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Muography: overview and future directions

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Cosmic-ray muography uses high-energy particles for imaging applications that are produced by cosmic rays in particle showers in the Earth's atmosphere. This technology has developed rapidly over the last 15 years, and it is currently branching out into many different applications and moving from academic research to commercial application. As in any new sub-field of research and technology, the nomenclature of the field itself is still developing and has not settled yet as new aspects of the field are appearing and with them the terms to describe them. This overview of the field of muography is not going to focus on the physics, on the reconstruction algorithms or on the involved detector technology. Detailed papers on these aspects are included in this issue of Philosophical Transactions A and I will refer to them. Instead, I will give an overview of the field as it is now, in 2018, and try to give an idea of the future directions in this field as I see them.

This article is part of the Theo Murphy meeting issue 'Cosmic-ray muography'.

1. Introduction

Cosmic rays, respectively, the secondary particles from the atmospheric showers that they cause, were discovered more than 100 years ago, in 1912, by Austrian physicist Victor Hess in high-altitude balloon flights [1]. Muons were discovered in 1936 at Caltech, when Carl Anderson and Seth Neddermeyer investigated cosmic rays in detail [2]. By the 1960s, cosmic-ray muons were no longer only a research subject, but they were well enough understood to be used as a research tool by Luis Alvarez in his search for hidden chambers in the Chephren

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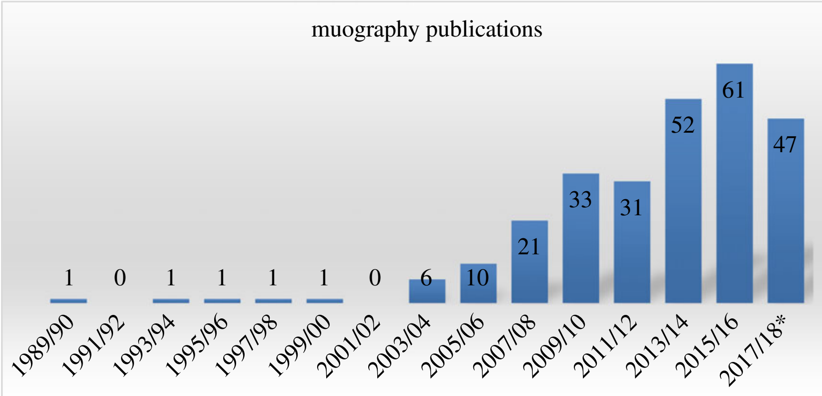

Figure 1. Increase of publications on muography over time (University of Glasgow Library). * up to end of August 2018. (Online version in colour.)

Figure 2. Developmental chain from research subject over research tool to technology. (Online version in colour.)

pyramid in Egypt [3]. In fact, they had already been used in 1955 by E.P.George in Australia to determine the ice burden over a tunnel [4]. Over time, it became routine in particle physics experiments to use them for the commissioning of new particle detectors. Their high average energy of 3 GeV leads to straight tracks in the Earth's magnetic field and their low flux of about $100\,\mathrm{Hz\,m^{-2}}$ at sea level is not challenging for any data acquisition system, but sufficient to take some useful data. At several underground experiments, the cosmic-ray muon shadow of the moon has been used to verify the position resolution of the detector. One example is the IceCube neutrino experiment at the South Pole [5]. Muon detection has been an important component of the CMS and ATLAS experiments at CERN and played an important role in the discovery of the Higgs boson in 2012 [6,7]. In fact, CMS is an acronym for 'Compact Muon Solenoid', emphasizing the importance of muon detection for the experiment. In 2003, researchers at Los Alamos National Laboratory published a seminal paper [8] on imaging with cosmic-ray muons that showed for the first time how the Coulomb scattering of muons in matter could be used for imaging applications. Previously, only information from the absorption of muons in matter had been used. This paper is the kick-off point for a rapid increase of publications on muography as shown in figure 1. In the developmental chain from the research subject to research tool to technology (figure 2), this marks the transition from a research tool to technology, i.e. a tool with applications outside of research.

