



OPEN First cosmic-ray muography of a crust-mantle transition zone

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Studying ophiolitic crust–mantle boundaries provides key insights into oceanic lithosphere formation, yet their internal density structure remains poorly constrained due to a scale gap: laboratory measurements capture centimeter-scale densities, whereas geophysical techniques average properties over kilometers and lack intermediate-scale continuity. Here, we use cosmic-ray muography to provide spatially continuous density constraints over tens to hundreds of meters, bridging this gap. We present the first muographic imaging of the crust–mantle transition zone (Moho Transition Zone, MTZ) at Wadi Fizh in the northern Samail Ophiolite. A multi-wire-proportional-chamber-based muography system was operated for 171 days at a distance of 400 m, producing a density image with ~3.5 m resolution. The mean density of layered gabbros is 3.03 g cm^{-3} , while lower densities (2.72 g cm^{-3}) are observed within the MTZ, consistent with enhanced alteration, and higher densities (3.38 g cm^{-3}) in the lower section indicate peridotitic rocks beneath a thin gabbroic cover. These results indicate that the crust–mantle transition at Wadi Fizh is spatially heterogeneous rather than a simple gradual boundary. Thus, muography enables continuous, in situ mapping of density variations at intermediate scales and provides a valuable complementary approach for studying the structure and evolution of the oceanic lithosphere.

Keywords Oceanic lithosphere, Moho, Ophiolite, Serpentinization, Muon, Muography

Mohorovičić discontinuity (Moho) is the boundary between the lowermost crust and the uppermost mantle within Earth's lithosphere¹. Processes occurring near the Moho in the oceanic lithosphere, such as mantle melting, melt migration, and crustal accretion, drive large-scale cycles of energy and matter that form natural resources and trigger geohazards². The architecture of the Moho is controlled by several factors, including spreading rate, lithologic heterogeneity, and tectono-magmatic history^{3–6}. For example, Ohira et al.⁷ observed a variety of Moho structures in the northwestern Pacific, where the Moho appears to be a sharp seismic boundary in regions with intermediate to fast seafloor spreading rates. This was interpreted as a lithological contact between gabbros and peridotites. In contrast, in other regions, the Moho was observed to be a multiple reflection boundary, or to be invisible and obscure, which is attributed to complex lithology; however, the exact cause remains unsolved.

Tamura et al.⁸ found that the Moho reflectivity increases beneath thicker oceanic crust and in regions of shallower water. However, factors such as the age of the lithosphere and local processes (e.g., off-axis magmatism and serpentinization) affect seismic observations. Understanding the origin of this variability in Moho structure remains a fundamental challenge. To date, the Moho has not yet been directly reached by ocean drilling (e.g., Ref⁹). Nevertheless, intact sections of oceanic lithosphere are preserved in ophiolites, which are sequences of crust and mantle rocks obducted onto continental margins^{5,10}. The Samail Ophiolite, an analogue of oceanic lithosphere formed at fast-spreading ridges, contains MTZs consisting of dunite intercalated with gabbro and wehrlite upward and harzburgite downward that extends up to several hundred meters above mantle diapirs, whereas the MTZ becomes thinner and sharper away from these diapirs^{11–15}. These variations in the MTZ

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structure may provide clues to understanding the diversity of Moho structures observed beneath the ocean floor today. Studying the structure and composition of MTZs in the Samail Ophiolite provides an opportunity to test relationships between physical properties and lithology, evaluate the spatial heterogeneity of the crust–mantle transition, and improve models of Moho formation and evolution.

Various geophysical, remote sensing, and laboratory-based techniques have been applied to study the structure and the composition of ophiolites. Gravity profiles measured across the Samail Ophiolite showed a strong correlation with the thickness of the ophiolitic sequences¹⁶. Anomalies in the gravity data have been interpreted as serpentinization of the mantle peridotites and thinning of ophiolite nappes. Image processing of remote sensing data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) has been used to delineate the Moho discontinuity and the associated rocks, as well as to map mineralogical variations¹⁷. Integrated geophysical studies combined seismic experiments, gravity modeling, and aeromagnetic data have enabled the reconstruction of the structural architecture of the Troodos ophiolite¹⁸ and the northern segment of the Samail Ophiolite¹⁹ at a regional scale. In addition, ambient seismic noise tomography was applied to image the composition and structure of the continental crust underlying the Samail Ophiolite²⁰. More recently, the Oman Drilling Project (ODP) sampled the crust and upper mantle sections of the ophiolite in situ with unprecedented spatial resolution²¹. The extracted cores were characterized using different laboratory-based techniques. Micro-imaging infrared spectroscopy was applied to investigate the spatial patterns of hydrothermal alteration²². Major and trace element compositions were quantified by X-ray fluorescence²³. Permeability profiles were inferred from resistivity measurements²⁴, gamma ray attenuation and P-wave velocity measurements were used to determine bulk density profiles and to evaluate pore structure characteristics¹⁷.

Although laboratory techniques provide high-precision densities at centimeter scale, they are limited to discrete samples and cannot capture spatially continuous heterogeneity at intermediate scales (meters to tens of meters). Moreover, discrepancies between different methods often lead to ambiguous interpretations of the MTZ. For example, Swift et al.²⁵ measured the profiles of seismic velocity versus depth below the sea floor. Acoustic wave velocity measurements of drilling cores from the hole 1256D significantly differ from the sonic log data and the P-wave velocities measured by ocean bottom seismometers. Similarly, discrepancies exist between the ophiolite drilling cores and seismic measurements. These differences arise primarily from the scale gap: laboratory measurements capture centimeter-scale heterogeneity, whereas seismic methods average over kilometer scales. Lithological variations over centimeters to tens of meters as well as the presence of pervasive cracks and fracture zones further complicate interpretation. Lithological variations over centimeters to tens of meters further complicate interpretation. Consequently, the spatially continuous density structure of the MTZ at intermediate scales remains poorly constrained, despite its importance for linking lithology, alteration, and mechanical properties. In this study, we address this limitation by applying muography, an in situ, non-invasive density imaging technique capable of resolving spatial density variations at meter-scale resolution over tens to hundreds of meters. Our goal is to bridge the scale gap between high-precision but spatially limited laboratory measurements and large-scale geophysical observations, providing continuous density maps of the MTZ. We aim to evaluate the spatial heterogeneity of the crust–mantle transition and compare results with existing petrological and geophysical models²⁶.

Muography is a novel geophysical imaging technique that utilizes cosmic-ray muons to probe large structures²⁷. Cosmic-ray muons are charged elementary particles generated continuously in Earth's atmosphere at altitudes of approximately 10–15 km above sea level as secondary products of the interactions of cosmic-rays with the atmospheric nuclei²⁸. Their high energy allows them to penetrate a few kilometers into rock, while their predictable attenuation enables quantitative density imaging^{29–31}. Although muography is commonly applied to subsurface or inaccessible targets, its application to well-exposed ophiolite sequences enables direct validation and interpretation of density structures in a geologically constrained setting. Here, we present the first muographic investigation of the crust–mantle transition zone in the Samail Ophiolite. By providing spatially continuous, in situ density constraints at intermediate scales, this study reveals structural heterogeneity that cannot be captured by discrete sampling or conventional geophysical methods alone, offering new insights into oceanic lithosphere formation and evolution.

