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Forsmark site investigation

Overcoring rock stress measurements in borehole KFM07B

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Summary

Overcoring stress measurements were conducted in borehole KFM07B at the Forsmark site. The equipment used for the measurements was the three-dimensional Borre probe. Measurements were planned to be conducted at six measurement levels in borehole KFM07B, but only one measurement level could be said to be completed successfully. All stress measurements were terminated after several failed attempts at Level 3. Level 1 included measurements between 67 and 73 m borehole lengths. For Level 2, measurements were attempted between 150 and 160 m borehole length and for Level 3 between 221 and 252 m borehole lengths.

As an outcome from the many failed installations at Level 2 due to debonding, a test program was performed to evaluate if: (i) the dip of the borehole, and/or (ii) the pH-value of the water, could affect the installation of the Borre probe or the bonding of gauges in the pilot hole. The program was performed during the drilling period between Level 2 and 3 and consisted of three different types of tests. The result from these tests and additional quality control checks showed that: (i) installation tool and procedures were faultless, (ii) glue quality and recipe were identical to previous, successful, installations at the site, (iii) the dip angle of the borehole did not affect the installation, and (iv) the pH-value of the borehole water in KFM07B did not affect the glue and the bonding of the strain gauges. Furthermore, the measurements in KFM07B and the test program together indicated that: (i) there are difficulties to efficiently clean a borehole with low dip angle (from horizontal) from drilling debris, and (ii) the choice of borehole grouting cement used in a borehole may be of vital importance to achieve proper bonding at the borehole wall.

From the successful measurements, it can be concluded that, the stress state near borehole KFM07B and at shallow depths (approximately 55 m vertical depth), is characterized by moderate stress magnitudes (around 7 MPa) and NE-SW, subhorizontal orientation of the major principal stress. These results are based on measurements with ratings *a* and *b*. If only the result from the single measurement (1:4:1) with rating *a* (i.e. the most reliable measurement at Level 1) is used, the resulting stress state is characterized by a maximum horizontal stress of 10 MPa, oriented WNW-ESE. All measurements at Levels 2 and 3 were classified as failed tests.

Sammanfattning

Bergspänningsmätningar med överborrningsmetoden har genomförts i borrhål KFM07B i Forsmark. Vid mätningarna användes Borre-cellen, vilken är en tredimensionell mätmetod. Mätningarna avsågs att utföras på sex mätnivåer i borrhålet, men endast en nivå kunde slutföras i sin helhet. Den första nivån omfattade mätförsök på mellan 67 och 73 m borrhålslängd. Mätningar på den andra nivån utfördes mellan 150 och 160 m hållängd. För tredje nivån genomfördes mätningarna mellan 221 och 252 m hållängd.

Som en följd av de många misslyckade installationerna på andra nivån på grund av dålig inlimning, genomfördes ett försöksprogram för att utröna huruvida: (i) borrhålslutningen, och/eller (ii) borrvattnets pH-värde kunde påverka installationen av Borre-cellen eller limmets förmåga att fästa givarna mot pilothålsväggen. Försöksprogrammet genomfördes under det att borrning mellan nivå två och tre pågick. Programmet innehöll tre olika typer av installationsförsök och resultaten från dessa visade att: (i) installationsverktyg och procedurer fungerade felfritt, (ii) limkvalité och sammansättning var identisk med tidigare lyckade installationer i Forsmark, (iii) borrhålets vinkel från horisontalplanet inte kunde påverka installationen, samt att (iv) borrhålsvattnets pH-värde inte påverkade limmet och dess förmåga att fästa givarna mot borrhålsväggen. Vidare indikerade mätningarna i borrhålet och försöksprogrammet att: (i) det existerar svårigheter att få bort allt borrkax från pilothålsväggen i ett kraftigt lutande borrhål, och (ii) valet av injekteringsmedel för borrhålet kan vara av vikt för möjligheterna att erhålla god vidhäftning mot borrhålsväggen.

Utifrån de lyckade mätningarna, kan spänningstillståndet i borrhål KFM07B och på lågt djup (ca 55 m vertikalt djup) karakteriseras av måttligt höga spänningar (omkring 7 MPa) och en NÖ-SV, nästintill horisontell, orientering av största huvudspänningen. Dessa resultat baseras på mätningar med både rangordning *a* och *b*. Beaktas enbart resultaten från den enda mätning (1:4:1) med rangordning *a* (dvs den mest trovärdiga mätningen på nivå 1) erhålls ett spänningsfält med maximal horisontell spänning med magnituden 10 MPa och orienterad i riktning VNV-ÖSÖ. Alla mätningarna på mätnivå 2 och 3 bedömdes som icke lyckade.

Contents

1 Introduction

This document reports the data gained from three-dimensional overcoring rock stress measurements in borehole KFM07B, which is one of the activities within the site investigation at Forsmark. The borehole is located in the Forsmark candidate area as shown in Figure 1-1, together with other drill sites within and close to the candidate area.

The borehole, which is a traditional cored borehole, was planned to be drilled with 55° dip from the ground surface and with 76 mm diameter down to a length of 650 m. Overcoring rock stress measurements were planned to be conducted at approximately 60, 130, 180, 230, 280 and 330 m vertical depths, during drilling of the hole. Due to severe problem with the overcoring measurements, drilling was interrupted already at 299 m borehole length and overcoring measurement attempts were made only down to 253 m borehole length.

The activities were conducted in compliance with the SKB internal controlling documents presented in Table 1-1. However, several nonconformities to the activity plan occurred, see Section 4.7, and the activity was interrupted before the complete measurement programme had been carried out. The final borehole length became 299 m.

Original data from reported activity are stored in the primary database Sicada, where they are traceable by the Activity Plan number (AP PF 400-05-003). Only data in SKB's databases are accepted for further interpretation and modelling. The data presented in this report are regarded as copies of the original data. Data in the databases may be revised, if needed. Such revisions will not necessarily result in a revision of the P-report, although the normal procedure is that major data revisions entail a revision of the P-report. Minor data revisions are normally presented as supplements, available at www.skb.se.

