities, the detection capability may decrease. The detectors and equipment used in muography are typically expensive and complex, resulting in high installation and maintenance costs.

Spent Nuclear Fuel Monitoring

Monitoring the spent nuclear fuel inside dry cask storage is performed to know the fuel's location and structural condition without harming its system using nondestructive assay (NDA) measures based on ionizing radiation. This can be performed using various imaging techniques such as x-rays, gamma-rays, neutrons, and muons (Greulich *et al.*, 2016). X-rays and gamma-rays emitted relatively low-energy photons, mostly below 1 MeV. These make it challenging to deliver radiographic images of the storage with concrete and metal structures, and they can cause radiation exposure to the human body (Medalia, 2010). The other monitoring method is by measuring neutrons emitted from the spent nuclear fuel inside dry cask storage using ^3He or BF_3 detectors, yet their detection efficiency is poor, so they are not enough to generate the tomography images (Medalia, 2010; Runkle *et al.*, 2010).

Currently, the reactor fuel in Indonesia from the three research reactors owned by BRIN is partly sent back to its country of origin and stored in temporary storage within the Interim Storage Facility for Spent Fuel (ISSF). However, in the long term, this temporary storage facility will be unable to accommodate the continuously increasing spent

fuel as the research reactors in Indonesia continue to operate. Moreover, the ISSF faces several issues, such as the aging of its system, structure, and components (SSC). Due to these challenges, the Nuclear Energy Research Organization-BRIN (formerly BATAN) has planned to establish a dry storage system before 2074 to address the spent fuel storage problems (Ratiko *et al.*, 2020).

In addition, as part of efforts to reduce dependence on fossil fuels in electricity generation and Indonesia's commitment to reducing carbon emissions by 29% by 2030 (Presiden Republik Indonesia, 2016), nuclear power plants can begin construction (Presiden Republik Indonesia, 2020). With a Nuclear Power Plant (NPP) in Indonesia, a dry storage system will also need to be built. So, in the future, monitoring the fuel used in the dry cask must be carried out. Aside from the previous method, muography is the most effective method to monitor the spent nuclear fuel inside dry cask storage. Muography exploits the cosmic rays muon, which penetrates deep into the large and thick shielded cask and provides the 3D imaging of the inner cask's structure without opening it (Park *et al.*, 2022; Poulson *et al.*, 2017).

Some advantages of using muography include the high penetration power of muons through dense and thick materials such as metals or concrete, which allows for monitoring storage containers without being hindered by their wall thickness. Monitoring can be done over long periods without dismantling or opening the storage container. This makes the application of muography for monitoring spent nuclear fuel safer than other methods, especially considering the radiation risks from spent nuclear fuel. Additionally, muography is highly effective in distinguishing between materials with different densities, including uranium, plutonium, and the materials that make up the storage containers. This technology allows for detecting and confirming the presence of nuclear materials within the container, including detecting any changes or shifts in the material's position inside the container. This is crucial for ensuring the integrity and stability of the materials during storage, reducing the risk of leaks or undesirable changes.

Some drawbacks of applying muography for monitoring spent nuclear fuel include the longer scanning time compared to other methods, which becomes a challenge in situations that require rapid monitoring, especially in nuclear facilities. Another limitation is that spent nuclear fuel has a density similar to that of the surrounding materials, which reduces the accuracy of muography detection. Furthermore, the equipment and detectors used in muography are generally complex and expensive, resulting in high installation and maintenance costs.

Mineral Exploration

Mineral exploration involves the systematic search for valuable and commercially viable natural rocks or minerals within the Earth's crust. In Indonesia, a country rich in natural resources, several exploration techniques have been developed and widely implemented to identify potential deposits. These methods include geological surveys to analyze rock formations, geochemical analysis to detect elemental concentrations, geophysical techniques to map subsurface structures, and remote sensing technologies to provide large-scale surface data. Additionally, Geographic Information Systems (GIS) play a critical role in integrating and analyzing exploration data to improve accuracy and decision-making in mineral resource identification.