Geological setting

The Samail Ophiolite is a mountain chain on the Arabian continental margin that extends over 400 km in length and approximately 80 km in width. This ophiolite preserves a complete oceanic crust–mantle sequence of pelagic sedimentary rocks, extrusive rocks, sheeted dike complex, gabbroic rocks, and ultramafic rocks, in descending order (Fig. 1)^{5,11}. Five or more paleoridge segments are identified through the ophiolite. These are defined by the presence of diapiric structures within the mantle peridotite at the segment centers, and mutually intrusive sheeted dikes and gabbros and doubly superimposed upper crustal structures at the segment boundaries^{3,4,31–35}. The measurement site is located at Wadi Fizh, corresponding to the northern end of a 60-km-long paleoridge segment between wadis Fizh and Ahin^{35–37}. Here, the Moho is represented by a 30-m-thick transition zone of dunite and wehrlite intervening gabbro layers between the layered gabbro and the underlying harzburgite tectonite^{14,15}, in accordance with the MTZ at the segment end¹⁴. The detailed field observations and mineral chemistry of the MTZ at the measurement site are given by Refs^{14,15}. The lowermost layered gabbro is underlain by the subhorizontal network of gabbro sills embedded in wehrlite layers less than one meter in thickness. This gabbro-wehrlite network complex gradually changes downward into a 8-m thick dunite zone intercalated with harzburgite that increases in proportion toward the mantle harzburgite over a depth of 20 m downward. The wehrlite and dunite are severely serpentinized except fresh chrome spinel and a small amounts of relict olivine. Diopsidite dikes found just above and below the MTZ are considered to be products of high-temperature hydrothermal alteration, suggesting the circulation of seawater or magmatic fluid in the deep crust and

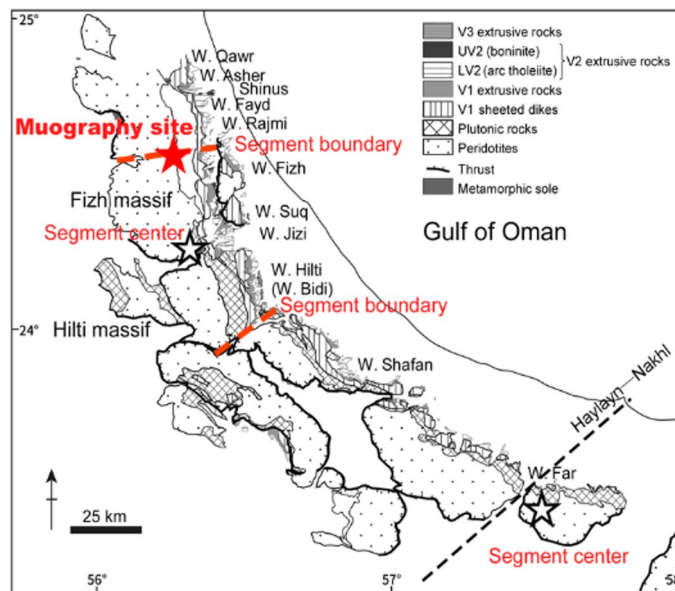


Fig. 1. A simplified geologic map of northern Samail Ophiolite. The solid star indicates the location of the measurement site. The W. is an abbreviation for Wadi.

uppermost mantle³⁸. The boundary between the layered gabbro and the uppermost dunite layer in MTZ gently dips to the east, undulating with a wavelength of 500–600 m and a wave height of ~100 m (Fig. 2).

Results

Experimental setting

Figure 2a shows the topographic map of the measurement site with contours of 20-m intervals based on the 1:50,000 topomap of the National Survey Authority (NSA), Sultanate of Oman. A Multi-Wire-Proportional-Chamber-based Muography Observation System (MMOS) was installed on the Moho plane at latitude of 24.45655°, longitude of 56.29703°, and at an altitude of 467 m above sea level, marked as red-colored × in Fig. 2a. The MMOS was oriented toward an azimuth 299° from geographic north (defined as $\tan(\theta_x) = 0$, and shown by the red-colored arrow in Fig. 2a), with tracking detector layers set vertically (i.e. perpendicular to the horizontal plane, defined as $\tan(\theta_y) = 0$). The MMOS tracked muons within ± 0.55 rad in both the horizontal and the vertical directions. The horizontal distance between the MMOS and the ridge of imaged LGb-Hz transition was about 400 m.

The target ridge segment is enclosed by the rectangle in Fig. 3a, where LGb covers most of the ridge. However, field surveys have revealed that the layered gabbro is thin and covers only the surface of the ridge, which is underlain by the dunite-rich MTZ (Fig. 2b, c and d). Figure 3b shows the rock thicknesses along the muon paths calculated using the 5-m DEM data of NSA from the location of the MMOS across the ridges within the black rectangle of Fig. 3a. The red-colored dashed line shows the boundary between the LGb and the MTZ.

Data collection and processing

The data collection campaign was conducted between 27 February 2024 and 22 January 2025. We conducted an off-line data analysis for detector calibration, data quality assurance, and muographic image processing (Methods). The detector calibration procedures involved offline alignment of detector layers and removing of noise and dead electronics channels. After the data quality assurance, the effective time of data collection was totaled 171 days due to detector malfunctions, power cuts, and the maintenance works. In the muographic images, each pixel corresponds to a pair of slopes, $\tan(\theta_x)$ - $\tan(\theta_y)$, which represent the tangents of the horizontal and vertical projection angles of muon tracks, measured relative to the orientation of the MMOS (Fig. 2). Each image has 65×65 pixels with a size of 0.0086 in both horizontal and vertical directions. Each angular bin corresponds to an approximately $3.5 \text{ m} \times 3.5 \text{ m}$ area at the peak of the ophiolite 400 m away from the MMOS. The measured flux, the modeled flux and the average mass density were determined for each angular bin.

The first muographic images

Figure 4a and b show the measured and modeled muon fluxes, respectively. The modeled flux was calculated assuming a uniform rock density of 3 g cm^{-3} within each slope bin. Both flux maps reflect the structure of the crust-mantle transition and the surrounding topography thanks to the spatial resolution of approximately 3.5 m.

The corresponding density image of the ophiolite segment was reconstructed with the same spatial resolution, as shown in Fig. 5a. Here the white-shaded region indicate slope bins without density values because these bins correspond to the open sky where the path lengths of muons was assumed to be zero. The densities were under-measured in angular bins where the path lengths of muons across the crust-mantle transition exceeded 500 m.