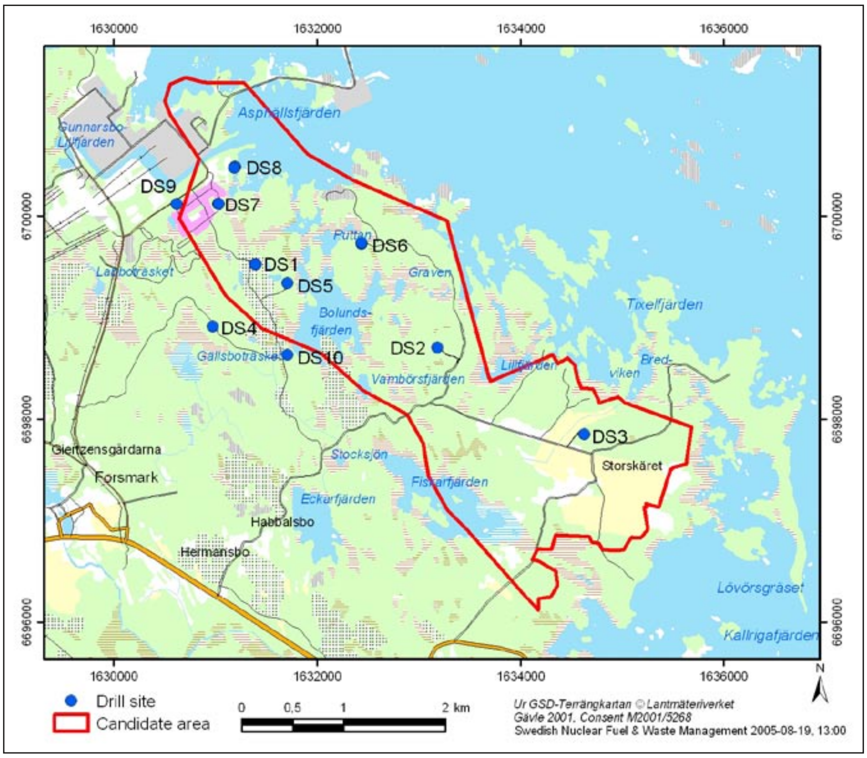


Figure 1-1. *Location of drill sites (DS) 1–10 within the Forsmark candidate area. The core hole KFM07B is placed at DS7.*

Table 1-1. Controlling documents for performance of the activity.

Activity Plan	Number	Version
Kärnborrning av och Bergspänningsmätningar i KFM07B	AP PF 400-05-003	1.0
Method Description for Rock Stress Measurements with the Overcoring Method	SKB MD 181.001	1.0

2 Objective and scope

The objective of the overcoring rock stress measurements was to: (i) determine the stress gradient through the fractured shallow rock mass to the almost fracture-free rock mass at greater depth, (ii) decrease the uncertainty in stress magnitude at deeper depth, and (iii) collect more data about when core disking occurs. This was to be achieved by 3–4 successful test results from each level at 75, 160, 220, 280, 340 and 400 m borehole length.

All measurements were conducted using the three-dimensional Borre probe for overcoring (developed and used by Vattenfall Power Consultant AB, formerly SwedPower AB). The method is described in detail in Chapter 3 of this report. Field measurements were done in three periods during 2005. The first period started August 8 and was completed August 14. The second field period commenced August 22 and was completed September 7 and the third period started September 19 and was completed October 5.

Execution of field measurements and data analysis is presented in Chapter 4 of this report. In addition to conventional analysis of overcoring data, a test program was performed to evaluate if the dip of the borehole or the pH-value of the borehole water could affect the bonding of gauges in the pilot hole.

All measurement results are presented in Chapter 5, along with a brief discussion of the test results. Measurement and analysis data from the tests are reported in Appendices A through G.

All stresses presented in this report are denoted using a geomechanical sign convention with compressive stresses taken as positive. Compressive strains are, however, defined as negative. All stress orientations are given with respect to geographic north (based on borehole orientation measurements), using a right-hand rule notation. Measurement positions are given as the hole length at the gauge position of the measurement probe.

The presentation of this report is restricted to the work done and the results obtained, as such. It is neither attempted to put the data into a geological/tectonic context, nor to discuss the implications of the results for future work.

3 Equipment

3.1 The overcoring method

Three-dimensional overcoring rock stress measurements are based on measuring strains when a sample of rock is released from the rock mass and the stresses acting upon it. The in situ stresses can be calculated from the measured strains and with knowledge of the elastic properties of the rock. The complete, three-dimensional, stress tensor is determined from a single measurement, under the assumption of continuous, homogeneous, isotropic and linear-elastic rock behaviour /Leeman and Hayes 1966, Leeman 1968/.

3.2 Description of field equipment

The Borre probe /Sjöberg and Klasson 2003/ is owned and used by Vattenfall Power Consultant AB (former SwedPower AB) for stress measurements in deep, water-filled boreholes. The equipment for overcoring rock stress measurements using the Borre probe comprises:

- pilot hole drilling equipment for wireline core drilling, including planing tool,
- inspection tool (test probe) with built-in borehole cleaning brush,
- Borre probe with built-in data logger,
- set of strain gauges (to be mounted on the Borre probe),
- glue (for bonding strain gauges to the borehole wall),
- cell adapter (installation tool),
- biaxial test equipment including load cell, pressure gauge, hydraulic pump and strain indicator, and
- portable computer.

A new pilot hole wireline drilling equipment was recently developed for use with two of the major wireline systems utilized in Sweden – the Hagby WL76 Metric Thinwall Wireline System, and the Atlas Copco CORAC N3/50 System. Both these systems produce a 76 mm overall hole diameter (albeit with slight differences in drill bit diameter for the two systems), whereas the obtained pilot hole diameter is 36 mm using the developed pilot hole equipment. In this project, the Atlas Copco CORAC N3/50 equipment was used for drilling.

The developed wireline pilot hole equipment is fitted to the wireline drill string. Thrusting of the pilot hole drill is controlled through water pressure in the drill string, whereas rotation is transferred through the drill string itself. The unique design of the equipment ensures that the pilot hole is always drilled for a length of 75 cm. The pilot core is recovered through the wireline drill string in the normal fashion for wireline systems. The drilling equipment also includes a planing tool attached to the wireline equipment, which is used to grind the base of the borehole to ensure that it is planar. Overcoring equipment includes a specially manufactured, thinwall, core barrel and coring bit producing a nominal core diameter of 61.7 mm, i.e. equal to that produced by using conventional Craelius T2-76 equipment. The latter is a requirement for being able to fit overcored samples into the biaxial test cell.

The most vital part of the equipment is the Borre probe, which is shown in Figure 3-1. The instrument carries nine electrical resistance strain gauges mounted in three rosettes. Each rosette comprises three strain gauges oriented (i) parallel (axial or longitudinal gauges), (ii) perpendicular (circumferential or tangential gauges), and (iii) at a 45° angle, to the borehole axis, respectively, see Figure 3-2. The strain-gauge rosettes are bonded to three plastic cantilever arms at the lower end of the probe, which is the only part of the instrument that enters into the pilot hole. The arms are located 120° apart with a known orientation to the main body of the instrument. Thus, the nine strain gauges of the Borre probe form an array representing seven spatially different directions. All strain gauges are mounted at a depth of 160 mm in the pilot hole.

The strain gauges are connected to a data logger inside the probe. The probe also measures the temperature in the borehole to assess the temperature effects on the readings during the overcoring phase. An extra wire is used, which is wired directly into the wheatstone measuring bridge, thus providing automatic temperature compensation for wire resistance during actual strain recording.

