Muon Imaging and its potential for fossil site location in the Cradle of Humankind UNESCO World Heritage site, South Africa

The Cradle of Humankind UNESCO World Heritage site (COHWHS) is an area of karstic dolomite containing large numbers of cave systems, sinkholes and other subterranean structures related to faulting and phreatic erosion (see Dirks and Berger, 2013). Fossil preservation and formation within these spaces is well documented and some of the most important records in Africa related to human origins and paleoenvironments have been recovered from these systems over the past century. The karst landscape is formed within dolomitic limestones dating to over 2.1 billion years old. The dolomites are visible on the surface in a broadly 10km wide swathe extending for almost 60 kilometers along the western and northern rim forming the top of the Witwatersrand supergroup with a core karstic area of around 50,000 hectares recognized and protected (Magnuson and Visser, 2003).

For almost eighty years it was thought that the number of fossil bearing localities within the region was relatively limited and the karstic systems relatively rare. However, more recent surveys over the past 15 years aided by satellite data have demonstrated that there are in fact thousands of cave systems in the region and hundreds of fossil bearing deposits. These surveys, further physical exploration and subsequent excavations have resulted in significant new and important discoveries of ancient hominins, including new species of hominin, and the discovery of important faunal and plant bearing fossil deposits which will undoubtedly contribute greatly to our understanding of ancient environments and further assist in building a more accurate record of past climates.

These discoveries demonstrate our historically poor understanding of not only the extent of these karstic systems, but also the need to apply better methods for discovering and exploring subterranean spaces as the recognition of such spaces can lead to important discoveries. There are also a number of specific scientific questions that have arisen at well-known sites that would benefit from better methods of recognizing subterranean spaces. In addition, the recognition of previously unrecognized subterranean spaces can assist the COHWHS Management Authority in planning development and conservation efforts.

To date, the discovery of such subterranean spaces has relied on largely four relatively unsophisticated methods: physical exploration by humans; chance discovery by borehole drilling; deliberate scientific core drilling; and natural collapse or erosion creating sudden exposure of subterranean spaces. Advances in Muon Imaging, however, shows great potential in locating presently unrecognized or inaccessible spaces that might advance the scientific and management points briefly mentioned above. If successfully applied in the COHWHS the modality could enhance many areas of exploration.

While the dolomites reach depths of up to three hundred meters, most accessible subterranean spaces sit above the water table in zones that range between 80 and 30 meters where they often meet the water table (Witthüser and Holland, 2008). Thus, the nearer surface sites are within the range of muography.

Muon imaging techniques

Muography, or muon radiography, is a powerful imaging technique that exploits the properties of subatomic particles called muons to create detailed images of the interior of objects or structures. Muons are similar to electrons, although about 200 times heavier, and are naturally occurring in cosmic rays that continuously bombard the Earth from space.

Muons produced from cosmic rays are highly energetic particles that can penetrate various materials, including rock, stone, and earth. Unlike X-rays or gamma rays, which can be absorbed or scattered by dense materials, muons can travel significant distances without interacting much with the substance they pass through.

To capture and record the behavior of muons, specialized detectors are placed on or near the object or structure of interest. These detectors are typically designed to track the trajectory of individual muons as they pass through the object being studied.

Muons are not all uniformly distributed in space. Their flux (the rate at which they arrive) varies due to factors such as the object's density and thickness. Muography takes advantage of this variation. Thick or dense materials block more muons, resulting in a lower flux behind the object.

By measuring the muon flux from different angles or positions and recording the particles that pass through the object, sophisticated computer algorithms can reconstruct an image of the object's interior. This image can reveal variations in density, which can signify the presence of voids, chambers, or other structural features.

Muography is a non-invasive and non-destructive technique, making it particularly useful in archaeology, geophysics, and other fields where it is essential to explore the interior of objects or structures without causing harm. In the context of archaeology, muography has been employed to investigate the interiors of ancient pyramids, caves, and historical sites to uncover hidden chambers, passages, or artifacts that provide valuable insights into the past (see for instance, D. Borselli et.al in Nature Scientific reports). Its applications also extend to geology, volcano monitoring, and nuclear waste characterization, demonstrating the versatility and significance of this innovative imaging method.