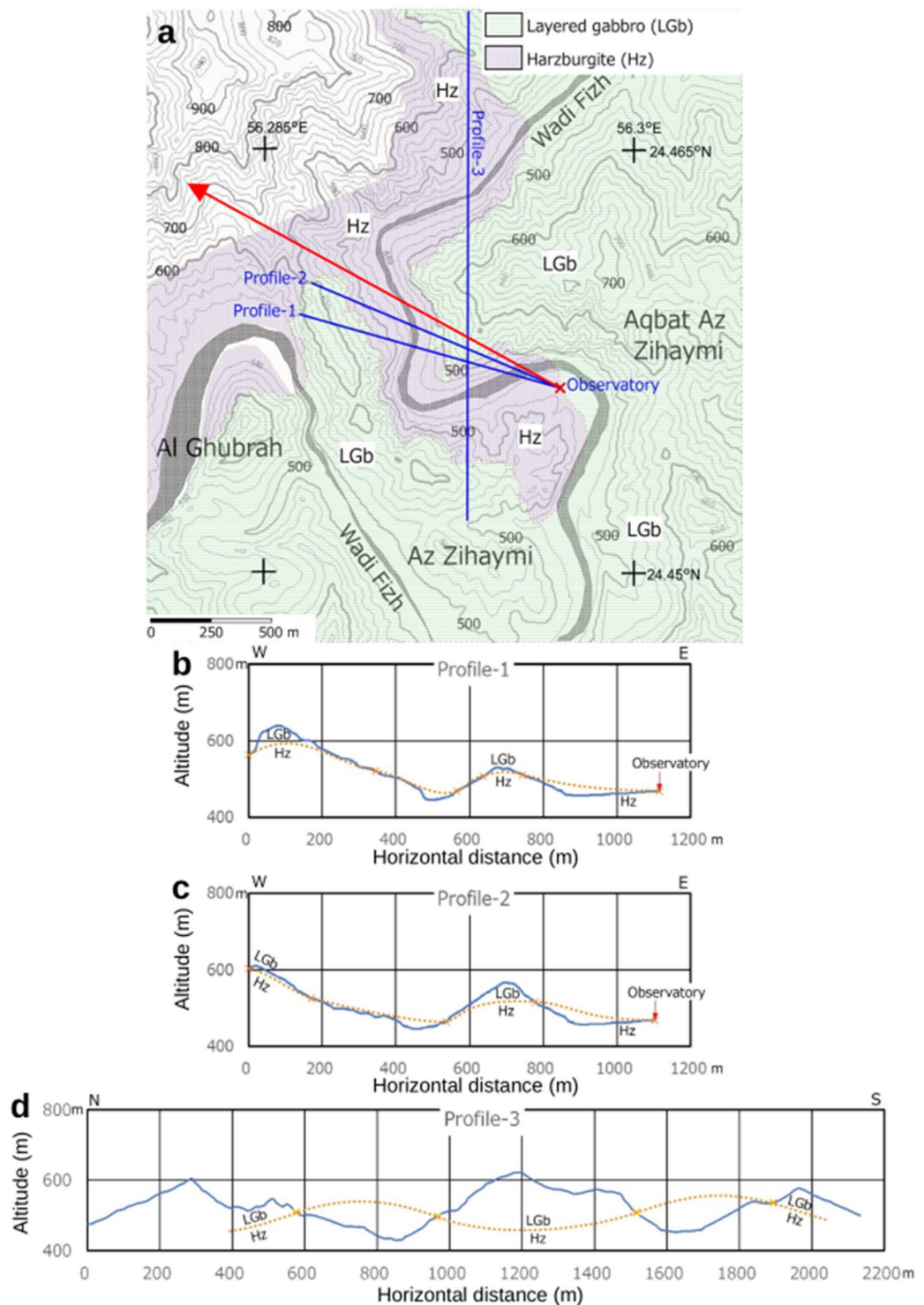


Fig. 2. The experimental arrangement and the distribution of major rock types are shown in the topographic map of Wadi Fizh. (a) The muon tracking system was installed at latitude 24.45655° and longitude 56.29703° , at 467 m above sea level (red $\times$). The muographically imaged ridge is located at a distance of about 400 m from the observational instrument. The red arrow indicates the azimuthal orientation of the tracker that was set to 299° from north. The green-hatched area and the purple-hatched area show the lower crustal layered gabbros (LGb) and the mantle harzburgite (Hz), respectively. The blue lines indicate two selected cross-sections across the target ridge. Black crosses indicate four reference points for the map. (b) Cross-section along the Profile-1 in Fig. 2a. The solid line shows topography (elevation above sea level), and the dashed line indicates the boundary between the LGb and Hz. (c) Cross-section along the Profile-2 in Fig. 2a. (d) Cross-section along the Profile-3 in Fig. 2a.

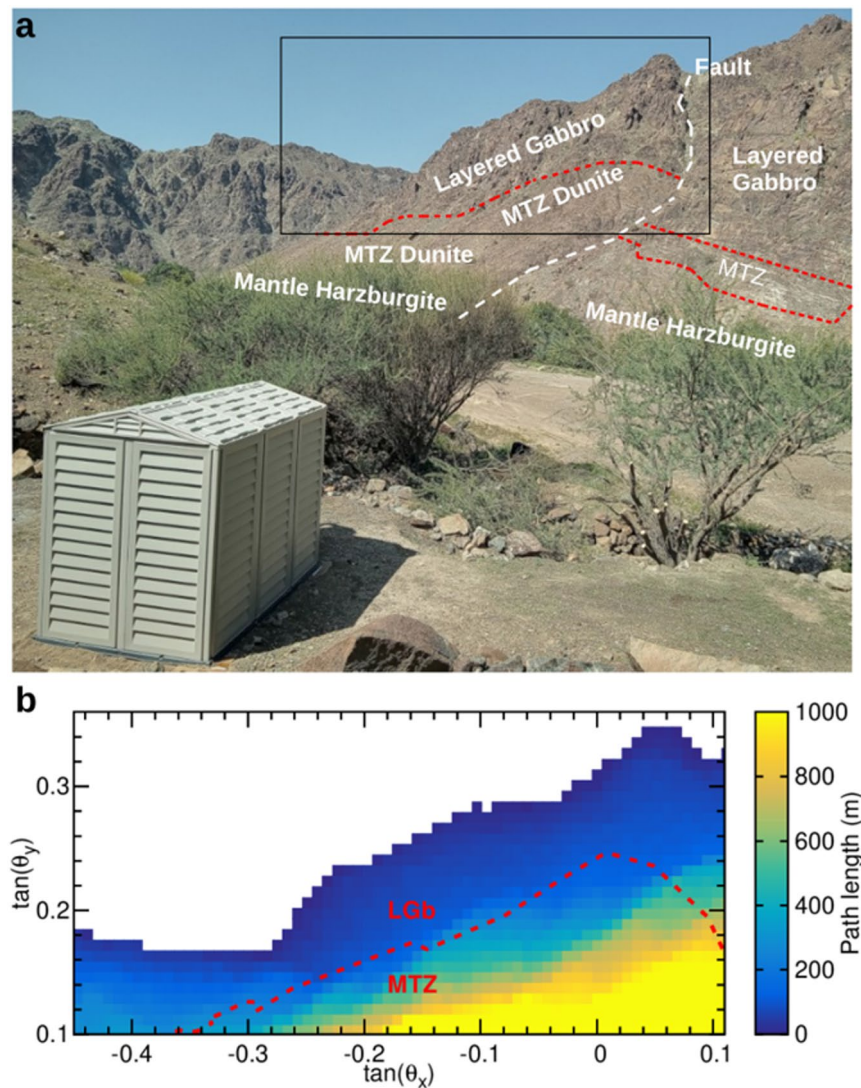
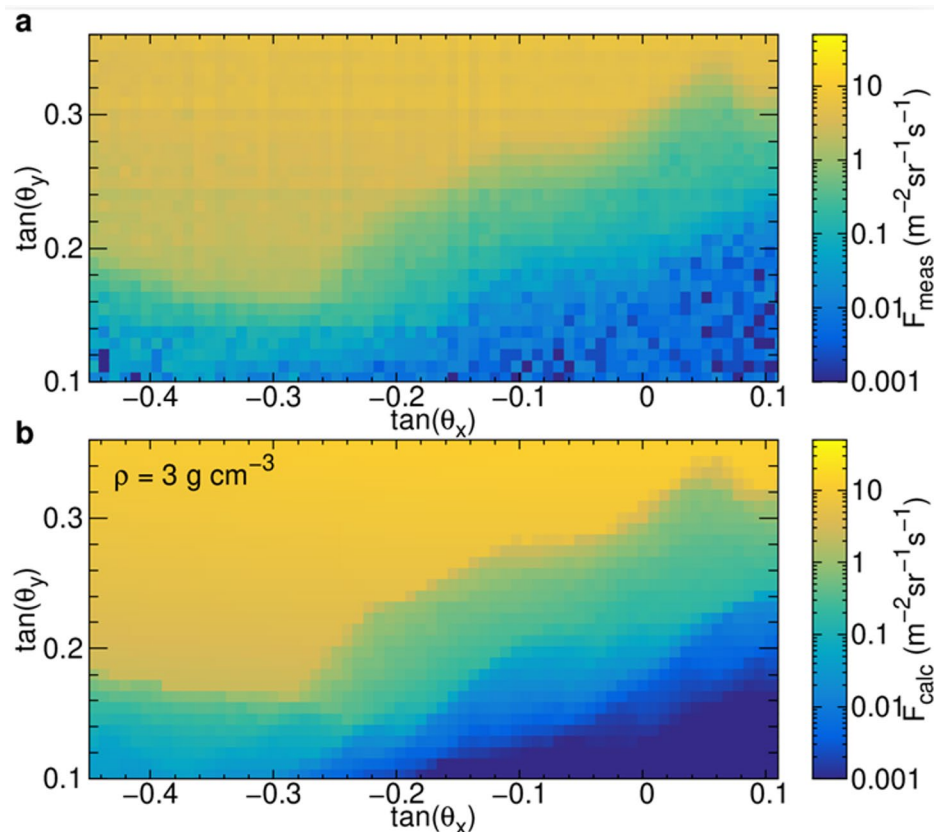


