DOI: https://doi.org/10.68732/4dc44f3d1aeaabef

ISBN: 978-9989-2053-7-8

Long-term monitoring of strain changes around a circular tunnel at the Grimsel Test Site

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Abstract

The Compact Conical Borehole Monitoring (CCBM) strain-gauge probe is derived from the Compact Conical Borehole Overcoring (CCBO) technique, both employing strain gauges mounted on a conical borehole bottom to measure the deformation response of the surrounding rock. While CCBO determines the in situ stress state from stress relief during overcoring, the CCBM configuration enables long-term monitoring of strain changes without induced stress relief, allowing the observation of time-dependent stress changes in the surrounding rock mass.

This study presents long-term strain monitoring within the secondary stress field around the circular tunnel, conducted using the CCBM probe at the Grimsel Test Site (GTS), Switzerland, operated by Nagra (National Cooperative for the Disposal of Radioactive Waste). The primary objective was to assess whether stress changes related to pumped-storage power plant operation could be identified in the recorded strain responses. The analysis, however, does not reveal a clear causal relationship between the operational cycles and the measured strain signals, indicating that other mechanisms dominate the observed response.

To complement borehole monitoring, Compact Flat Wall Monitoring (CFWM) devices were installed directly on the tunnel surface to record strain changes in the near-field rock mass. A joint analysis of strain data from both monitoring systems confirms the presence of time-dependent variations in deformation in the vicinity of the circular tunnel, which are discussed in terms of their possible origin.

Keywords

CCBO, CCBM, CFWM, Strain monitoring in secondary stress field, Grimsel Test Site.

1 Introduction

Understanding the excavation-induced zone (EIZ) around circular underground openings is essential for the safe design of tunnels and underground structures, as well as for the assessment of the long-term performance of underground facilities such as repositories for radioactive waste. Stress redistribution and time-dependent deformation processes in the near-field rock mass play a key role in the mechanical response of underground excavations and therefore require detailed in situ investigation.

The measurements presented in this study were conducted within the framework of the LASMO (Large-Scale Monitoring) project at the GTS (Kober et al. 2016). At several locations within the underground research laboratory (Fig. 1), strain measurements were performed using Compact Conical Borehole Overcoring (CCBO) probes, Compact Conical Borehole Monitoring (CCBM) probes, and Compact Flat Wall Monitoring (CFWM) devices (Hastíková and Franěk 2016). This paper presents selected results of in situ measurements conducted in tunnel L408.

The CCBO method is a stress-relief technique based on the overcoring of a conical strain-gauge probe installed at the bottom of a borehole, where the measured strain release can be used to determine the full in situ stress tensor. The method was originally developed in Japan by Sugawara and Obara (1999). Subsequent developments focused on the technical design of the conical probe and its measurement capabilities (Knejzlík et al. 2008). The method was later subjected to critical analysis, with respect to the influence of material anisotropy and the formulation of distribution matrix coefficients used in stress determination (Petrlíková 2024; Petrlíková et al. 2025a).

The evaluation of the full stress tensor using the CCBO method is performed assuming a linear elastic and homogeneous theoretical material model. The influence of inhomogeneities in local material is mitigated by excluding selected strain gauges from the evaluation. Strain gauges affected by local heterogeneity or instrumental disturbances are identified and subsequently excluded from further processing. This procedure is applied provided that the distribution matrix—describing the relationship between the measured strains and the unknown stress tensor—remains stable, which is ensured by maintaining a sufficient number of independent strain measurements relative to the six independent components of the full stress tensor, such that the system of equations is overdetermined (Petrlíková 2024).

Some of the full stress tensors, determined at the site, were presented in recent studies (Petrlíková 2024; Petrlíková et al. 2024;Petrlíková et al. 2025b; Petrlíková et al. 2026). In this paper, greater emphasis is placed on strain rather than stress, because long-term data are available from the CCBM strain-gauge probes, which were installed at the ends of boreholes extended by approximately 0.5 m beyond the previously overcored CCBO probe locations. These CCBM probes were designed for the long-term monitoring of strain changes in the surrounding rock mass (Knejzlík et al. 2008) and the monitoring period lasted approximately four years. After completion of the monitoring phase, the CCBM probes were also overcored, enabling determination of the full stress tensor at the probe location.