Muon tomography is a specialized application of muography that utilizes the principles of tomography to create three-dimensional images of the interior of objects or structures. It builds upon the basic concepts of muography but, using multiple arrays of detectors, adds an additional dimension of depth, providing more detailed and comprehensive information about the internal composition of the studied object.

An extensive review of the muon imaging techniques can be found in IAEA-TECDOC-2012.

Proposed experiments to assess efficacy of Muon Imaging for discovery of unknown subterranean spaces in the COHWHS

Two experiments are proposed to assess the efficacy of this imaging method for exploration in the COHWHS.

Exploring for alternative access points to the Dinaledi subsystem

The first will attempt to address a well-recognized hypothesis that there was an additional and easier access route into the well-studied Dinaledi subsystem where numerous remains of *Homo naledi* (Berger et al., 2015) have been discovered over the past decade. The Dinaledi subsystem is well known for its present-day inaccessibility, being accessed via narrow and vertical spaces that prove extremely difficult for humans to navigate (see Dirks et al., 2015). Some commentators have suggested there must be a more accessible entry into the system (e.g. Thackeray, 2016; Val, 2016), although physical exploration to date has not shown evidence of such a hypothetical passage or space (Randolph-Quinney et al., 2016). The Dinaledi subsystem's floor sits between approximately 30 and 35 meters below the present surface making it well within the maximum depth of 50 meters for muography. Placement of detectors in the Dinaledi subsystem in several areas could be used to discover any spaces or passages that are now sealed off from the main chambers making up the subsystem and thus invisible to physical exploration. The results of such a study would be of great value in settling the question of whether there were other entrances or whether there is no evidence of additional spaces above and proximal to these spaces. Either result is of value to this important question and would result in publishable results. The high-profile nature of this question would also bring attention to this relatively new exploration modality and perhaps make obvious other researchers identify questions testable with Muon Imaging. In addition, the potential for discovering proximal spaces not yet recognized by physical exploration which may contain additional remains of Homo naledi is possible. An added benefit is that imaging from the area of the Hill Antechamber towards the Dragons Back Chamber would likely create a map of the inaccessible Chute Labyrinth, something presently not possible due to size constraints and the danger of the environment.

Set up of the equipment in this challenging environment would be difficult but could be accomplished by disassembly of the detector and reassembly in the space. Successful placement of the detector in such a space would advance understanding of spaces where muography could be applied.

Lateral muography of the Gladysvale Cave

The Gladysvale cave system is a large, well known cave site in a region of the COHWHS where more montane and higher relief areas are found (Berger, Keyser and Tobias, 1993; Schmid, 2002). In specific areas of the accessible three chambered system, it is clear that there are unreachable spaces beyond that have never been accessed or mapped by contemporary humans based upon airflow and physical exploration. It is proposed to use muography to attempt lateral imaging of the hillside to assess whether such chambers could be visualized in order to assess the efficacy of lateral muography in this environment and demonstrate, if successful, its application for exploration for unknown subterranean systems in areas of higher relief. This project not only could determine future exploration efforts into unseen spaces but also act as a demonstration for management bodies making decisions about development and conservation of cave systems. Gladysvale is chosen not only for its appropriate position, but also for the significant depth of study into the system and detailed mapping created over the past three decades making it ideal for an initial muographic experiment (Lacruz et al, 2002; Hausler et al., 2004).

Other possible applications

Another possible application could be the utilization of muography (or better, muon tomography, in this case) for inexpensive and low impact imaging of individual fossils within isolated blocks of fossil bearing breccias. Losse blocks are common at sites in the region due to earlier mining activities and many contain valuable and informative fossils. Present imaging used conventional computed tomography or higher energy synchrotron imaging, both of which are expensive modalities and expose fossils to higher doses of radiation which may affect some studies. This avenue of imaging and exploration could be explored as part of this project.

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