Fig. 3. The studied lower crust-mantle section in Wadi Fizh. **(a)** Red dashed lines indicate the boundary between the lower crustal layered gabbro (LGb) and the Moho Transition Zone (MTZ). The white dashed line marks the location of a fault. The black rectangle highlights the region investigated by muography. The tracking system was operated in the hut. Note that the LGb ridge in the lower left of the rectangle has a thin gabbro layer underlain by MTZ dunite (The ridges shown by the western ends of Fig. 2b and c). **(b)** Muon path lengths calculated from the detector location are shown as a function of $\tan(\theta_x)$ and $\tan(\theta_y)$, which represent the tangents of the horizontal and vertical projection angles of muon tracks. The slope bin size is 0.0086×0.0086 , corresponding to a spatial resolution of 3.5 m at a distance of 400 m. The red dashed line indicates the boundary between the LGb and MTZ sections.

This underestimation was caused by the contamination from background muons in the selected track set. The angular bins with the underestimated density values were excluded from further analysis. Figure 5b shows the density error values which were quantified by averaging the upper and lower densities calculated for the $F - \Delta F$ and $F + \Delta F$ values, respectively. Three regions were designated across the crust-mantle transition: a high density-region of the ridge behind in the lower left (Hz), a region across the upper part of the ridge (LGb), and a region across the MTZ. The averaged rock thicknesses were estimated as 159 m, 301 m and 70 m across the Hz, the MTZ, and the LGb, respectively. Figure 5c and d, and 5e show the density distributions extracted from the regions Hz (blue-colored histogram), MTZ (green-colored histogram), and LGb (orange-colored histogram), respectively. A density bin size of 0.1 g cm^{-3} was used for each histogram. The density values ranged from 2.3 g cm^{-3} to 6 g cm^{-3} with a mean of.

3.38 g cm^{-3} for the Hz (Fig. 5c). The density values above 4.5 were considered non-physical and were excluded from the mean calculation. The densities were measured between 1.7 g cm^{-3} and 4 g cm^{-3} with a mean of 2.72 g cm^{-3} for the MTZ (Fig. 5d). For the LGb (Fig. 5e), the density values ranged from 1.6 g cm^{-3} to 5.5 g cm^{-3} with a mean of 3.03 g cm^{-3} .



Figs. 4. Muon fluxes are shown after the ridge as a function of $\tan(\theta_x)$ and $\tan(\theta_y)$, which represent the tangents of the horizontal and vertical projection angles of muon tracks. The slope bin size is 0.0086×0.0086 . (a) Measured cosmic-ray muon flux is shown. (b) Example of calculated muon fluxes. Here, flux values were calculated by assuming a uniform density of 3 g cm^{-3} for the crust and mantle.

The impact of systematic effects on the reconstructed density structure was evaluated (see in Methods). The dominant contribution arises from the digital elevation model, while atmospheric effects, muon spectrum modeling, altitude dependence, and chemical composition introduce smaller corrections. These contributions were combined in quadrature to obtain total relative density uncertainties of 7.45%, 3.7%, and 9.6% for the Hz, MTZ, and LGb regions, respectively. In absolute terms, these correspond to uncertainties of 0.25 g cm^{-3} , 0.10 g cm^{-3} , and 0.29 g cm^{-3} . The observed RMS variations within each region exceed these systematic uncertainties, indicating that the reconstructed spatial heterogeneity reflects genuine structural variations rather than methodological artifacts.

Discussion

The first muographic measurements of a crust-mantle transition in Wadi Fizh demonstrate that muography can capture spatially continuous density variations across an ophiolite sequence, bridging the gap between high-precision but discrete laboratory measurements and large-scale geophysical observations.

The reconstructed densities reveal distinct patterns across three lithological regions: the lower crust layered gabbro (LGb), the crust-mantle transition zone (MTZ), and the mantle harzburgite covered by a thin LGb layer (Hz). The mean density across the LGb region (3.03 g cm^{-3}) is broadly consistent with reported values for layered gabbros ($\sim 2.95\text{--}3.0 \text{ g cm}^{-3}$), suggesting that the layer is relatively intact at meter scales. The MTZ exhibits lower mean densities (2.72 g cm^{-3}), which are compatible with serpentinized dunite and wehlite as exposed in the field^{14,15}, although the exact degree of alteration cannot be directly inferred from muography alone. This pronounced alteration may be related to the high-temperature hydrothermal circulation involved in the formation of diopside surrounding the MTZ in Wadi Fizh³⁸. This mean density is smaller than the typical density values of reported for other MTZs in the Samail Ophiolite (e.g., Ref¹⁶, where lithological profiles are characterized with gradual lithological transition from mantle to crust^{14,15,36–40}). High-density anomalies in the Hz region (mean 3.38 g cm^{-3}) may indicate underlying mantle peridotite capped by the thin LGb layer. This supports the field observations of undulating Moho surfaces (Fig. 2b, c and d), suggesting that the crust-mantle boundary is not a simple planar interface. These results hint that future measurement of 3-dimensional density distribution will allow investigation of diversity of Moho along the paleoridge segment and explore whether the discontinuity forms either sharp, blurred or multiple seismic reflections, thus providing constraints on the physical processes that shaped diverse oceanic Moho structures.