The present version of the logger is termed Borre III and has two recording modes – sparse and dense recording. Sparse recording – every 15 minutes – is conducted from the time of activation to a selected start time for dense recording. The sparse recording provides a quality check of glue hardening and possible disturbances prior to overcoring. Dense recording is done in user-specified intervals of between 3 and 60 seconds, from the pre-set start time (set to just before anticipated start of actual overcoring) until the core is recovered and logging terminated. The data logger is programmed through connection to a portable computer before installation of the probe in the borehole. No further connection to the ground surface is required after this programming.

Description of the details of the Borre probe and other components of the equipment is further presented in /Sjöberg and Klasson 2003/ and in SKB MD 181.001 (SKB internal controlling document).

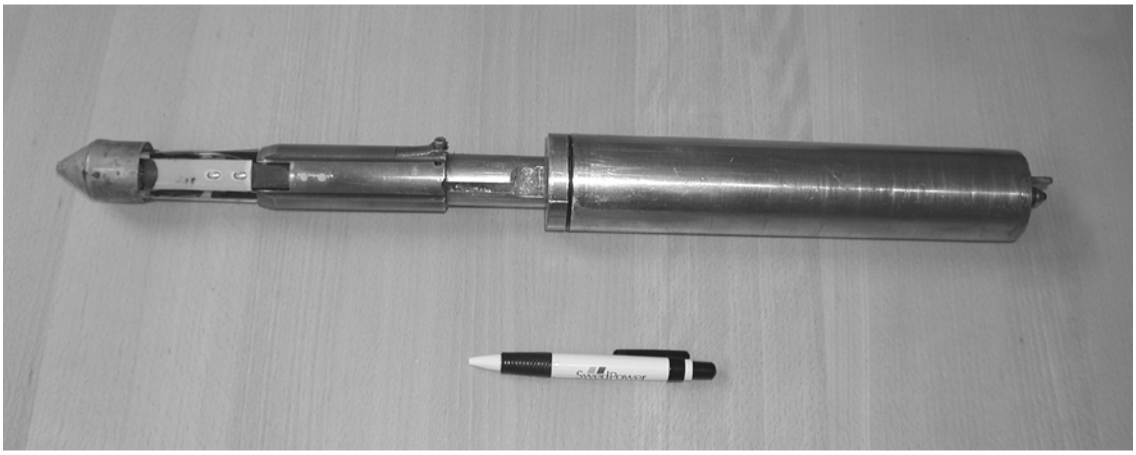


Figure 3-1. *The Borre probe.*

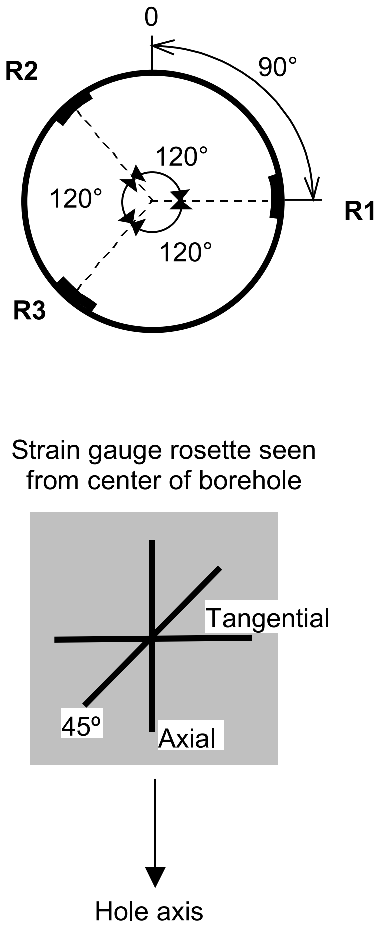


Figure 3-2. Strain gauge configuration of the Borre probe. Axial strain gauges are denoted L1, L2, and L3 (gauge nos. 1, 4, 7), tangential gauges are denoted T1, T2, and T3 (gauge nos. 2, 5, 8), and inclined gauges are denoted 45-1, 45-2, and 45-3 (gauge nos. 3, 6, 9).

4 Execution

4.1 General

In the following, the execution of overcoring measurements is briefly described. Measurements were conducted in accordance with extensive quality operating procedures for the method used. A list of the constituent procedures is given in Appendix H, see also SKB MD 181.001 (SKB internal controlling document).

4.2 Borehole data

The details of the core drilling of borehole KFM07B are not covered in this report, but are presented in /Claesson and Nilsson 2007/. However, a brief description is given below as this is believed to have some influence on the execution and results of the measurements. The borehole was drilled with 116 mm diameter to a length of 5.18 m, and with 96 mm diameter to 65.69 m length. For the remainder of the hole, a 76 mm hole diameter applies (final hole length of 298.93 m). A steel casing with outer diameter of 90 mm and inner diameter of 78 mm was installed down to a borehole length of 65.26 m. The gap between the casing and the borehole wall was grouted with a total of 648 kg cement ("Vitcement" 450 kg, Silica 198 kg) down to 65.69 m hole length. This was carried out on June 22, 2005, i.e. well in advance of the commencement of the overcoring campaign.

Additional grouting was conducted to seal a conductive zone in the borehole on August 19, 2005. Grouting was conducted between 81.10 and 145.71 m borehole length, with a total of 3,187 kg cement ("Vitcement" 2,175 kg, Silica 948 kg, Salt 64 kg).

Finally, the entire borehole was grouted on September 16, 2005, between 80.50 and 208.62 m borehole lengths. A total of 1,102 kg cement ("Vitcement" 750 kg, Silica 330 kg, Salt 22 kg) was used.

4.3 Preparations

Preparations before measurement start include (according to the method description):

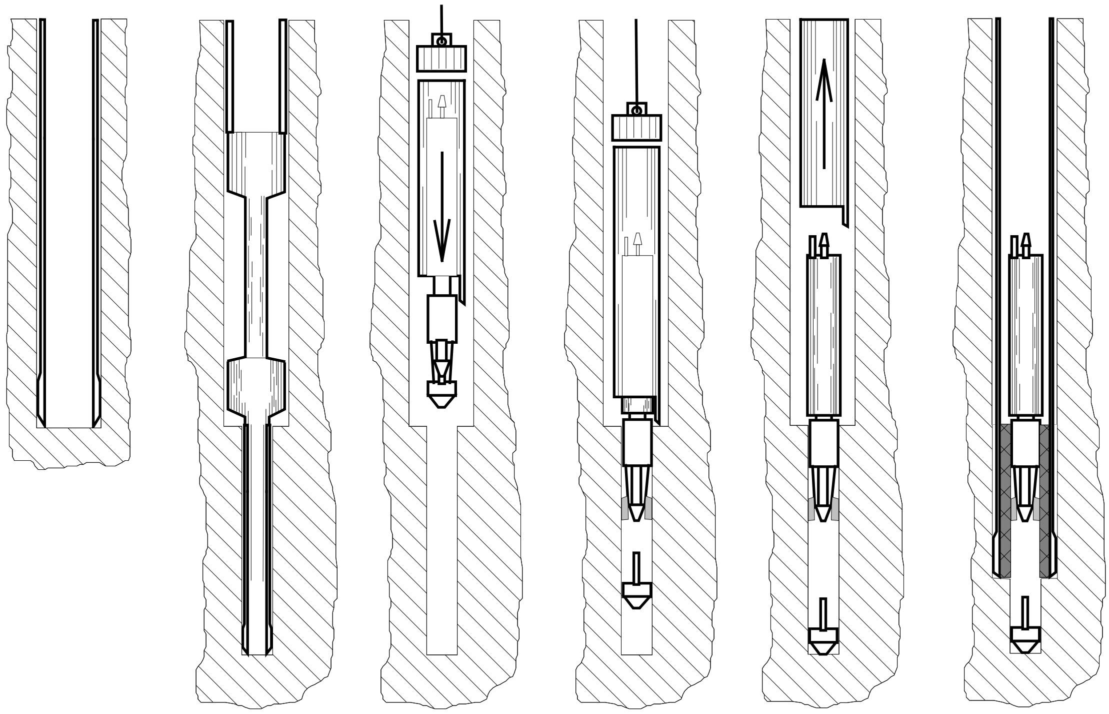
- functional checks of strain gauges and data logger in the probe,
- calibration of biaxial test equipment,
- glue test on every new glue purchase, and
- functional checks of drilling and installation equipment.