The properties of a technological tool define the possible and useful applications of the tool. Cosmic-ray muons are highly penetrating, their average energy is about 10 000 times the energy of a typical X-ray and they can penetrate hundreds of metres of rock. This means that they are suitable to image objects that are behind or inside of shielding material that is too thick or deep for other imaging methods. They are natural and ubiquitous, which means that any imaging method using them is entirely passive and therefore neutral with regards to health and safety regulations. Their low flux means that they are suitable only for applications that are not time-critical. Finally, cosmic-ray muons are cost-free and their availability is unlimited on human timescales. This makes them a perfect resource.

2. Muography applications

For this overview paper, I am choosing the term 'muography'—literally 'writing with muons'—to mirror terminology like 'radiography' or 'lithography'. 'Muon imaging' is similarly neutral, but 'muography' has been established for a while in the community of volcanologists that use cosmic-ray muons to image volcanoes. Other terms that are frequently used are 'muon tomography' and 'muon radiography' which I will use for three-dimensional imaging similar to X-ray tomography and two-dimensional absorption imaging, respectively (figure 4).

More and more applications for muography are emerging, but most of them can be grouped into the categories geoscience, nuclear safety and security, civil engineering and archaeology. The infographic in figure 3 provides an overview of potential applications. These are fields where applications can be found that combine shielding, resolution and time scales for which muography is a suitable imaging method.

The most frequent application in geoscience is the imaging of the inside of volcanoes. This method is now widely used by volcanologists, e.g. in Japan, Italy and France. There are several papers in this special issue that deal with this particular application [9–11]. Other geoscience applications include prospecting, especially brown site mining exploration [12], imaging of underground structures [13,14] and the monitoring of carbon capture storage sites [15]. Muography for geoscience applications fills a niche between other imaging technologies like ground penetrating radar and seismology, imaging at depths and resolutions that are not suitable for those.

Nuclear safety and security is another obvious application: the very fact that radioactive material and waste is typically stored in shielded containers that are designed to contain the radiation also means that similar radiation cannot be used to image their contents. This is where the high average energy and the minimum ionizing nature of cosmic muons comes into play. The ability of muography to distinguish between nuclear fuel and other metals including lead is crucial for applications in nuclear security, in particular for cargo screening for national security [8], but also for safeguards applications, e.g. the monitoring of dry storage casks [16,17]. The search for special nuclear materials inside cargo containers was one of the first potential applications of muon tomography. The imaging of the contents of nuclear waste containers and the quality assurance for nuclear waste treatment processes [18,19] are further key applications in the field of nuclear safety. Finally, nuclear reactors themselves also can be imaged with cosmic muons. There have been attempts to image the corium in the Fukushima–Daichi reactors [20], supported by simulations that indicate that this should be possible.

Civil engineering applications include the monitoring of the inside of blast furnaces [21], the monitoring of historical buildings [22], large structures like bridges and wind turbines and potentially also structures at oil rigs. Civil engineering is by far the largest potential market for commercial muography, but it is so far also the least explored field. This may have to do with the fact that this is typically a field that is more used to industry-led innovation, while the applications in nuclear safety and security and in volcanology are typically publicly funded. Most research in muography is still being carried out in the context of university research and national laboratories, and these are more likely to look for applications for which public funding is available.

Probably the best-known application of muography concerns the Pyramids in Egypt. In principle, this archaeological application is a particular civil engineering application. From the point of view of the measurement, there is no fundamental difference between a cavity in a nineteenth century bridge or in a pyramid. The ScanPyramids project recently discovered cavities in the Pyramid of Khufu (Cheops) [23], using three different sets of muon detectors and combining the results. They have found indications for a large cavity above the Grand Gallery and for a previously unknown access corridor from the North face of the pyramid.