The long-term strains recorded in the vicinity of the circular tunnel provided direct information on the deformation behavior of the surrounding rock mass. The CCBM probe was equipped with 18 strain gauges arranged in six strain rosettes, each comprising three gauges oriented in different directions (Fig. 2b). For improved interpretability, these measured strains were transformed into three principal strain components (amplitudes and directions) using the distribution matrix (Petrlíková 2024; Petrlíková et al. 2025a). In this transformation, the solution was normalized with respect to Young's modulus, such that the resulting principal strains were expressed in relative form and primarily depended on Poisson's ratio, which was assumed to be 0.25 as a characteristic value for the rock material investigated.

Strains at the tunnel surface were further presented based on measurements obtained from Compact Flat Wall Monitoring (CFWM) cells (Fig. 2a). These devices were employed due to the relatively heterogeneous nature of the Grimsel granodiorite present at the measuring site (Nagra 2019; Selvadurai et al. 2019; Schneeberger et al. 2017). Given this heterogeneity, CFWM devices were developed and installed directly on the tunnel surface to complement the borehole measurements. These flat strain-gauge devices are equipped with strain-gauge rosettes of the same dimensions as those used on the CCBM probes. The rosettes are supplemented by surrounding strain gauges with a length approximately five times greater, in order to record strain changes over a (theoretically) more homogeneous material volume and to reduce the influence of local mineral-scale deformations.

This overall measurement scheme enables the detailed investigation of deformation behavior in the vicinity of a circular underground excavation, including the tunnel surface. It should be noted that the primary objective of the monitoring program was to assess whether the proximity of the pumped-storage reservoirs is reflected in measurable stress changes within the surrounding rock mass. This effect was not confirmed by the measurements. Nevertheless, the presented preliminary results made it

possible to identify certain deformation-related phenomena while excluding others, thereby providing important constraints for the interpretation of time-dependent strain changes within the excavation-induced zone.