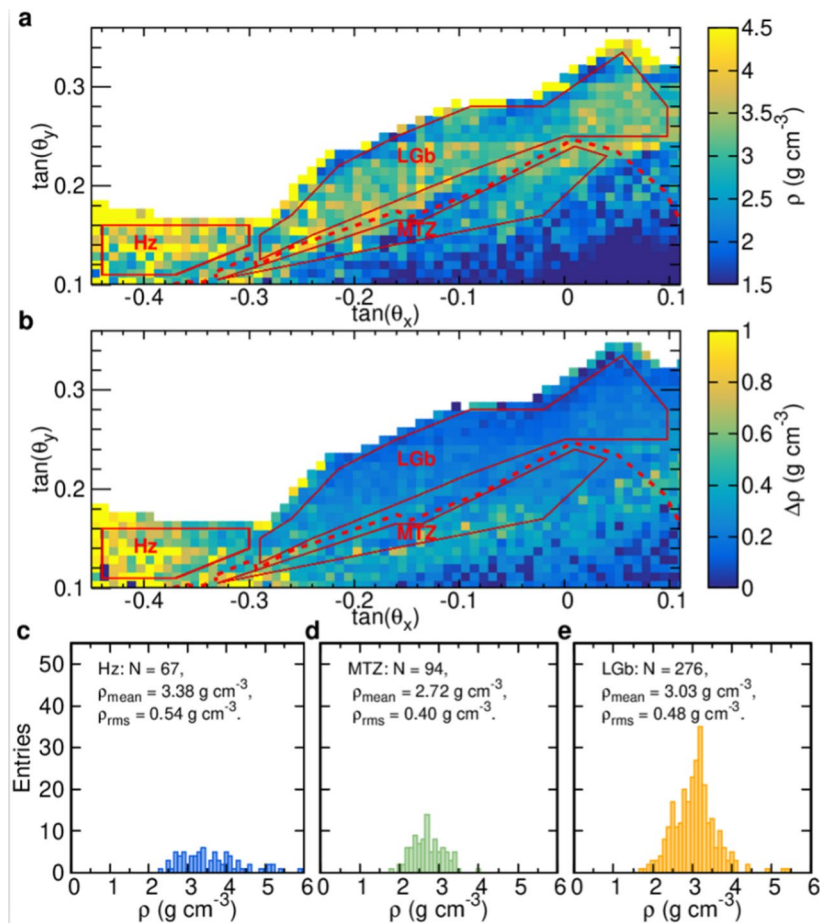


Fig. 5. The mass densities of rocks measured across the crust-mantle transition are shown as a function of $\tan(\theta_x)$ and $\tan(\theta_y)$, which represent the tangents of the horizontal and vertical projection angles of muon tracks. The slope bin size is 0.0086×0.0086 . Density map (a) and uncertainties (b) of crust-mantle transition. Density distributions for the Hz region (blue-colored histogram) (c), MTZ (green-colored histogram) (d), and LGb (orange-colored histogram) (e), respectively.

The RMS values of the mean densities (e.g., 0.4 g cm^{-3} for the MTZ) reflect spatial variability within each lithological unit rather than measurement uncertainty. The estimated systematic uncertainties (see in Methods) are substantially smaller (e.g., 0.1 g cm^{-3} for the MTZ), indicating that the observed heterogeneity is robust. This variability highlights the capability of muography to resolve intermediate-scale structural features that are not accessible to point-based laboratory measurements or kilometer-scale seismic averages. Accordingly, the primary value of muography in this context lies in mapping continuous structural variations rather than in providing unambiguous lithological identification.

The applicability of muography to ophiolite studies is constrained by several limitations. Muography primarily resolves bulk density contrasts, which provide insight into structural organization but do not uniquely constrain lithology or fluid-rock processes. As a result, interpretations are not unique and require independent petrological and geochemical validation. This ambiguity is particularly relevant where different lithologies exhibit similar densities; for example, serpentinized peridotites and gabbros may not be distinguishable based on density alone. The integrated use of muographically derived densities and seismic velocities⁴¹ offers a promising approach to constrain the elastic properties (bulk and shear moduli) of the rocks, thereby providing additional insight into lithology. Muography is sensitive only to sufficiently large density contrasts (typically $>0.1 \text{ g cm}^{-3}$), which limits its ability to resolve subtle compositional variations within the crust-mantle transition zone. In addition, muography reconstructs density integrated along muon trajectories, so the resulting images represent path-averaged properties rather than fully resolved three-dimensional structures. Future studies incorporating multi-directional measurements⁴² and joint inversion with complementary datasets (e.g., gravity⁴³) will help reduce these ambiguities and improve structural interpretation. Resolution and depth sensitivity impose further constraints. The current spatial resolution, on the order of a few meters, is insufficient to resolve fine-scale features such as gabbro sills, which typically occur at millimeter- to centimeter scales. Achieving sub-meter resolution would require larger detectors deployed closer to the target and longer acquisition times, which may not be practical in many field settings. At the same time, the penetration capability of muons is limited by their energy spectrum²⁹: as the thickness of the target increases, the transmitted muon flux decreases rapidly (Fig. 4),

while background contamination becomes significant, particularly for path lengths exceeding ~500 m. This limits the thickness of ophiolite sections that can be reliably imaged. Field deployment introduces additional practical constraints. Challenging topography, variable environmental conditions, and limited access to power can restrict measurement duration and spatial coverage. Addressing these challenges will require more flexible and scalable observation systems, as well as closer integration with complementary geophysical and geological methods.

Conclusions

This study demonstrates the potential of muography to image the crust–mantle transition in ophiolites, providing meter-scale, spatially continuous density maps that are inaccessible to discrete laboratory measurements or conventional geophysical methods. The reconstructed density patterns reveal heterogeneity within the lower crust, the MTZ, and underlying mantle units, highlighting undulations in the Moho and variations in crustal thickness along the Wadi Fizh segment. While absolute lithology and fluid–rock interactions cannot be directly determined from muography alone, the technique enables mapping of density contrasts and structural organization at intermediate scales. These results provide a foundation for future multidisciplinary investigations that combine muography with petrological and geochemical analyses, offering new insights into the formation, structure, and evolution of oceanic lithosphere.

Methods

Muon detector

The technical details of the applied tracking detector has already been presented in our earlier works^{44–46}. This technology has successfully been applied in various environments, including underground mines and near active volcanoes³¹. In this study, we used an MMOS consisting of seven MWPCs, each with a surface area of 0.8 m × 0.8 m and a thickness of 0.02 m. Each MWPC provided a 1 + 1 dimensional positional information by two perpendicular wires planes. Wire spacing was 0.012 m in both wire planes, which allowed a spatial resolution of approximately 4 mm for each MWPC. Five of the seven detectors operated reliably during the measurement period, thus we used the data from these detectors for this study. The five MWPCs spanned a length of 1.397 m in the tracking detector.