It is instructive to consider which applications are suited for muon tomography and which for muon radiography. Figure 4 shows an overview of tomography and radiography applications and the scale of their typical objects. The different applications are spread over five orders of magnitude in scale, ranging from centimetre to hundreds of metres, where the typical scales for

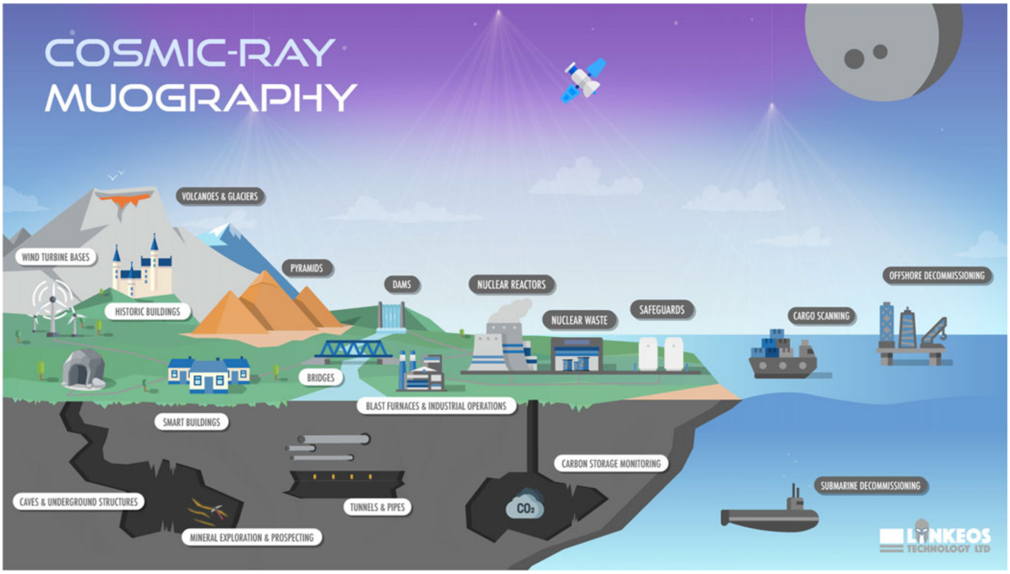

Figure 3. Schematic infographic illustrating the different applications of muography, courtesy of Lynkeos Technology Ltd.

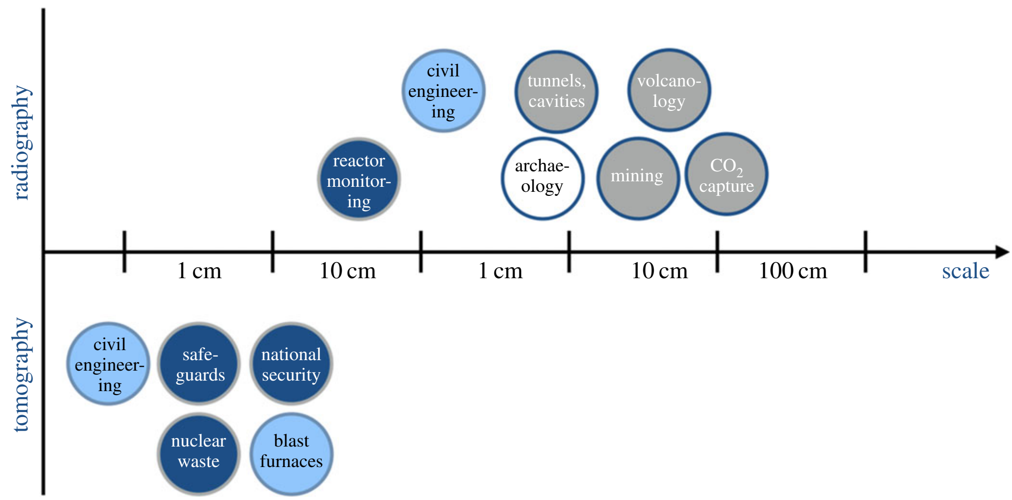

Figure 4. Typical scale of muon radiography and tomography applications, with civil engineering applications in light blue, nuclear safety and security applications in dark blue and geoscience applications in grey. (Online version in colour.)

muon tomography are in the centimetre to tens of centimetres range, while muon radiography ranges from tens of centimetres to hundreds of metres.

3. Detector systems

There are currently three main types of detector system: mobile radiography systems, static tomography systems and borehole detectors. Figure 5 illustrates the typical detector systems and imaging techniques used for absorption radiography and scattering tomography.