2 Site description, stress orientation and measurement configuration

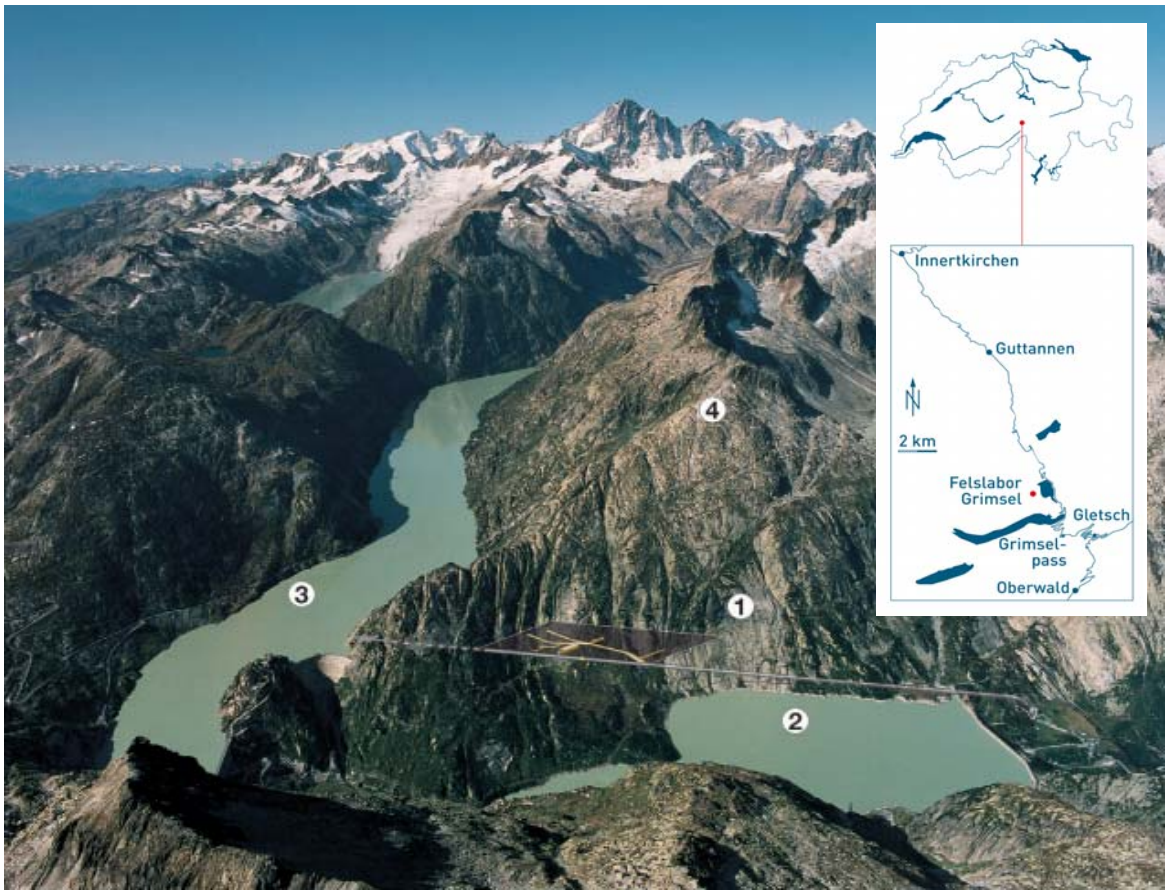


Fig. 1Grimsel area, view to the west. 1 – Grimsel Test Site, 2 – Lake Raeterichsboden, 3 – Lake Grimsel, 4 – Juchlistock. Modified after Kober et al. (2016).

At the investigated location, the in situ stress field is characterized by a maximum principal stress $\sigma_1$of approximately 14 MPa, predominantly oriented in a west–east orientation, with a possible variability of the order of ±30°. The intermediate principal stress σ_2 reaches approximately 10 MPa, while the minimum principal stress σ_3 is assumed to be approximately 9 MPa. The direction of the maximum principal stress σ_1 also exhibits a significant plunge of approximately 35°, indicating the pronounced three-dimensional character of the stress field within the rock mass (Krietsch and Gischig 2019; Nagra 2019).The axis of the monitored tunnel (L408) is oriented approximately N25E–S25W. With respect to this tunnel orientation, the direction of the maximum principal stress σ_1 is approximately perpendicular to the tunnel axis. This geometric relationship results in a non-uniform distribution of tangential stress around the tunnel perimeter, with its magnitude varying along the circumference depending on the angular position relative to the direction of σ_1.

Although measurements were conducted at several locations, and were repeated at different circumferential positions around the tunnel perimeter, one representative borehole was selected here to illustrate the observed phenomenon. The results presented in this paper therefore correspond exclusively to the instrumentation installed on the left sidewall of tunnel L408 (looking in the direction of tunnel advance, towards the north). The selected borehole for the CCBO and CCBM probes was located at an inclination of approximately 5° above the horizontal reference plane passing through the tunnel centre. The selected CFWM strain-gauge cell presented here (Fig. 2a and Fig. 3) was installed at a circumferential position approximately 45° below the horizontal tunnel diameter, directly at the tunnel surface. In the vicinity of the tunnel, the CCBO probe was positioned at a distance of approximately 2.5 m from the tunnel boundary, while the CCBM probe (Fig. 2b andFig. 4)

was installed at a distance of approximately 3 m. These distances correspond to approximately 1.4–1.7 times the tunnel radius for a tunnel diameter of 3.5 m. At such distances, the influence of tunnel-induced tangential stress amplification is significantly reduced, compared to the tunnel boundary, and the stress state represents a transitional condition between the excavation-affected zone and the far-field in situ stress state.