4.4 Execution of measurements

Overcoring stress measurement using the Borre probe involves:

1. Pilot hole drilling and examination.
2. Preparation and installation of the Borre probe.
3. Overcoring and recovery of the probe.
4. Biaxial testing of the overcore sample.

The procedure for stress measurement using the Borre probe is briefly summarized in Figure 4-1. Each stage is succinctly described below.



1 2 3 4 5 6

Figure 4-1. *Installation and measurement procedure with the Borre probe:*

1. *Advance 76 mm-diameter main borehole to measurement depth. Grind the hole bottom using the planing tool.*
2. *Drill 36 mm-diameter pilot hole and recover core for appraisal. Flush the borehole to remove drill cuttings.*
3. *Prepare the Borre probe for measurement and apply glue to strain gauges. Insert the probe in installation tool into hole.*
4. *Tip of probe with strain gauges enters the pilot hole. Probe releases from installation tool through a latch, which also fixes the compass, thus recording the installed probe orientation. Gauges bonded to pilot hole wall under pressure from the nose cone.*
5. *Allow glue to harden (usually overnight). Pull out installation tool and retrieve to surface. The probe is bonded in place.*
6. *Overcore the Borre probe and record strain data using the built-in data logger. Break the core after completed overcoring and recover in core barrel to surface.*

4.4.1 Pilot hole drilling

The 76 mm borehole is advanced to the target test depth, specified in advance. Once at this depth, a decision as to whether attempt pilot hole drilling is made. The main criterion for attempting a pilot hole is that the 76 mm drill core shall carry homogeneous rock close to the hole bottom. Discrete fractures may be accepted if the overall fracture frequency and/or orientation of discontinuities indicate that the pilot hole core shall be homogeneous and free of open fractures. If these requirements are not met, the 76 mm borehole is extended another 1–3 m.

Once a decision on pilot hole drilling is taken, the bottom of the 76 mm hole is grinded to ensure that it is planar. Using wireline pilot hole drilling, a 0.75 m long pilot hole is drilled. The borehole is flushed and the return water checked for cleanness (free of debris). The retrieved pilot core is inspected to determine whether the hole location is suitable for testing. The criteria on the pilot hole core for the decision to go on with the test are the following (lengths are distances from the bottom of the 76 mm borehole):

- 3–25 cm: (length) Continuous core, mechanical fractures accepted. No healed fracture that can be extrapolated to cross close to the gauge position at 16 cm during the subsequent overcoring process.
- 15–17 cm: (length) No larger and/or different mineral crystals than elsewhere on the core shall be present around 16 cm. Pegmatite shall be avoided if possible.
- Any direct or indirect information on core damage (core disking, microcracking, etc) on the pilot core surface is an evidence of non-linear and inelastic behaviour, which renders the core unacceptable.

As the hollow overcored core is more vulnerable to core damage, there is no reason to proceed with measurement if there is any core damage or any features present as described above.

If these criteria are not met, but conditions appear to be better at a slightly deeper location in the pilot hole, planing and grinding of the bottom of the 76 mm hole may be performed to reach a more suitable location for the strain gauges (always installed 16 cm from the bottom of the 76 mm hole). Planing of up to 10 cm can normally be achieved in practice. If planing is not possible within the above limits, a new pilot hole is instead drilled.

If the pilot hole is judged acceptable for installation, a test probe is lowered down the borehole to check that the pilot hole is open and free from debris.

4.4.2 Preparation and installation

If the conditions for a suitable pilot hole are satisfied, and the pilot hole is open and free from debris, the Borre probe is prepared for installation into the pilot borehole. The preparations include:

- attaching strain gauges to the probe and connecting them to the logger,
- programming of the data logger with start time and sampling interval,
- attaching the probe and the compass to the installation tool, and
- mixing and applying glue to the strain gauges.

The probe is then installed into the pilot hole, as shown in Figure 4-1. The probe is left in the hole for a minimum of 8 hours (usually overnight) for proper bonding of strain gauges to the pilot hole wall.

4.4.3 Overcoring

Overcoring of the probe involves flushing before and after overcoring, to stabilize temperatures. A checklist is followed to control drilling rate, rotational speeds, flushing, etc (according to the method description). Coring advance is done at a specified constant rate (normally 3 cm/min). In practice, it is difficult for the drilling contractor to maintain a constant rate throughout the overcoring process; hence, variations are almost always present. The coring advance was registered manually using a watch and markers on the drill string for every 4th cm up to 32 cm overcoring length, as well as the length for completed overcoring (normally 100 cm length).

The borehole is left with no on-going activity for approximately 15 minutes after completed overcoring but before the core is broken loose from the hole. This procedure ensures that sufficient strain data are recorded to assess temperature effects, possible non-ideal rock behaviour etc, which may affect strain readings and measurement results adversely.

After overcoring, the probe is recovered with the overcore sample inside the core barrel. Strain data are transferred from the data logger to a portable computer. The overcore sample is then mapped with respect to length, concentricity, gauge positions, lithology, structures, microcracks and other possible defects.

4.4.4 Biaxial testing

Biaxial testing of the overcored specimens is conducted to determine the elastic constants of the rock at the measurement position. Testing is carried out on-site as soon as possible after overcoring, using the equipment shown in Figure 4-2. The overcore sample must be at least 24 cm long, without fractures, for biaxial testing to be possible.

