Cosmic-ray based geothermal exploration – A short introduction to muography

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Muography is a novel geophysical imaging method for large solid objects and it maps relative density variations in 2D, 3D or 4D (density data + time analysis). In geothermal exploration, muography can be used, for example, for remote detection of faults and estimation of associated permeabilities. In the best-case scenarios, muography can be used to direct further geothermal exploration drilling and mitigating exploration risks associated with permeability models. The method is feasible for the 1-2 km in the vertical direction or, if applied at the ground surface level, up to 2-3 km in horizontal and near-horizontal directions.

Keywords: geothermal energy, geothermal exploration, muography

1. Introduction

Even in countries with active high-enthalpy geothermal systems, like Iceland, Italy, New Zealand and Turkey, discovery and characterisation of a geothermal resource is often challenging. This is particularly true if the resource lacks obvious surface expressions like hot springs or geysers. In those cases, the geothermal resource may be hiding, for example, under a blanket of impermeable rocks preventing transportation of fluids and gases from deep-seated thermally heated sources to the surface (Hanson et al. 2014). These types of geothermal resources are often called as blind or hidden geothermal systems (Hanson et al. 2014). In contrast, heat flows in ancient cratonic shield areas are low and classical surface expressions associated with convective hydrothermal systems simply do not occur as there are no convective hydrothermal systems. In brief, exploration of economically feasible geothermal resources is often challenging, and the challenges are not the same everywhere. Developments in methods and techniques in geothermal exploration are thus important. We introduce herein a new technique that may be useful in geothermal energy exploration in the future. This technique is called muography.

2. Principles of muography

Muography is based on the utilisation of cosmic-ray induced atmospheric muon particles as probes to image density variations in solid (and liquid) materials. In geology, this novel geophysical imaging method can be used for density characterisation and monitoring of soil and rock formations of any kind, as long as there are adequately large density variations present (e.g., lithological boundaries, ore bodies, major alteration zones, and major damage zones). So far, density imaging of interiors of volcanoes is the most widespread application. Muographic imaging in geology and engineering (Zhang et al. 2020) is based on variable attenuation of muon flux in different directions (less muons are detected from the direction of denser materials). It can be performed as 2D muon radiography (e.g., Lesparre et al. 2012), 3D muon tomography (e.g., Guardincerri et al. 2017), and time-lapse (time-sequential) muography (e.g., Tanaka, 2020). Furthermore, depending on the need and availability of muon detectors, the latter can be performed in 2D or 3D. Time-sequential muography has been used, for example, to visualise and analyse magma movements in a volcano (Lesparre et al. 2012) or groundwater movements in faults (Tanaka et al. 2011). Densities are visualised as variations in the mean density of a soil or rock volume (i.e., as pixels in 2D, voxels in 3D, and time-referenced pixels or voxels in time-lapse muography).

Muography surveys can be conducted by a variety of detector types. Without going into technical details, the detectors can be divided into two classes based on the mobility and place of emplacement: cylindrical borehole probes and ‘telescopes’ (a common term used in the literature for these kinds of instruments, but rather vague in content as a telescope can be actualised with a number of different techniques). In general, telescopes are small enough to be mobile (e.g., 1 m^3) but still way too large to fit into the borehole. Telescopes are the best option for density imaging wherever there is a need for particularly high resolution and enough room for this detector type (e.g., underground tunnels, caves, or mountainous areas where a telescope can be positioned directly on the ground to image a mountain or volcano). However, as is well known, such underground spaces are not in abundance in most landscapes and many terrains are relatively flat. Boreholes, on the other hand, are more numerous. In Finland alone, way more than 37 000 deep boreholes have been drilled so far, as based on the database of the National Drill Core Archive in Finland (GTK, 2020a,b). These boreholes equal to over 3500 km of drill core. As a comparison, Sweden’s National Drill Core collection consists of more than 3000 km of drill core from more than 18 000 boreholes (SGU, 2020). Norway’s National Drill Core and Sample Centre contains 750 km drill core in total (NGU, 2019). It is worth noting that the actual total number of boreholes in these three countries is considerably larger than those inferred from the official sources as many companies have also their own drill core storage facilities. It can nevertheless be estimated that only a fraction of boreholes is truly available for borehole muography due to decrease in numbers owing to borehole collapse, destruction of rock sequences (e.g., due to mining), and a lack of access licence. Yet, borehole muography offers more possible locations for muography than telescope-based muography.

The lowest density variations that may be observed by muography with a significance level of 3σ are around 2% at 150 m of depth, 4% at 300 m, and 10% at 700 m (Hivert et al. 2017). The 1% difference in a mean rock density translates into approximately 3% difference in the measured muon flux. Moreover, if a rock having a porosity of 10% is saturated with water, measured muon flux is reduced by 10% (Tanaka and Sannomiya, 2013). Due to these reasons muography has potential as a tool for detection and monitoring of natural bedrock aquifers, or at least those associated with high-porosity faults and fracture zones.