The measurement location, tunnel section L408, is predominantly composed of Grimsel granodiorite (GrGr). In contrast to the other monitored sections investigated within the present measurement campaign, no meta-basic dykes were identified at this site. A fault structure with an observed thickness of up to approximately 10 cm occurred in close proximity to the measurement location. According to Schneeberger et al. (2017), this structure is classified as a Group A fault.

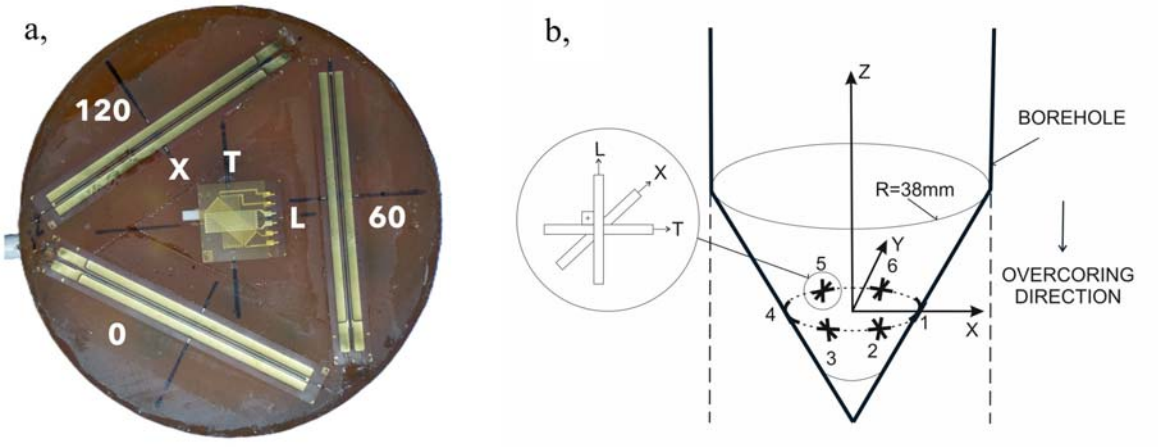


Fig. 2 (a) CFWM cell, real geometry of strain rosettes T-L-X and 0-60-120 installed on the left sidewall of the tunnel; (b) schematic diagram of the CCBO/CCBM probe with T-L-X strain rosettes (CCBM without overcoring). Modified after Petrlíková et al. (2026).

3 Results

Fig. 3presents long-term strain measurements from CFWM cell F3, installed at a circumferential position approximately 45° below the horizontal tunnel diameter. The 2D evaluation in the plane of the cell indicates that the principal strain direction is predominantly tangential to the tunnel boundary, rather than aligned with the tunnel axis. Given the regional in situ stress field, characterized by a maximum principal stress of approximately 14 MPa, oriented predominantly west–east, and considering that the tunnel axis is oriented approximately N25E–S25W, the measured strain orientations correspond to the expected circumferential variation of tangential stress around the tunnel perimeter. Similar behavior was observed at other circumferential positions around the tunnel, including near the sidewall, confirming this pattern. The long-term records show gradual stabilization of the strain trend, while the initial rapid increase is likely to be related to local grain-scale adjustments, pore pressure redistribution, and progressive stiffening of the adhesive layer, as the surface preparation for installation consisted of boring a flat surface in the tunnel wall for installation of the CFWM cell.