The test sequence comprises both loading and unloading in order to study possible inelastic behaviour of the rock. The sample is loaded to a maximum radial pressure of 10 MPa, in increments of 1 MPa, and then unloaded in the same manner. The strains induced in the overcore sample are monitored by the strain gauges installed by the Borre probe, using the built-in data logger of the probe. After completed test sequence, the Borre probe is disconnected from the overcore sample. Supplementary logging of the core is performed to check for potential new fractures. Inner and outer core diameter, as well as the annular thickness of the overcore sample, are also measured.

4.4.5 Supplementary testing of installation conditions and quality control

In addition to ordinary measurements, a test program was carried out to evaluate if the dip of the borehole or the pH-value of the water could affect the bonding of gauges in the pilot hole. The program consisted of three different types of tests:

- *Type 1*: The Borre probe was installed in a previously overcored rock sample from KFM07B. The wall in the pilot hole was carefully cleaned (by hand). The complete installation was performed under water. Water was taken directly from the borehole KFM07B; alternative (if borehole is unavailable), water with similar content of cement pasta as the borehole water was used.
- *Type 2*: A new, overcored, sample was drilled (from KFM07B) and flushed as described in the procedures for a normal overcoring stress measurement. The Borre probe was installed in the overcore sample after the sample was taken up to surface. The complete installation was performed under water, with water taken directly from the borehole KFM07B.
- *Type 3*: The Borre probe was installed in a previously overcored rock sample from KFM07B. The installation was conducted with the rock sample fixed at a dip angle of 50° from the horizontal plane for the first test, thus replicating the actual hole dip for KFM07B. The dip angle was increased to 60° and 70°, respectively, for the following two tests. The pilot hole in the sample was carefully cleaned (by hand) and has been involved in successful measurements earlier (Level 1). Installation was performed under completely dry conditions.

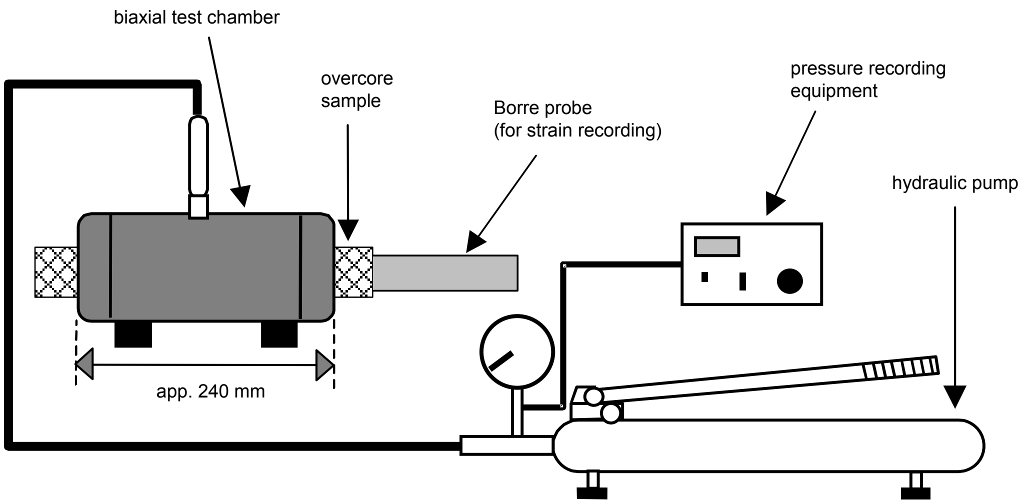


Figure 4-2. *Schematic drawing of the biaxial load cell with pressure generator and recording equipment.*

For test *Type 1* and *2*, the Borre probe is placed under the water for 5–10 minutes before the probe is installed in the rock sample to simulate transportation of the probe down to installation depth at a normal installation. All installations in the test program were conducted in the container shown in Figure 4-3. Biaxial tests were performed after each test to quantitatively assess bonding of the gauges. Visual observations of the gauges and the quality of bonding were also undertaken.

In addition to these tests, a quality control of all equipment and all possible aspects of the execution of measurements was conducted to identify other sources of error. It should be noted that such checks are part of the normal quality operating procedures. This additional quality control included: (i) biaxial tests on aluminium samples to check the function of the biaxial load cell and the Borre probe, (ii) functional check of the installation tool and procedures, (iii) control of glue quality, and (iv) control of previous experiences of installation in inclined boreholes. All original data are stored in the SKB database SICADA, where they are traceable by the Activity Plan number.

4.5 Data handling

The raw data include overcoring strain data files, biaxial strain data files, and completed check-lists and QA Report Forms from measurements. Routine data processing of measurement data involves importing the strain data file from overcoring into an in-house developed Microsoft Excel application for presenting overcoring strain response. Graphing of the strain response is performed automatically by the software application, and strain differences calculated based on input start- and stop-times for the overcoring process.

Similarly, the strain data file from biaxial testing is imported into the corresponding Excel application for presentation of biaxial test response and automatic calculation of elastic constants (Young's modulus and Poisson's ratio).

Calculation of stresses is carried out using another in-house developed Microsoft Excel application, with input in the form of strain differences, values on elastic constants, and borehole and recorded strain gauge orientation from the probe installation. The stress calculations are based on the theory presented by /Leeman 1968/. Calculation is performed for a single measurement, or for several successive measurements on one or several test levels, with automatic calculation of mean stresses for each level.

Figure 4-3. *Photo of arrangement for holding the core and probe at a certain dip angle. The blue box is filled with borehole water for test Type 1 and 2 but empty for test Type 3.*

The primary data reported from the overcoring stress measurements are:

- magnitudes of the three principal stresses,
- orientations of the three principal stresses (bearing and dip),
- magnitudes and orientations of the stresses acting in the horizontal and vertical planes, and
- values on elastic constants from biaxial testing.

4.6 Data analyses

The Borre probe is a "soft" stress cell, which means that the stiffness of the strain gauges is negligible in comparison to the stiffness of the rock. Thus, only the strains induced by overcoring and the elastic constants of the rock, in addition to the orientation of the probe in the borehole (including borehole orientation), are required to determine the complete stress tensor. Calculation of stresses from strain is done under the assumption of continuous, homogeneous, isotropic, and linear-elastic rock behaviour /Leeman 1968/. The stress relief is identical in magnitude to that produced by the in situ stress field but opposite in sign.

The analyses of obtained test data comprise (i) analysis of overcoring strain data, (ii) analysis of biaxial test data, and (iii) stress calculation, using data from the first two tasks. For each task, quality control checks and data assessments are included. Detailed descriptions of each step are given in SKB MD 181.001 (SKB internal controlling document), and are briefly summarized below. Transient strain analysis (as used for previous measurement campaigns, see e.g. /Sjöberg 2004/, was not applied in this case, due to the limited amount of successful tests and the shallow measurements depths.