Figure 6 shows a photograph and a schematic drawing of the experimental setup with five MWPCs (gray-colored rectangles) and two 2-cm-thick lead walls (hatched rectangles). The lead walls were used to absorb and deflect low-energy muons, which may scatter from the surface of ophiolite or from the atmosphere into the detectors (e.g., Ref⁴⁷). The numbers shown below the MWPCs and lead walls indicate their distance from the first tracking layer in millimeters. The tracking system was powered by the local electricity network, supplied from an apartment located approximately 300 m from the MMOS. The detector layers were continuously flushed with an argon-carbon-dioxide (Ar-CO₂) gas mixture in a proportion of 80%:20%. This gas mixture enabled signal generation on the wires via ionisation of argon atoms by penetrating charged particles, typically producing 100 ionisation electrons per centimeter. A high-voltage of +1,700 V was applied to the wires to amplify the signal to a measurable signal in the order of 10,000 electrons. Custom-designed front-end electronics amplified the analogue signals by a factor of ten and discriminated them by shift registers, converting them to binary output on each electronics channel.

Detector operation and data collection were controlled by a microcomputer. Data collection was triggered by triple coincidence of MWPCs. The recorded data included time stamps, analogue signal amplitudes (ADCs), trigger patterns, high-voltage values, temperature, humidity, pressure, and the hit coordinates of the detected particles. These data were stored into ASCII files on an event-by-event basis. The trigger was temporarily blocked during the data readout. The trigger frequency ranged from 5 Hz to 35 Hz, with an average of 10.4 Hz. A significant reduction in the trigger rate was observed after the removal of uninterruptible power supply from the power supplying system.

Muon flux measurement

The muon flux values were calculated for each slope bin by dividing the number of reconstructed tracks (N) by the measurement time (T), corrected for the dead time (t_{dead}), the trigger efficiency ($\epsilon_{trigger}$), the tracking efficiency ($\epsilon_{tracking}$), and the detector acceptance factor, which accounts for the sensitive surface area (A) and the solid angle (Ω):

$$F = N / [T \times (1 - t_{dead}) \times \epsilon_{trigger} \times \epsilon_{tracking} \times A \times \Omega] \quad (1)$$

The tracks were counted as a function of horizontal and vertical slopes on event-by-event basis. The reconstruction of particle trajectories was conducted independently in the horizontal and vertical directions. For each MWPC, the centroids, sizes and multiplicities of signal clusters were determined. A combinatorial algorithm then produced track candidates by merging one cluster centroid from each MWPC. A straight line was fitted on the clusters of each track candidate. The track candidates were ranked according to the goodness of fit (χ^2/ndf), and the best-fitting one was selected for further analysis. To suppress tracks originate from electronic noise and low-energy scattered particles, only tracks with clusters in at least four MWPCs, analogue signal amplitudes above 200 ADC in at least four MWPCs, and a goodness of fit $\chi^2/\text{ndf} < 2$ were retained.

The measurement time T was 171 days after quality assurance of the track data. Figure 7a and b show the distributions of the time differences between consecutive events. Assuming that the detected particles arrived from different air showers with uniform probability over time, the interarrival times follow an exponential distribution, consistent with a Poisson arrival process. As shown in Fig. 7b, the distribution starts from 112.5

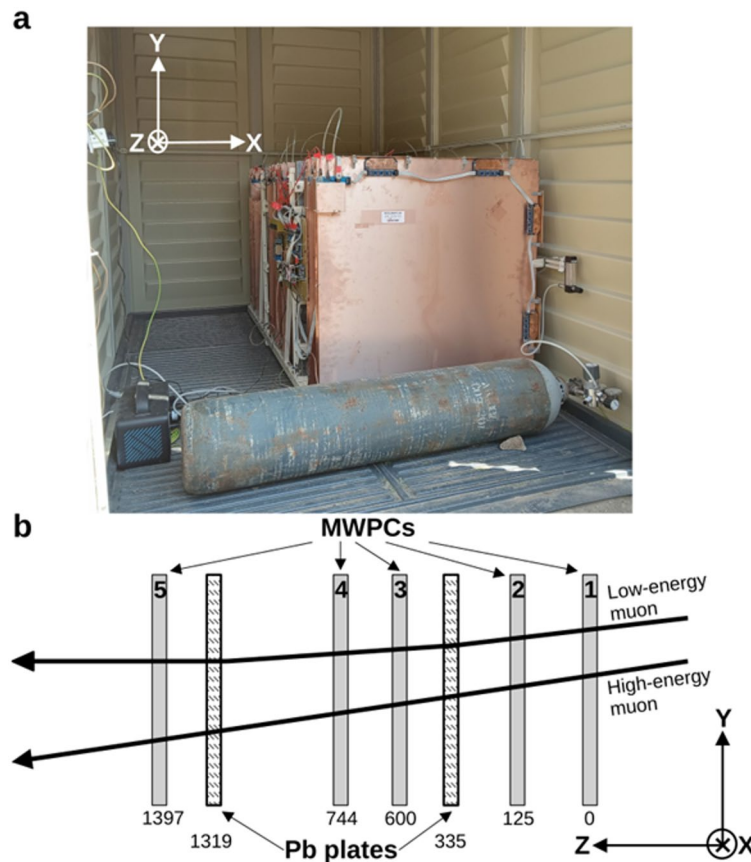


Fig. 6. The structure of the muon tracking system. (a) A photograph of the tracker built up from seven MWPC detectors and two 2-cm-thick lead plates is shown. White-colored coordinate system shows the orientation of the tracker. The gas system and the power system are shown in the foreground. (b) A schematic drawing about the arrangement of the MWPCs (grey-colored rectangles) and the Pb plates (hatched rectangles) is shown. The coordinate system corresponds to the coordinate system shown in Fig. 3a. The numbers from 1 to 5 show order of MWPCs. The numbers from 0 to 1397 show the horizontal distance of detectors from the first MWPC in mm units. Black arrows aim to visualize the penetration of low-energy (upper) and high-energy (lower) muons throughout the tracking system.

microseconds due to the data readout, which blocked the trigger for this period after each event. This dead time resulted in only a negligible reduction (0.12%) of the muon yield over the entire data acquisition period.

The trigger efficiency was evaluated for each chamber by calculating the ratio of tracks that produced trigger signal in the investigated chamber to the total number of tracks. Figure 7c shows the time evolution of the trigger efficiency with a 6-hour bin size. The trigger efficiencies exceeded 93% for every MWPC throughout the measurement period. The overall trigger efficiency of the tracking system approached 100%.

The tracking efficiency was measured for each MWPC as a function of time and of tracks slopes. A tracklet was constructed from clusters detected in four MWPCs. This tracklet was extrapolated to the fifth MWPC. The tracking efficiency of the investigated chamber was given by the ratio of the cases in which a cluster was found on the fifth MWPC to the number of tracklets. The overall tracking efficiency of the detector system was calculated from the individual tracking efficiencies of MWPCs by the following formula:

$$\varepsilon_{\text{tracking}} = \prod_{i=1:5} \varepsilon_i + \sum_{i=1:5} \prod_{j=1:5} [(1 - \delta_{ij}) \times \varepsilon_i + \delta_{ij} \times (1 - \varepsilon_i)] \quad (2)$$

where the δ_{ij} Kronecker delta gives $\delta_{ij} = 1$ for $i = j$, and 0 otherwise. Figure 8 summarizes the tracking performance. A 6-hour time binning was applied for monitoring the time evolution of tracking efficiencies. Figure 8a shows the track rate as a function of time, represented by black points with one standard deviation error bars. The mean track rate was 0.163 Hz (red-colored line). Tracking efficiencies exceeded 92% for each MWPC throughout the data collection period (Fig. 8b). The overall tracking efficiency of the detector system is shown as a function of horizontal and vertical slopes in Fig. 8c. These efficiencies were found well above 95% in the studied angular regions.