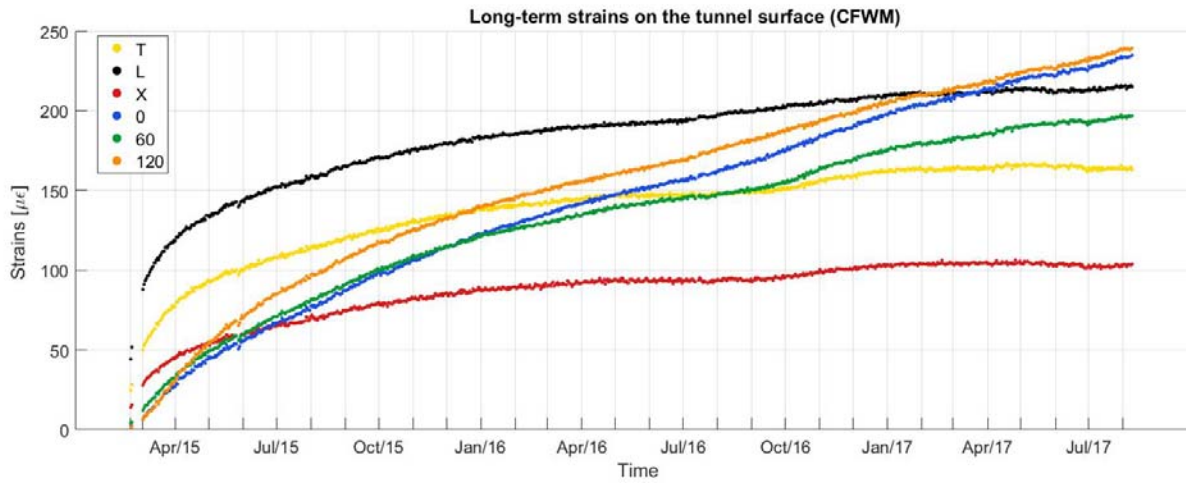


Fig. 3 Long-term strains measured on the tunnel surface via CFWM probe (tension positive).

On the tunnel surface, the measured maximum strains are up to twice as large as those recorded by the CCBM probe 10 (Fig. 4). The CCBM measurements were performed at a distance where the tangential stresses associated with secondary stress redistribution are no longer dominant; rather, the stress state approaches the primary in situ conditions. The strain-time curves exhibit a similar initial trend to that observed in the CFWM cells, suggesting that a comparable mechanism is active, with deformations gradually stabilizing over time. At the beginning of the fourth quarter of 2015 (and again in the second quarter of 2017), a change in the strain trend is observed. Similar changes were recorded at other locations more than 200 m away, indicating a broader phenomenon within the monitored rock volume, the underlying cause of which remains under discussion.

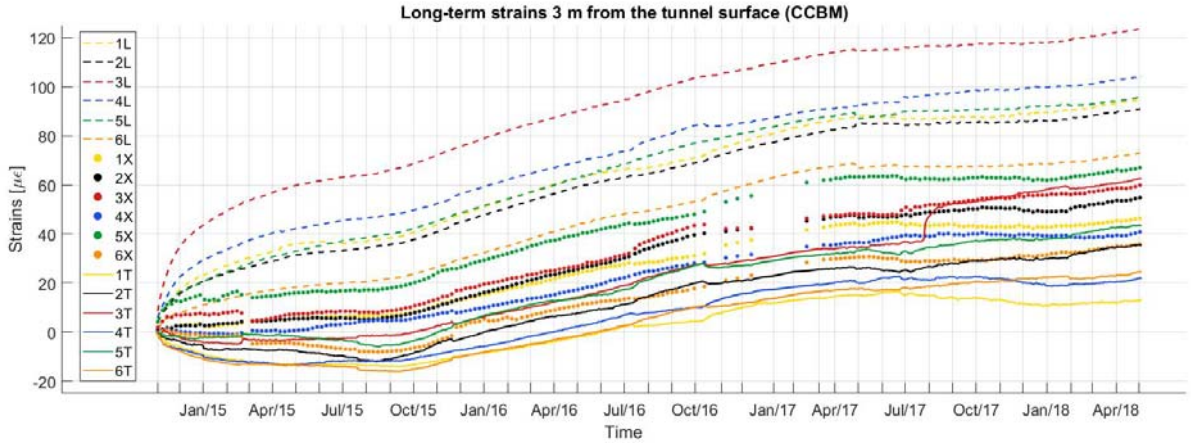


Fig. 4 Long-term strains measured 3m from the tunnel surface via CCBM probe (tension positive).