The recorded strain gauge response and temperature are plotted vs. recorded time, and the strain differences due to overcoring and stress relief are calculated for each strain gauge for later use as input to the stress calculation. The overcoring strain change is normally determined as the difference between (i) recorded strain after completed overcoring with flushing on, and (ii) recorded strain at the start of overcoring with flushing on. It is important that all conditions, except the overcoring stress relief itself, are as similar as possible for these two instances (e.g. flushing, water pressures, temperatures, etc). Furthermore, the strain values should be stable (little or negligible strain drift) at these instances. In some cases, stable and ideal strain response can be observed during the first portion (typically 20–30 cm) of the overcoring process, whereas significant strain drifts occur during the rest of the overcoring. In theory, practically all of the strain relief takes place during the first 24 cm of overcoring (with gauge positions at 16 cm), see e.g. /Hakala et al. 2003/. For such cases, strain differences may be determined from stable values of this portion of the strain response curve (corresponding to approximately 20–30 cm drill bit position or more). It should also be noted that small changes in strains (a few μstrains), which may arise from choosing slightly different start- and stop-times for the overcoring, have very small influence on the calculated magnitudes and orientations of the in situ stress state.

Recorded strain and pressure data from biaxial testing are plotted and examined. Elastic constants are determined from recorded strain and pressure data from the biaxial testing. For this, the theory for an infinitely long, thick-walled circular cylinder subjected to uniform external pressure is employed (see e.g. /KTH 1990/). Since the Borre probe incorporates three pairs of circumferential and axial strain gauges, three pairs of elastic property-values are obtained from each biaxial test. The aim is to obtain rock parameters that apply to the relaxation experienced by the rock during overcoring. Therefore, the values of E (Young's modulus) and ν (Poisson's ratio) are taken to be secant values, calculated from strain data obtained during unloading of the core specimen. Usually, the secant values between the pressures of 8 and 3 MPa are calculated and averaged for the three strain rosettes. However, elastic constants may be calculated for other pressure intervals, if recorded strain readings are significantly unstable and/or display notable non-linearity for certain pressures.

Calculation of stresses from measured strains is based on the classical theory by /Leeman 1968/. The details of the formulation can also be found in e.g. /Amadei and Stephansson 1997/ and are not repeated here. Strain measurements from at least six independent directions are required to determine the stress tensor (which has six components). When all nine gauges of the Borre probe function properly during a measurement, redundant strain data are obtained. A least square regression procedure is used to find the solution best fitting all the strain data, from which the stress tensor components are calculated. For each test, one tangential or inclined gauge and/or two axial gauges may be rejected or recalculated without impairing the determination of the stress tensor. Recalculation is only performed if evidence of malfunctioning gauges exists, see also /Sjöberg and Klasson 2003/ and SKB MD 181.001 (SKB internal controlling document). Subsequently, the magnitude and orientation vector of each of the three principal stresses are calculated, as well as the stresses acting in the horizontal and vertical planes.

For the case of several measurements on one test level, the mean stress state is calculated. This is conducted by first taking the stress tensor components for each of the measurements (defined in a common coordinate system, e.g. the site coordinate system), and averaging each of the stress tensor components. From these mean values, the mean principal stresses, as well as the mean horizontal and vertical stresses, are determined. Also all calculated data are stored in SICADA, traceable by the Activity Plan number.

4.7 Nonconformities

Divergence from Activity Plan (AP PF 400-05-003) and Method Description for Rock Stress Measurements (SKB MD 181.001) at overcoring rock stress measurements in borehole KFM07B.

Planned activities:

- Overcoring rock stress measurements were planned to be conducted at a) four levels (1–4), between 75 and 280 m borehole length, and b) if the stress or rock conditions are favourable, at two more levels (5 and 6), at 340 and 400 m borehole length. Each level would be stopped after 3–4 successful tests at each level.

Performed activities:

- Overcoring rock stress measurements were only conducted at three measurements levels, down to a maximum borehole length of 259 m and drilling was interrupted 299 m borehole length. Successful tests were only obtained at the first measurement level, between 67 and 73 m borehole length.
- In addition to ordinary measurements, a test program was carried out. The test program consisted of three different types of tests to evaluate if the dip of the borehole or the pH-value of the water could affect the bonding of gauges in the pilot hole.

5 Results

5.1 Overview

Measurements were planned to be conducted at six measurement levels in borehole KFM07B. However, only one measurement level could be said to be completed successfully. Level 1 included measurements between 67 and 73 m borehole length. For Level 2, measurements were attempted between 148 and 160 m borehole lengths and for Level 3 between 221 and 252 m borehole lengths. At Level 2 and 3, the overcoring and biaxial test results as well as the number of failed installations indicated severe problems with debonding in the pilot hole and/or drill cuttings in the borehole. Extended periods of flushing as well as attempts of cleaning the hole mechanically and with various types of chemicals at Levels 2 and 3 were performed without resulting in notably improved borehole conditions. After 6 (two attempts at position 1:5:1) failed installations at Level 3, SKB decided to terminate the measurement campaign.

A brief summary of conducted measurements is given in Table 5-1. All tests have been numbered as follows: *measurement level : test no. : pilot hole no.* Thus, e.g. test 3:2:2 denotes measurement Level 3, test (or measurement) no. 2 at that level, and pilot hole no. 2 (to reach an acceptable measurement location for this test). Each test is presented with a rating reflecting successfulness and reliability of that particular measurement. Ratings were assigned per the following criteria:

Rating	Description and criteria
a	**Successful test** • Geometrical conditions achieved (strain gauges at correct position, etc). • Stable strain response prior to, and during, overcoring with minimal strain drift (strain change less than 10 μstrain per 15 min for undisturbed conditions). • No fractures and/or core disking observed in the overcore sample (at least 24 cm intact core). • Linear and isotropic (20–30% deviation acceptable) strain response during biaxial testing. Minor hysteresis (< 100 μstrain) accepted. • Stress calculation possible with classical analysis (Section 4.4.1). Values on elastic constants may be assumed from nearby tests if biaxial test data are lacking, and all other criteria above are satisfied.
b	**Partly successful test** • Signs of debonding but fairly stable strain response up until peak value (typically at 24–30 cm drill bit position). • Stress calculation possible with classical analysis (Section 4.4.1) but results judged uncertain and/or less reliable. • Additional stress determination may be conducted using inverse solution of transient strain analysis (Section 4.4.2).
c	**Failed test** • Installation failed or incomplete. • Debonding of strain gauges and/or large strain drift. • Fractures/joints detected in overcore sample.

Table 5-1. General test data from measurements in borehole KFM07B, Forsmark.