Muon tomography requires at least two detector planes above and two below the object that is to be imaged. The upper detectors can be seen as defining the radiation source, similar to the

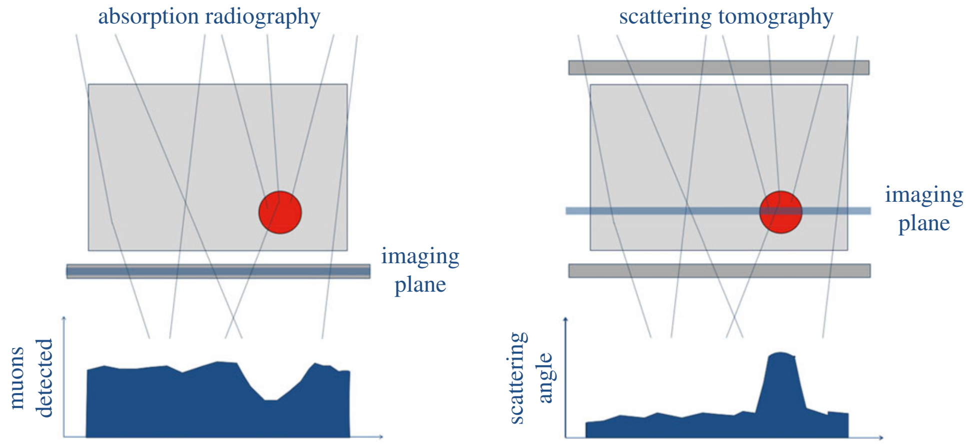

Figure 5. Schematic visualization of absorption radiography and scattering tomography and the corresponding detector geometries. (Online version in colour.)

Figure 6. Examples of static muon tomography systems, Los Alamos MMT (*a*), Lynkeos MIS (*b*) and INFN Padova (*c*). (Online version in colour.)

X-ray source in a CT system, while the lower detectors detect the presence, absence and scattering of the muons that were defined by the upper detectors. This is, in fact, very similar to a CT system, but due to the angular distribution of cosmic muons and due to the geometric limits imposed by the detector system only a narrow angular range around the vertical is covered. This necessarily means that the resolution of such a muon tomography system in the horizontal plane (in x and y) will be much better than the vertical resolution (along with the z-axis). The existing muon tomography systems are static systems, i.e. they require that the object or sample is placed inside their active volume. This active volume is most typically of the order of m3; the largest one has an active volume of tens of m3. Typical examples of static muon tomography systems are the system at INFN Padova [24] and the Lynkeos Muon Imaging System produced by Lynkeos Technology Ltd. in Scotland [18]. The Los Alamos MMT [25] can also be transported in a trailer for fieldwork (figure 6). The largest static system is the cargo container scanning system produced by Decision Sciences in the USA.

Muon radiography requires at least two detector planes in order to define the tracks of the detected cosmic muons to produce a two-dimensional absorption image. Often three or four detector planes are used for better resolution and efficiency. Muon radiography results are not necessarily limited to two-dimensional images; the information from several detectors imaging the same volume can be combined to form a three-dimensional image, as was done e.g. by the ScanPyramids project [23]. The large scale of the objects typically makes it impossible to use muon tomography, so that radiography is the only option for two-dimensional as well as three-dimensional imaging.

Figure 7. The mobile muon telescopes used by MURAY in Italy (*a*), ToMuVol in France (*b*) and CRM GeoTomography in Canada (*c*). (Online version in colour.)

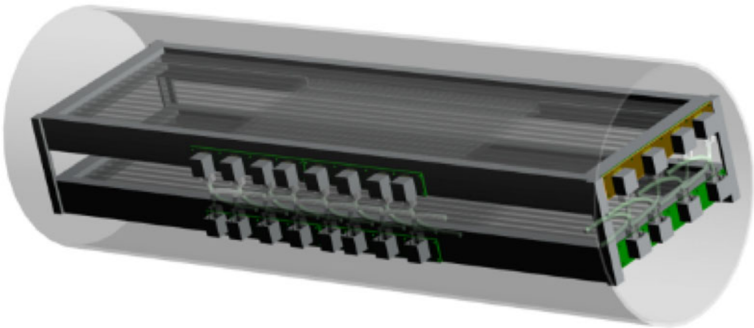

Figure 8. PNNL borehole detector design. (Online version in colour.)