Fig. 5 shows the principal strains (ε_1, ε_2, ε_3), back-determined using the distribution matrix (Petrlíková et al. 2025a), which accounts for the conical geometry of the CCBO and CCBM probes and is based on a linear elastic material model. Given the four-year monitoring period, the total strain change cannot be strictly interpreted within a purely linear-elastic framework; the calculated increments should therefore be regarded as effective values. For the evaluation of whether the deformation process is predominantly volumetric or deviatoric, the principal strains were analyzed using the distribution matrix. The results indicate a dominantly deviatoric deformation.

The maximum principal strain increment is oriented along the borehole axis, i.e. radially with respect to the tunnel boundary. This orientation reflects the direction of the largest change in strain, rather than the absolute principal stress orientation. Similar behavior was observed at other monitoring locations within the same experimental framework.

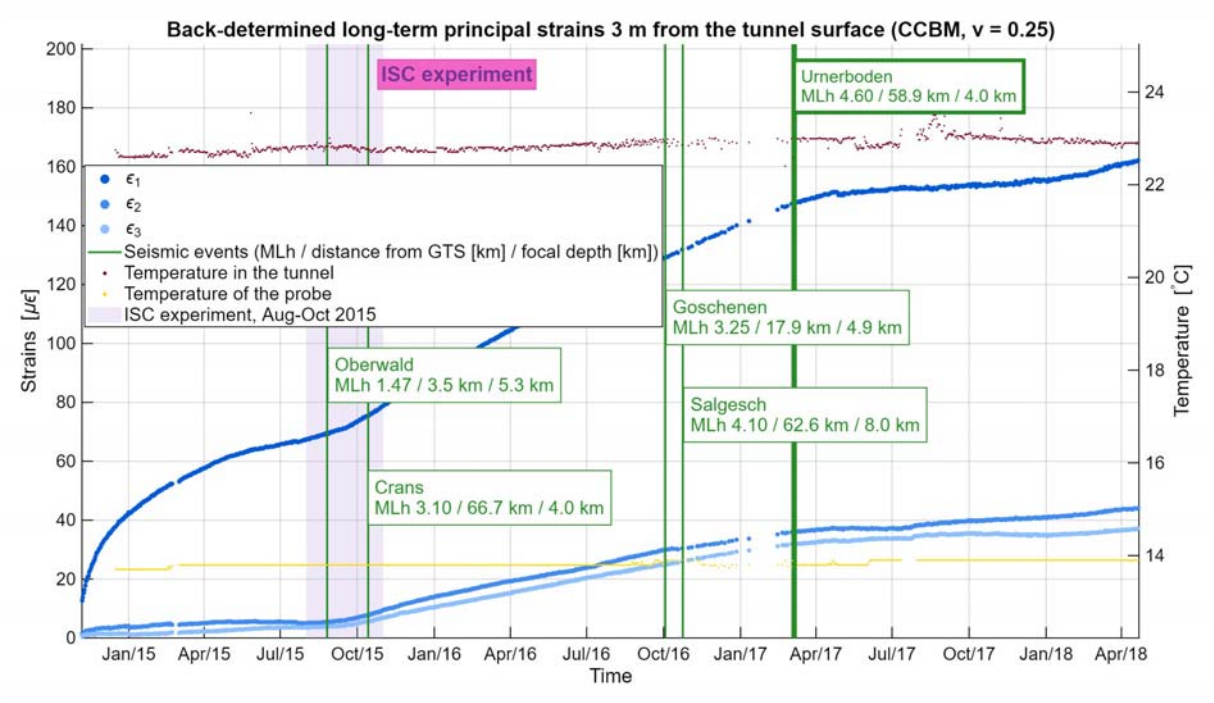


Fig. 5 Back-determined long-term principal strains 3 m from the tunnel surface (CCBM, ν = 0.25; tension positive), with temperature records and time markers of selected seismic events and the 2015 ISC experiment.

4 Discussion

The measured strain changes provide direct information about variations in the deformation state around the tunnel over time. For this reason, the results are primarily presented in terms of strain changes, rather than determined stress changes, which represent an indirect quantity derived from material assumptions.