Test no. (pilot hole no. *)	Hole length [m]	Vertical depth [m] **)	Overcoring	Biaxial testing	Transient strain analysis	Rating	Comments
1:1:1	67.91	53.82	Yes	Yes	No	*b*	Installation and overcoring successful with acceptable strain response. Biaxial testing indicated debonding. Time at which debonding occured is unknown.
1:2:1	68.94	55.36	Yes	Yes	No	*b*	Installation and overcoring successful with acceptable strain response. Biaxial testing indicated debonding. Time at which debonding occured is unknown.
1:3:1	70.09	56.27	Yes	Yes	No	*b*	Installation and overcoring successful with acceptable strain response. Biaxial testing indicated debonding. Time at which debonding occured is unknown.
1:4:1	71.00	57.00	Yes	Yes	No	*a*	Installation and overcoring successful with acceptable strain response. Biaxial testing indicated debonding, however much less compared to other measurements. Time at which debonding occured is unknown.
1:5:1	72.45	58.15	Yes	Yes	No	*b*	Installation and overcoring successful with acceptable strain response. Biaxial testing indicated debonding. Time at which debonding occured is unknown.
2:1:2	150.91	119.65	Yes	Yes	No	*c*	Overcoring and biaxial testing indicated debonding. Reason for debonding is unknown; all steps at installation were successful.
2:2:1	151.80	120.34	Yes	Yes	No	*c*	Overcoring and biaxial testing indicated debonding. Reason for debonding is unknown; all steps at installation were successful.
2:3:1	152.83	121.13	Yes	Yes	No	*c*	Overcoring and biaxial testing indicated debonding. Reason for debonding is unknown; all steps at installation were successful. Overcore sample filled with clay and/or drill cuttings.
2:4:1	153.74	121.90	Yes	Yes	No	*c*	Overcoring and biaxial testing indicated debonding. Reason for debonding is unknown; all steps at installation were successful. Overcore sample filled with clay and/or drill cuttings.

Test no. (pilot hole no. *)	Hole length [m]	Vertical depth [m] **)	Overcoring	Biaxial testing	Transient strain analysis	Rating	Comments
2:5:1	156.53	121.83	Yes	Yes	No	*c*	Overcoring and biaxial testing indicated debonding. Reason for debonding is unknown; all steps at installation were successful.
2:6:1	157.53	123.98	Yes	Yes	No	*c*	Overcoring and biaxial testing indicated debonding. Reason for debonding is unknown; all steps at installation were successful.
2:7:1	158.66	125.62	Yes	Yes	No	*c*	Overcoring and biaxial testing indicated debonding. Reason for debonding is unknown; all steps at installation were successful.
2:8:1	159.64	126.38	Yes	Yes	No	*c*	Overcoring and biaxial testing indicated debonding. Reason for debonding is unknown; all steps at installation were successful.
3:1:2	221.11	174.89	No	No	No	*c*	Probe did not release from the installation tool for unknown reasons.
3:2:2	225.49	178.37	No	No	No	*c*	Drill bit broke while starting the overcoring, pieces of the broken bit damaged the core and the probe.
3:3:4	247.18	195.57	Yes	Yes	No	*c*	Core disking observed for over-cored samples (rejected pilot hole) 3:3:1, 3:3:2, and 3:3:3. Overcoring and biaxial testing indicated debonding. Reason for debonding is unknown, all steps at installation were successful.
3:4:1	248.19	196.36	Yes	Yes	No	*c*	Overcoring and biaxial testing indicated debonding. Reason for debonding is unknown, all steps at installation were successful.
3:5:1	251.89	199.29	No	No	No	*c*	Probe did not release from the installation tool for unknown reasons.

*) Numbering scheme: *(measurement level : test no. : pilot hole no.).*

**) Vertical depth (below ground surface) interpolated from borehole orientation measurements (every three metres).

It should be noted that borehole grouting was conducted between measurements at Level 1 and Level 2 to seal a water-conductive zone. Grouting was also conducted between Level 2 and Level 3 (cf Section 4.2).

Borehole orientations for the measurement depths in question are shown in Table 5-2, as measured after completed drilling of the hole. These orientation data were used in the stress calculations described below, together with the recorded orientations of the installed Borre probe.

Table 5-2. Borehole orientation for overcoring measurement points in borehole KFM07B. Orientations taken from nearest (3 metres) measured section.

Level no.	Test no. (pilot hole no. *)	Hole length [m]	Borehole bearing [°] **)	Borehole dip [°] ***)
1	1:1:1	67.91	135.68	52.92
1	1:2:1	68.94	135.67	52.93
1	1:3:1	70.09	135.66	52.92
1	1:4:1	71.00	135.65	52.91
1	1:5:1	72.45	135.64	52.96
2	2:1:2	150.91	136.80	50.42
2	2:2:1	151.80	136.81	50.42
2	2:3:1	152.83	136.81	50.41
2	2:4:1	153.74	136.82	50.40
2	2:5:1	156.53	136.81	50.40
2	2:6:1	157.53	136.83	50.37
2	2:7:1	158.66	136.82	50.38
2	2:8:1	159.64	136.82	50.38
3	3:1:2	221.11	135.40	52.64
3	3:2:2	225.49	135.47	52.57
3	3:3:4	247.18	135.52	52.18
3	3:4:1	248.19	135.52	52.17
3	3:5:1	251.89	135.51	52.11

*) Numbering scheme: *(measurement level : test no. : pilot hole no.).*

**) Clockwise from geographic north.

***) Positive downward from the horizontal.

5.2 Overcoring test data

Results from all tests with rating *a* and *b* in Table 5-1 are presented in the following and in Appendices A through F. Key measurement data (recorded times for borehole activities) for these tests are presented in Appendix A. Furthermore, core logs and photos are presented in Appendices E and F. The core logs were conducted during the field campaign. For the unsuccessful tests (rating *c*), photos of the pilot core and overcore samples have been included in Appendix F.

The strain response for each test is shown in Appendix B. Each test is presented with two plots displaying (i) the complete strain record (from activation of probe to core recovery), and (ii) the strain response from overcoring start to overcoring stop. The latter was used to define strain differences for later input to stress calculation. The times for which the strain differences have been determined ("OC Start" and "OC Stop") are shown in the figures, as well as in Appendix A. For the unsuccessful tests (rating *c*) at Levels 2 and 3, two typical examples of overcoring strain response are illustrated in Appendix B (Figures B-11 and B-12). The gauge positions relative to the borehole are shown for reference on each overcoring response curve.

In the following, a short description is presented for each of the measurement attempts at the three levels.

5.2.1 Measurement Level 1

A total of five installations were attempted at the first measurement level in borehole KFM07B. During installation and overcoring of all tests, no exceptional events were observed. Out of these measurements, one successful test (1:4:1) and four partially successful tests (1:1:1, 1:2:1, 1:3:1 and 1:5:1) were obtained. Tendencies of debonding during overcoring occurred for test nos. 1:1:1 and 1:3:1, but was constrained to one strain gauge rosette for test no. 1:1:1. However, for test no. 1:3:1 all strain gauge rosettes showed tendencies of debonding after 16 cm of overcoring drilling (i.e. after the drill bit passes the position of gauges). Examination of the strain gauges installed at all successful or partly successful tests showed only small remnants of glue, which is the normal condition for successful bonding. An example is shown in Figure 5-1.