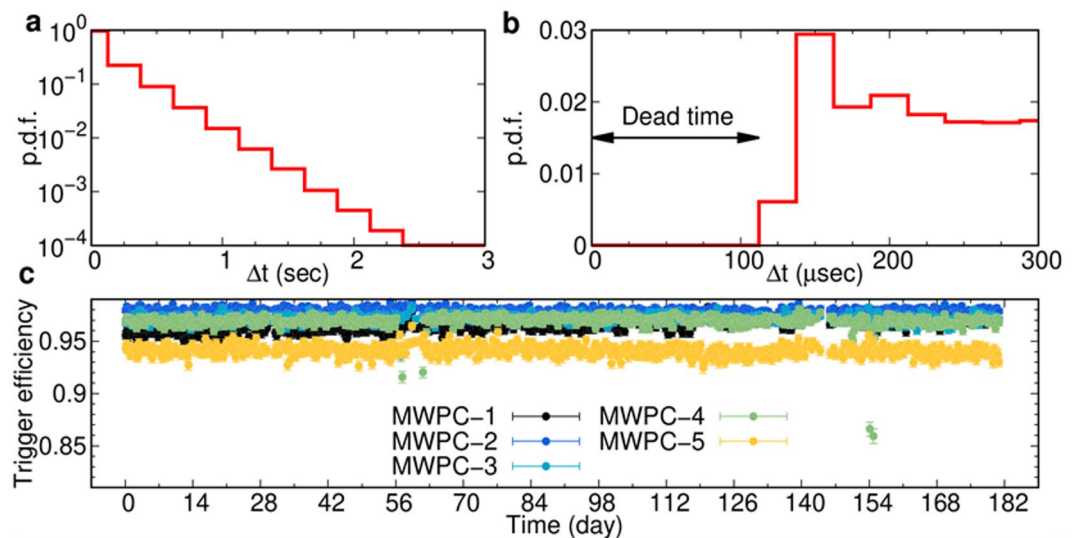


Fig. 7. The performance of the triggering of data collection. **(a)** The distribution of time difference between the consecutive events is shown in second units. The Poisson nature of muons is demonstrated here. **(b)** The same data are shown with a time binning of 25 microseconds. The dead time of the tracking system was quantified to 112.5 microseconds. **(c)** Trigger efficiencies are shown as a function of time for the entire data collection period. The trigger efficiencies were measured above 93% for each detector.

Muon flux modeling

The density-lengths (i.e., integrated densities along muon paths) were determined for each slope bin by minimizing the difference between the modeled and measured muon fluxes. The modeled muon fluxes (F_{calc}) were calculated as follows. Zenith-angle (θ) and energy (E) dependent muon spectra were integrated over energy to simulate the attenuation of muon flux after traversing different density-lengths. In this work, the energy spectra were parametrised with an empirical formula based on a modified Gaisser model⁴⁸. The altitude (A) dependence of modeled fluxes was taken into account by a factor $F_{calc}(A) = F_{calc}(0\text{ m}) \times e^{[-A/K(E)]}$, where $F_{calc}(0\text{ m})$ is the flux at sea level and the $K(E)$ is an energy-dependent parameter, given by $K(E) = 4,900 + 750 \times E$ (E in GeV, K in m). The E_{min} minimum energy were calculated from the X density-lengths expressed in meter-water-equivalent (m.w.e.) units based on the following parametrization⁴⁹:

$$E_{min} = (e^{X/a_0 - a_2})/a_1 \quad (3)$$

where the parameters a_0 , a_1 and a_2 were 2,298.2 m.w.e., 0.001920 1/GeV, 0.99809, respectively. The muon fluxes were modeled for different density-lengths up to 2,000 m.w.e. with a 2 m.w.e. stepping. The corresponding density values were then obtained by dividing the density-lengths by the path-lengths.

Systematic effects

The systematic effects in muographic imaging have been discussed and quantified in earlier studies^{28–31}. Here, we describe site- and detector-specific systematic effects relevant to this work. The remaining effects are considered negligible within the current experimental and analysis framework.

Production rate of cosmic-ray muons depends on the thermal state of the atmosphere. The relative variation in muon flux can be expressed as:

$$\Delta F / F = \alpha_T \times \Delta T_{eff} / T_{eff} \quad (4)$$

where α_T is the temperature coefficient and T_{eff} is the effective temperature, defined as weighted average of temperatures at different altitudes. In this study, $\alpha_T \approx 1$ was assumed, consistent with high-energy muons arriving from near-horizontal directions⁵⁰. The effective temperature was calculated following the procedure developed for the MINOS experiment⁵⁰, using the atmospheric data from the nearest station (ID 41,256)⁵¹. The zenith angle and energy threshold were set to 100 GeV and 79.5°, respectively. Figure 9 shows the temporal variation of the effective temperature during the measurement period. The average value was 232.8 K, with variations within $\pm 2\%$ of this mean. Based on Eq. 4, the relative flux variation was estimated to 2%. Densities were reconstructed for flux values decreased and increased by 2%. The relative density uncertainty for each region was then estimated as half of the difference between the resulting densities, normalized by their mean value.

Two modified Gaisser muon spectrum models⁴⁸ were applied for the density reconstruction. The relative density uncertainty for each region was estimated as half of the difference between the resulting densities, normalized by their mean.