The initial exploration stage can be conducted by collecting geological information through remote sensing. This technology involves multispectral and hyperspectral sensors capable of detecting variations in mineral composition based on spectral reflection from the Earth's surface (Andriansyah *et al.*, 2021). The next stage involves geological mapping, which includes direct observation of rocks and geological structures in the field to identify the presence of minerals (Falah and Tabbu, 2023). Subsequently, soil, rock, or sediment samples from various depths must be collected for chemical analysis to detect the mineral content. Anomalous concentrations of certain elements can indicate the presence of mineral deposits underground.

In addition, geophysical methods that utilize the physical properties of rocks and minerals to detect and map mineral deposits beneath the surface are also commonly used. Information about subsurface structures, geophysical anomalies, and the potential existence of minerals can be obtained without extensive excavation or drilling. Exploration data from satellite imagery, geophysical data, geological data, and geochemical data are integrated into maps that can be analyzed spatially using Geographic Information System (GIS) technology.

Exploration drilling is the final and most crucial stage of mineral exploration. After confirming the potential for minerals, drilling is conducted into the Earth to obtain core samples from subsurface rocks. A single drill hole may not necessarily discover mineral deposits in core drilling technology. Additionally, drilling depths can range from several to thousands of meters, and the costs can be substantial.

Mineral exploration requires varying amounts of time, ranging from several years to decades. This is due to the complexity of the geology of the mineral deposits, the area being explored, and the

availability of technology. Muography can also be applied in mining and rock engineering to observe the density contrast of a rock mass since it is quite complex and costly to do using conventional X-ray or core drilling (Zhang *et al.*, 2020). Muography is chosen not only because its operational costs are much lower but also because its equipment can be reused (Leone *et al.*, 2021).

Muography instruments used for mineral exploration can be strategically positioned underground, within natural caves, or in existing mining tunnels. It enables access to subsurface areas without the need for invasive drilling or excavation. This non-destructive approach significantly reduces the environmental footprint typically associated with conventional exploration methods, such as core drilling. Furthermore, by minimizing the need for extensive excavation, muography lowers operational costs, making it a more sustainable and economically viable alternative for subsurface mineral detection in both new and existing mining sites.

Some advantages of muography compared to existing exploration methods include the ability of muons, as a source of muography, to penetrate thick rock layers up to several kilometers deep, making it effective for detecting the presence of minerals in rock layers that are difficult to reach with other methods. Muography's advantage in detecting material density makes it suitable for identifying mineral deposits or underground cavities. The application of muography can reduce exploration costs compared to existing methods, which are often very expensive and can save time in exploration due to its shorter scanning time compared to existing methods. High-resolution density mapping can be performed with muography, providing a clearer picture of subsurface geological conditions and aiding exploration decision-making. Therefore, this technology is suitable for application in Indonesia, especially in mining areas or new mining sites.

However, despite these advantages, the use of muography also has limitations. Muography has constraints in detecting small details with low density beneath the surface. This becomes a challenge if the exploration requires high precision in narrow areas. Muography's resolution can decrease at very deep depths due to the reduced number of detected muons. In mineral exploration, muography data must often be combined with other methods to achieve more accurate results.

Conclusions

Over the past decade, muography technology has gained widespread global recognition for its diverse applications that support human activities, including volcanology, archaeology, and mineral exploration. This imaging technique offers a significant advantage in safety, as it relies on naturally occurring cosmic-ray muons and does not involve the use of radioactive elements. Its non-invasive and non-destructive nature further highlights its suitability for a wide range of scientific and industrial purposes.

Muography is particularly well-suited for application in Indonesia, including monitoring magma activity in volcanoes to provide sufficient data for early warning of volcanic eruption hazards to surrounding communities. Furthermore, muography can be used to assess the condition of rock structures in ancient temples at risk of decay or cracking due to age. Mineral exploration, cargo inspection at border entry points, and future spent nuclear fuel monitoring can also be conducted using muography technology.

Among the various types of detectors used in muography, plastic scintillation detectors are particularly well-suited for application in Indonesia. Their ease of installation, combined with exceptional durability under diverse weather and environmental conditions, makes them ideal for deployment in the country's challenging geographic and climatic settings. Plastic scintillators offer real-time analysis capabilities, which are crucial for continuous monitoring in applications such as volcanic activity, archaeological studies, and mineral exploration. These advantages highlight their practicality and effectiveness for advancing muography research and implementation in Indonesia.

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