The typical detector set-up is a telescope of three or four identical detector planes inside a transport container. The applications, e.g. in volcanology, usually require a mobile detector system. The typical size of a muon radiography detector plane is about 1 m^2, not least because this is about the limit for mobility. Typical examples are the muon telescopes used by the MURAY experiment in Italy and by ToMuVol in France, as well as the systems used by CRM GeoTomography in Canada (figure 7).

Borehole detectors are, as the name already suggests, designed to be used in underground applications using boreholes. The size of the borehole defines the size and geometry of the detector. Borehole detectors are in principle small radiography detectors with cylindrical geometry. They have additional requirements for the detector design, e.g. data transport to the surface and water resistance that complicate the design. On the other hand, they have to be much smaller than the regular muon radiography detectors. The borehole detector from PNNL (figure 8) is a good example of this detector type.

4. Commercialization

As cosmic muons have become a technological tool and muography a technology, this is also the point where commercialization starts to make sense. The first company founded in this field was Decision Sciences International Corporation in the USA, a spin-off company from Los Alamos National Laboratory, where the seminal research paper on muon tomography [8] was published in 2003. Five of the currently six muography companies worldwide were founded very recently, and most of them are spin-off companies from research laboratories or universities. The company foundation often followed academic research projects, e.g. Lynkeos Technology Ltd. was founded

company	founded	country	main applications
Decision Sciences	2001	USA	cargo scanning, nuclear reactors
Lingacom	2012	Israel	cargo scanning, mining exploration
CRM GeoTomography	2013	Canada	mining exploration
Muon Systems	2015	Spain	industrial applications, cargo scanning
Lynkeos Technology	2016	UK	nuclear safety and security
Muon Solutions	2016	Finland	mining exploration

Figure 9. Overview of currently active commercial companies in the field of muography. (Online version in colour.)

following a 7-year research project starting in 2009 at the University of Glasgow and the UK National Nuclear Laboratory (NNL Ltd.).

The first applications that were realized were cargo scanning for national security and mining exploration. Cargo scanning uses the potential of muon tomography to detect special nuclear materials inside cargo containers that are densely packed with other materials so that they cannot be penetrated by X-rays. However, the low natural flux of muons requires the addition of other measurement techniques—muography alone would be too slow or lead to too many false positives. Mining exploration, starting with brown site exploration, uses the capability of muon radiography to image higher density ore inside lower density rock. At existing mines, it is possible to place muon detectors below potential ore deposits and use the combination of several muon radiography detectors to produce a three-dimensional image of the ore deposits. For prospecting, a set-up with several borehole detectors can play the same role. Nuclear safety and security, more precisely the imaging of the contents of shielded nuclear waste containers, was the third application that has been commercialized. As the very point of shielded containers is to contain the radioactivity inside, it is clear that similar radiation cannot be used to image their contents. X-ray and gamma sources and detector are therefore not able to image nuclear waste containers, but cosmic-ray muons with a typically energy that is three orders of magnitude higher than that of gamma rays are able to do so. This application requires a muon tomography set-up.

Figure 9 gives an overview of the commercial companies in the field of muography that currently exist. To my knowledge, as of 2018 three of the listed muography companies are trading, i.e. have sold products or services: Decision Sciences have sold a cargo scanning system to Singapore in 2017, CRM GeoTomography have imaged ore deposits at a Uranium mine in Canada in 2017 and Lynkeos Technology have imaged the contents of vitrified waste containers in 2017 and set up a demonstrator system at Sellafield in 2018. The products of the other companies are currently at various stages of development.

5. Future directions

The muography applications that have been realized and commercialized up to now are not necessarily going to be the main applications in the future. They just happened to be those that offered a good combination of available funding and technical suitability. To get an impression of which future directions can be expected in muography, it is instructive to consider the suitability of muography and the technical maturity of the application. I have attempted to do this in the diagram in figure 10, plotting suitability versus maturity.