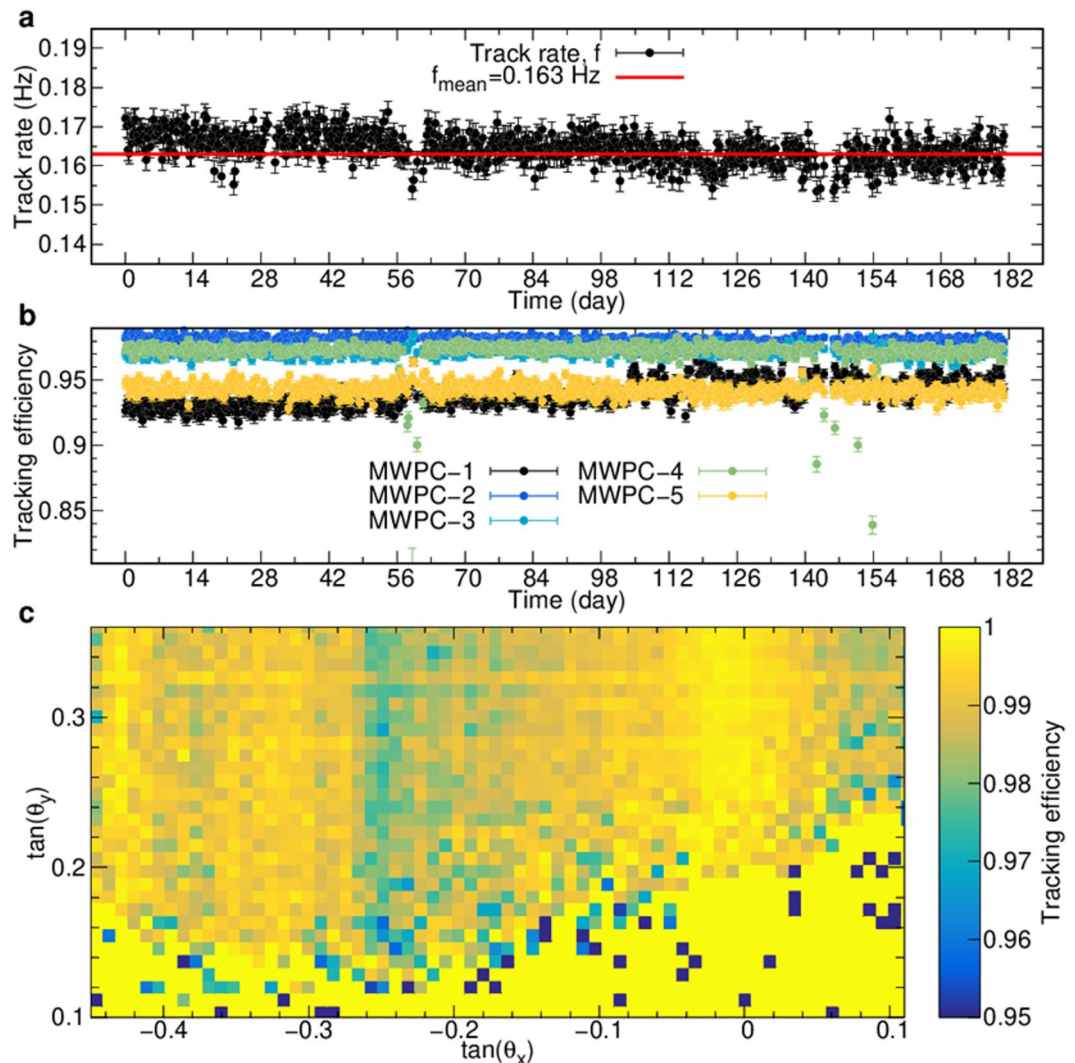


Fig. 8. The performance of track reconstruction. (a) Track rate is shown for the entire data collection period. The red-colored line shows the arithmetic mean track rate of 0.163 Hz. (b) Tracking efficiencies are shown as a function of time. (c) Tracking efficiency is shown as a function of $\tan(\theta_x)$ and $\tan(\theta_y)$, which represent the tangents of the horizontal and vertical projection angles of muon tracks. The slope bin size is 0.0086×0.0086 .

The effect of altitude dependence was evaluated by deriving densities assuming observation altitudes of 0 m and 467 m above sea level. The corresponding relative density uncertainty was estimated using the same approach as for the muon spectra.

The difference in integrated fluxes calculated between standard rock and peridotite for the same density-length is $< 2\%$, due to their different chemical compositions³⁰. The corresponding relative density uncertainty was determined using the same approach as for atmospheric effect.

The grid size of the DEM introduces uncertainties in the calculated path lengths and, consequently, in the derived densities. Assuming a uniform discretization error, the elevation uncertainty is estimated as $\Delta Z \approx \Delta X / \sqrt{12} = 1.44$ m for a grid size of $\Delta X = 5$ m. Propagating this uncertainty along the muon path yields a path-length uncertainty of $\Delta L \approx \Delta Z / \sin(\theta_y)$. The values of ΔL were quantified for each slope bin. The average uncertainties were estimated to be 11.6 m, 7.9 m, and 6.6 m for the Hz region, MTZ, and LGb, respectively. The corresponding relative path-length errors are 7.3%, 2.6%, and 9.4%, respectively, which propagate into relative density uncertainties of the same values.

Table 1 summarizes the δ relative errors caused by the systematic effects. The total relative density values were calculated as the square root of the sum of the squared individual relative errors. The total errors were quantified as 7.45%, 3.7%, and 9.6% for the Hz region, MTZ, and LGb, respectively. Thus, the systematic density errors were found to be 0.25 g cm^{-3} , 0.10 g cm^{-3} , and

0.29 g cm^{-3} for the Hz region, MTZ, and LGb, respectively.

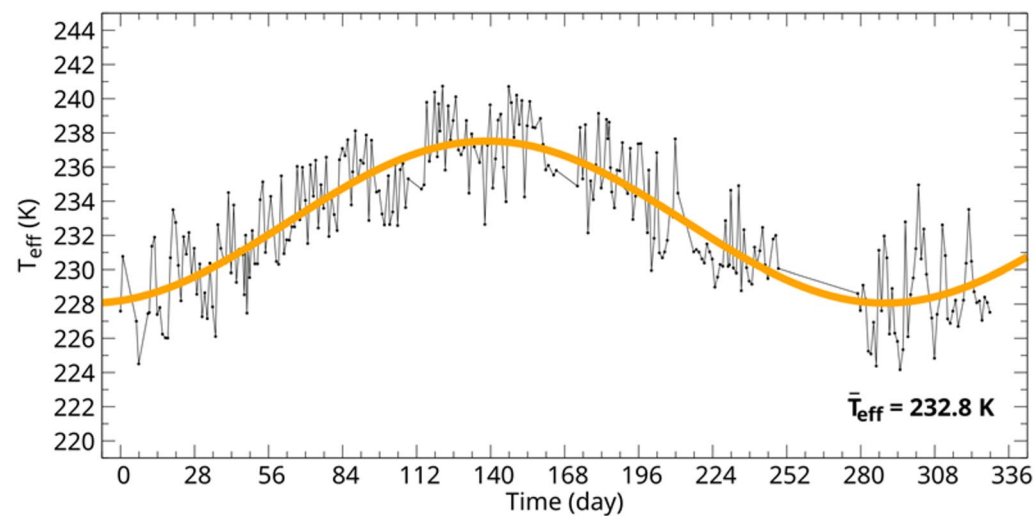


Fig. 9. The effective temperatures are shown for the data collection period. The cosine fit shows an average seasonal variation of 4 K around the average value of 232.8 K.

Systematic uncertainty	δ_{Hz} (%)	δ_{MTZ} (%)	δ_{Lgb} (%)
Atmospheric effects	0.9	0.9	1.4
Energy spectra model	0.8	2.3	0.7
Altitude dependence	0.1	0.0	0.3
Chemical composition	0.9	0.9	1.4
Digital elevation model	7.3	2.6	9.4
Total	7.45	3.7	9.6

Table 1. Summary of systematic effects. The relative density uncertainties were calculated for each effect, and the total uncertainty was obtained as the square root of the sum of the squared individual relative uncertainties.

Data availability

The data sets and software of this study are available in a data repository in Open Science Framework (<https://doi.org/10.17605/OSF.IO/5YX8U>). Raw data is available from LO upon reasonable request.

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Author contributions

SU, LO, HKMT, DV, SMA, NSSA, IAMAS, YK, TM, TL designed the muographic survey. TL, DV constructed the muon detectors. LO, TL, SU installed the muon detectors. NSSA maintained the muon detectors. LO analysed the muon data. SU, YK, TM conducted the geological survey. SU prepared Figs. 1, 2 and 3a. LO prepared Figs. 3b, 4, 5, 6, 7, 8 and 9. LO, SU wrote the manuscript. All authors reviewed the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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