The temperature recorded near the monitored probe remained within a narrow range (Fig. 5), not exceeding 0.5 °C over the evaluated period, and did not show any systematic trend corresponding to the observed strain evolution. The thermo-elastic strain associated with such temperature variation would be only of the order of a few microstrains. Temperature effects can therefore be regarded as representing only a minor fraction of the measured strain amplitudes.

The orientation of the deformation indicates that the strain evolution follows the mechanical framework of the excavation-influenced zone (EIZ), decomposing into radial and tangential components. The measured positive trend in the radial direction corresponds to tensile strain changes, i.e., a reduction of radial compressive stress. At the tunnel surface, tangential strain changes indicate a gradual decrease of tangential compressive stress at the monitored point on the tunnel boundary.

Seasonal variations in reservoir levels are documented in the Grimsel area; however, both the amplitude and timing of these fluctuations vary from year to year. The recorded strain evolution does not exhibit clearly reversible periodic behavior corresponding to reservoir cycles and, therefore, reservoir operation does not appear to represent the principal driver of the long-term deformation trend. In this context, delayed shear displacement along pre-existing fractures or vein structures cannot be excluded. Such structurally controlled processes could account for the observed inflection points, as well as the predominantly deviatoric character of the strain increment.

An alternative interpretation of the measured strain evolution should also be considered. The volumetric expansion of the rock may result from an increase in pore pressure associated with the adhesive sealing of the conical probe to the borehole bottom. The presence of a waterproof film at the probe–rock interface modifies the local hydrogeomechanical conditions and may lead to a redistribution of the total stress acting on the strain gauges installed on the conical surface. In this configuration, the rock may exhibit its greatest compliance along the cone surface (the L direction in

Fig. 3), where tensile strains tend to develop due to expansion of the pore space, while compression occurs in the inward direction. This interpretation is not inconsistent with the principal strain orientation shown in Fig. 4. The observed behavior is further supported by the compressive strains recorded by the T gauges and the tensile strains recorded by the L gauges. After approximately half a year, around April 2015, a more stabilized state appears to be reached. From this period onwards, the strain evolution becomes almost linear, which may indicate that the initial probe-related response was followed by longer-term effective stress changes associated with the mechanisms considered in this discussion.

Generally, the overall strain evolution shows a similar character at all monitoring locations. The records exhibit a long-term increasing trend with comparable changes in slope and a predominantly deviatoric strain increment. This similarity is observed even between monitoring sites separated by up to approximately 200 m, suggesting that the later strain evolution reflects a broader change in the stress–strain state of the rock mass monitored within the LASMO project (Kober et al. 2016).

The comparable response at spatially separated locations also indicates that the strain evolution cannot be attributed solely to local experimental activities. The In-situ Stimulation and Circulation (ISC) experiment, including hydraulic-fracturing and stress-measurement activities, was performed at the GTS in 2015 and is indicated in Fig. 5for comparison (Kober et al. 2016; Krietsch and Gischig 2019). These activities may have affected the nearest probes, but they cannot fully explain the similar strain evolution observed across the monitored rock volume.

The influence of regional seismic perturbations also cannot be excluded. Selected seismic events are therefore indicated in Fig. 5, based on the annual earthquake reports of the Swiss Seismological Service (Diehl et al. 2015; Diehl et al. 2018; Diehl et al. 2021). In particular, the ML 4.6 Urnerboden earthquake on 6 March 2017 was the strongest earthquake within Switzerland since 1991 and may have acted as a transient regional stress perturbation. Although the strain records do not show a uniformly sharp inflection immediately after this event at all monitoring locations, a change in the character of the strain evolution is observed at several sites during 2017. Seismic perturbations therefore represent a possible, although unconfirmed, factor that may explain changes in the slope of the increasing measured strain trend.

Acknowledgment

This research was co-funded by the European Union under the project INODIN, no. CZ.02.01.01/00/23_020/0008487.

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