Applications that can be expected to play an important role in the future are those which score high in suitability and those that at the same time are not yet very mature are those that are likely

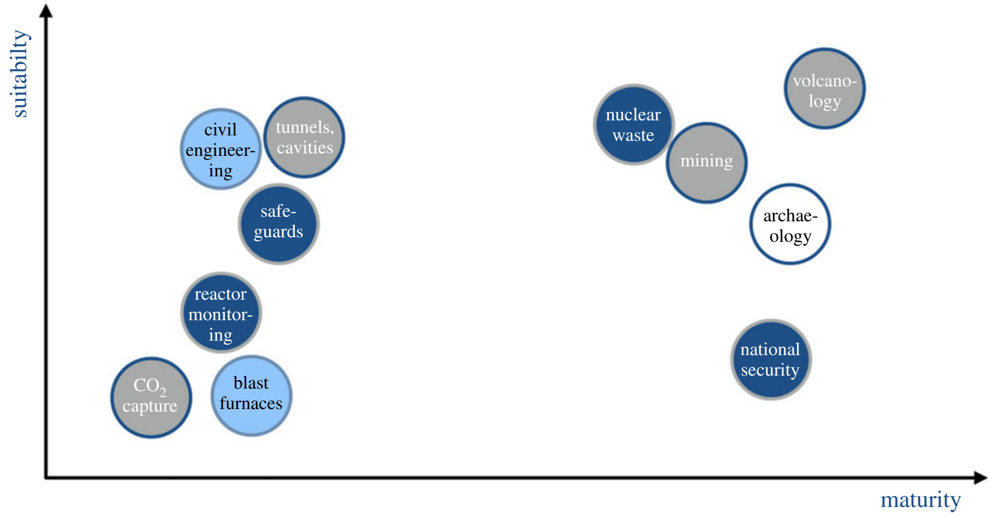

Figure 10. Suitability and maturity of muography applications. This is a qualitative diagram based on my personal opinion. (Online version in colour.)

going to be developed in the future. These applications are civil engineering (e.g. monitoring bridges), tunnels and cavities and nuclear safeguards (e.g. monitoring of dry storage casks).

If this is combined with the detector types that are currently being used for which applications, it seems logical that mobile detector systems for radiography, but also for tomography, are going to be more typical in the future. At the same time, detector systems will have to become commercial products and be designed with the application in mind, rather than being based on available detectors from particle or nuclear physics experiments. Ultimately, this may lead to the commodification of large-scale tracking detectors, in a way that has already taken place for detector technologies with medical applications.

I expect muography to become a technology that finds its place between other imaging technologies and that is used when it is simply the best technology for the purpose. In some cases, there is no alternative that could deliver comparable results, and where this is combined with a commercial interest it will lead to successful commercialization.

Data accessibility. This article has no additional data.

Competing interests. I am a Prof. of Physics at the University of Glasgow and Managing Director of Lynkeos Technology Ltd. Lynkeos Technology Ltd., is a spin-off company of the University of Glasgow and one of the companies that are active in the area of muography and that are listed in the overview above. The article has been reviewed by an editor that has no such involvement.

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References

1. Hess VF. 1913 Über den Ursprung der durchdringenden Strahlung. *Phys. Z* **14**, 610.
2. Neddermeyer SH, Anderson CD. 1937 Note on the nature of cosmic ray particles. *Phys. Rev.* **51**, 884. (doi:10.1103/PhysRev.51.884)
3. Alvarez LW *et al.* 1970 Search for hidden chambers in the pyramids. *Sci. New Series.* **167**, 832–839.
4. George EP. 1955 Cosmic rays measure overburden of tunnel. *Commonwealth Engineer* **43**, 455–457.
5. IceCube Collaboration. 2014 Observation of the cosmic ray shadow of the moon with IceCube. *Phys. Rev. D* **89**, 102004. (doi:10.1103/PhysRevD.89.102004)