As a geophysical method, muography can be combined with other geophysical methods. In these regards, Pasquet et al. (2019) discusses about pairing of muography with seismics and electrical resistivities, and Holma et al. (2019) with microseismic monitoring. Muography data has also been jointly inverted with gravity data (e.g., Barnoud et al. 2019), while Lesparre et al. (2012) compares muography data with electrical resistivity and gravity data.

3. Applications of muography in geothermal exploration

Deep geothermal systems can be classified into: (1) hydrothermal (convective) systems; (2) enhanced geothermal systems (EGS) (also called as hot dry rock systems); and hot aquifers. Classification can also be based on temperature; in which case the geothermal systems fall either to high enthalpy (above 150°C) or low enthalpy (less than 150°C) systems. In some cases, the terms ‘medium enthalpy’ and ‘ultra-high enthalpy’ have been found to be more appropriate. As an example of the latter, the Japan Beyond-Brittle Project targets supercritical geothermal resources in an EGS reservoir in ~400-500°C rocks (Asanuma et al. 2019). Borehole muography is not applicable in high-temperatures due to detector-related technical limits (we estimate T_{max} to be close to 50°C).

Favourable geothermal reservoir settings are often characterised by interactions of fluids flowing along fractures in the bedrock. As (1) muon detectors reveal density changes with a reasonably high resolution (at least at depths above 1 km) and (2) fractures typically have lower bulk densities than non-fractured rocks, major faults are visible by both muon telescopes and borehole muon probes as low-density features. While muography can be used in exploration of geothermal deposits that are related to fractures, it may not be effective in exploration of non-fracture related geothermal deposits, unless there occur associated density contrasts. Other constraints include telescopes that can be used only if there are tunnels or caves where they can be installed, or there is enough topography so that telescopes can be installed on the side of the object of interest, such as a mountain or similar steep landform. Telescopes set up on the ground can be applied for the detection of density contrasts in solid materials up to 2-3 km thick in a horizontal or near-horizontal direction (e.g., Tanaka et al., 2014). This enables telescopes for geothermal exploration in mountainous areas. Borehole probes, in contrary, can be used anywhere there are available boreholes. However, as the muon flux diminishes substantially with increasing depth, the maximum depth borehole detectors can be used effectively is likely somewhere between 1-2 km. The gradually increasing geothermal gradient is another constrain for borehole muon detectors. Hence, the method works best in detection and monitoring of permeable fault zones in the uppermost 1-2 km. Nevertheless, as sub-vertical fault zones are typically rooted to much greater depths, sub-vertical structures inferred from muographic data may, at least in some instances, be extrapolated to continue with reasonable reliability to greater depths.

Major changes in water table levels in permeable beds and fractures in bedrock are typically related to seasonal recharge and discharge events, or occasional storms or droughts. If the water level of a bedrock aquifer changes, the bulk density of the affected rock volume changes and, if the change is strong enough, is hence observable by muography. Indeed, Tanaka et al. (2011) have demonstrated that muography can detect time-dependent density changes in rock volumes caused by fluctuation of water levels in major structures. Hence, long-term muography measurements can be used in the detection and monitoring of natural bedrock aquifers associated with faults and fracture zones.

Major fault zones have a capacity to be hydraulic conduits connecting shallow and deep geological environments, even though some segments of these structures may form effective barriers for fluid flow (Bense et al. 2013). In the areas of high heat flow, large faults may enhance permeability anisotropy and control the fluid velocities and hydrothermal convection. In such cases the regional heat flux distribution can change, as shown by Bächler et al. (2003) in their study of the Rhine Graben, Germany. The authors report temperature undulations along one of the studied faults reaching ±8°C at 500 m depth and ±12°C at 1 km depth. Moreover, the temperatures were 20–40°C higher than expected in both depths. The highest measured temperature at 1 km depth (98°C) was interpreted as a clear evidence that the fluid source must be at least at the depth of 3 km and possibly deeper. Bächler et al. (2003) also conclude that as the minimum horizontal stress is typically perpendicular to the strike of a graben, fracturing along graben-parallel structures stimulates fluid flow. In brief, the graben-controlling master faults are important as permeability structures and temperature anomalies. Muography can be used to map these faults in detail and for collecting time-dependent density change data of the hydraulic behaviour of the fault over time.

4. Concluding remarks

Temperature, permeability, and volume are the three subsurface parameters that are most critical to constrain a geothermal resource (Witter et al. 2019). Muography can be used to increase knowledge of permeability by remote detection of faults and determination of their direction and widths. Muography may also proof useful for improving geological working models in geothermal exploration and, by doing so, it may guide drilling and mitigate exploration risks.

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