6. CMS Collaboration. 2012 Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Phys. Lett. B* **716**, 30–61. (doi:10.1016/j.physletb.2012.08.021)
7. ATLAS Collaboration. 2012 Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Phys. Lett. B* **716**, 1–29. (doi:10.1016/j.physletb.2012.08.020)
8. Borozdin K, Hogan GE, Morris C, Priedhorsky WC, Saunders A, Schultz LJ, Teasdale ME. 2003 Surveillance: radiographic imaging with cosmic-ray muons. *Nature* **422**, 277. (doi:10.1038/422277a)
9. D'Alessandro R *et al.* 2019 Volcanoes in Italy and the role of muon radiography. *Phil. Trans. R. Soc. A* **377**, 20180050. (doi:10.1098/rsta.2018.0050)
10. Oláh L, Tanaka HKM, Hamar G, Varga D. 2019 Investigation of the limits of high-definition muography for observation of Mt Sakurajima. *Phil. Trans. R. Soc. A* **377**, 20180135. (doi:10.1098/rsta.2018.0135)
11. Tanaka HKM. 2019 Japanese volcanoes visualized with muography. *Phil. Trans. R. Soc. A* **377**, 20180142. (doi:10.1098/rsta.2018.0142)
12. Schouten D. 2019 Muon geotomography: selected case studies. *Phil. Trans. R. Soc. A* **377**, 20180061. (doi:10.1098/rsta.2018.0061)
13. Bonneville A *et al.* 2019 Borehole muography of subsurface reservoirs. *Phil. Trans. R. Soc. A* **377**, 20180060. (doi:10.1098/rsta.2018.0060)
14. Saracino G, Ambrosino F, Bonechi L, Cimmino L, D'Alessandro R, D'Errico M, Noli P, Scognamiglio L, Strolin P. 2019 Applications of muon absorption radiography to the fields of archaeology and civil engineering. *Phil. Trans. R. Soc. A* **377**, 20180057. (doi:10.1098/rsta.2018.0057)
15. Gluyas J *et al.* 2019 Passive, continuous monitoring of carbon dioxide geostorage using muon tomography. *Phil. Trans. R. Soc. A* **377**, 20180059. (doi:10.1098/rsta.2018.0059)
16. Poulson D, Bacon J, Durham M, Guardincerri E, Morris CL, Trellue HR. 2019 Application of muon tomography to fuel cask monitoring. *Phil. Trans. R. Soc. A* **377**, 20180052. (doi:10.1098/rsta.2018.0052)
17. Yang G, Clarkson T, Gardner S, Ireland D, Kaiser R, Mahon D, Jebali RA, Shearer C, Ryan M. 2019 Novel muon imaging techniques. *Phil. Trans. R. Soc. A* **377**, 20180062. (doi:10.1098/rsta.2018.0062)
18. Mahon D, Clarkson A, Gardner S, Ireland D, Jebali R, Kaiser R, Ryan M, Shearer C, Yang G. 2019 First-of-a-kind muography for nuclear waste characterization. *Phil. Trans. R. Soc. A* **377**, 20180048. (doi:10.1098/rsta.2018.0048)
19. Clarkson A *et al.* 2015 Characterising encapsulated nuclear waste using cosmic-ray muon tomography. *JINST* **10**, P03020. (doi:10.1088/1748-0221/10/03/P03020)
20. Miyadera H, Borozdin KN, Greene SJ, Lukić Z, Masuda K, Milner EC, Morris CL, Perry JO. 2013 Imaging Fukushima Daiichi reactors with muons. *AIP Adv.* **3**, 052133. (doi:10.1063/1.4808210)
21. Vanini S, Calvini P, Checchia P, Rigoni Garola A, Klinger J, Zumerle G, Bonomi G, Donzella A, Zenoni A. 2019 Muography of different structures using muon scattering and absorption algorithms. *Phil. Trans. R. Soc. A* **377**, 20180051. (doi:10.1098/rsta.2018.0051)
22. Zenoni A *et al.* 2014 Historical building stability monitoring by means of a cosmic ray tracking system. In *Proc. of the 4th Int. Conf. on Advancements in Nuclear Instrument Measurement Methods and their Applications*. ANIMMA 2015, 20–24 April 2015. Lisbon: IEEE.
23. Moroshima K *et al.* 2017 Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons. *Nature* **552**, 386–390. (doi:10.1038/nature24647)
24. Checchia P *et al.* 2019 INFN muon tomography demonstrator: past and recent results with an eye to near-future activities. *Phil. Trans. R. Soc. A* **377**, 20180065. (doi:10.1098/rsta.2018.0065)
25. Perry J. 2003 Dissertation University of New Mexico. See http://digitalrepository.unm.edu/ne_etds/4/.