For the first four tests, the probe was installed so that gauge rosette no. 3 faced downwards in the borehole, whereas for test no. 1:5:1, rosette no. 2 faced downwards (see Appendix B). Common for these tests is that the "drop" in strain after reaching peak values is largest for the tangential and inclined gauges. The largest "drop" in absolute terms occurs for the strain gauges facing downwards in the borehole.

5.2.2 Measurement Level 2

In total, 8 measurements were attempted at this level. Rock conditions were good, as indicated by the photos in Appendix F. No exceptional events were observed during installation and overcoring. However, none of these measurements were judged experimentally successful. All tests failed due to debonding to the borehole wall, thus resulting in unrealistic strain response (cf Figure B-11). For some of these tests, the overcored sample was filled with clay and/or drill cuttings, as shown in Figure 5-2.

In general, for all strain gauges installed facing upwards in the pilot hole, the strain rosette was properly glued (the glue was pressed from the surface of the strain gauges). On the other hand, for the gauges facing downwards in the pilot hole, large amounts of glue were sometimes remaining on the surface of gauges (Figure 5-3). Regardless of the rosettes had been properly glued or not, all rosettes were easily dismantled from the surface of the pilot hole. The force needed to dismantle the strain gauges was thus much less than normally required.

The surface in the pilot hole was experienced as more smooth and "slippery" compared to earlier measurement campaigns. Visual inspections of the pilot hole showed that the borehole wall was glossy and shiny, except at the location where the gauges had been glued. A very fine dust could also be brushed out from the pilot hole after the cores had been completely dried.

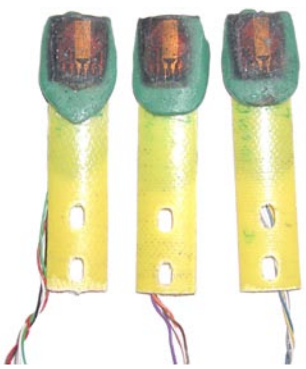


Figure 5-1. *Strain gauges after dismantling from overcore sample for test no. 1:2:1 (68.94 m borehole length) showing only small remnants of glue on the gauges. Strain rosette no. 1 is placed to the left, no. 2 in the middle, no. 3 to the right.*

Figure 5-2. *Clay and/or drill cuttings in overcored sample for test no. 2:4:1 (153.74 m borehole length).*

Figure 5-3. *Strain gauges after dismantling from overcore sample for test no. 2:1:2 (150.91 m borehole length). Strain rosette no. 1 is placed to the left, no. 2 in the middle, no. 3 to the right.*

5.2.3 Core disking observations

During measurements at Level 3, core disking was observed in a few instances. For test no. 3:3:4, three pilot hole cores were rejected (due to fractures in the core). Subsequent overcoring of these resulted in disking of the hollow core. This overcoring was performed using wireline drilling; hence, the overcoring diameter was 50 mm causing a very thin-walled rock cylinder. The core disking was most pronounced for the first sample (3:3:1), see Figure 5-4. For the second and third sample, only one instance of core disking was observed. The observed core disking was logged, with the results shown in Table 5-3. A mean disk thickness of around 10 mm can be inferred.

Figure 5-4. *Core disking of overcored sample for rejected pilot hole (3:3:1, 226.40 m borehole length).*

Table 5-3. Logging of core disking in borehole KFM07B, 226.40 m borehole length (pilot hole diameter 36 mm, overcoring diameter 50 mm).

Disk no.	Minimum disk thickness [mm]	Maximum disk thickness [mm]
1	11	12
2	10	12
3	7	–
4	4	7
5	8	9
6	11	13
7	10	–
8	8	9
9	11	14
10	9	12
11	9	11
12	9	10
13	11	–
14	11	–
15	8	9
16	8	9
17	10	11
18	11	–
19	9	12
20	7	9
21	8	–
22	14	–
23	10	–
24	7	–
25	7	–
26	16	20

5.2.4 Results from testing of installation conditions and quality control

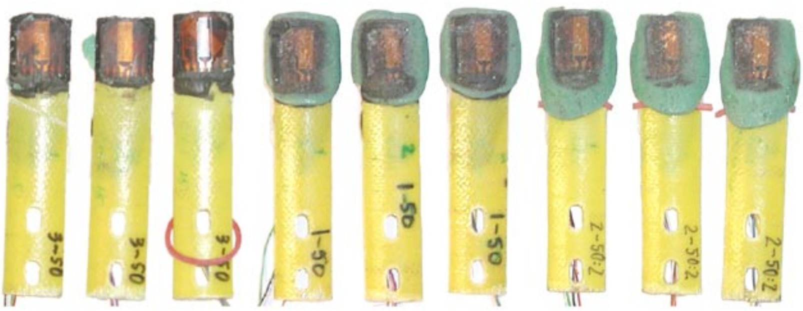
In between measurements at Level 2 and 3, the test program for evaluation of the effects from borehole dip and borehole water pH on bonding of strain gauges was performed, see Section 4.4.5. The test program began with *Type 3* tests, cf Section 4.4.5, to establish if the other tests in the test program could be performed with the actual borehole dip. *Type 3* tests started with an installation of the probe in a core sample with a dip of 50° from the horizontal plane, i.e. slightly less than actual borehole dip. The core was then submitted to biaxial testing to verify that installation and bonding was acceptable. The result showed excellent bonding of the strain rosettes for the *Type 3* test. It was thus decided that no more tests of *Type 3* were needed since the results showed that the dip angle did not affect the installation.

The *Type 1* test was performed with a dip of 50° from the horizontal plane. The result from the subsequent biaxial test showed good bonding between gauges and the borehole wall. This result verified that the pH-value of the borehole water does not affect the glue or the bonding of the strain gauges. It should be noted that the pilot holes in the cores used in both *Type 1* and *3* tests were carefully cleaned by brushing them by hand before installation.

The *Type 2* test was performed on a new, overcored rock sample, flushed according to instructions for overcoring measurements. The probe was installed in similar manner as for *Type 1* tests, however without manual cleaning of the pilot hole. The results from the subsequent biaxial test were similar to the results from the measurements performed at Level 2, i.e. showing clear signs of debonding.

For *Type 1* and *3* tests the glue was properly pressed from the surface of all the strain rosettes, as for a normal, successful installation (Figure 5-5). For test *Type 2*, there was a difference in how the glue has been pressed from the gauge surface between the different strain rosettes. Strain rosette no. 1 was properly glued, whereas various amounts of glue remained on rosette nos. 2 and 3 (Figure 5-5). There was, in general, more glue remaining on one side of these rosettes, indicating that the gauges also had been forced sideways. For all tests in the test program the Borre probe was installed with strain rosette no. 1 facing upwards in the pilot hole. These results were thus consistent with those found for the installations in the borehole at Levels 2 and 3 (cf Sections 5.2.2 and 5.2.5). The force needed to dismantle the strain gauges from the borehole wall for *Type 2* was much less compared to the other two test types.

The performed quality control of equipment and installation procedures can be summarized as follows. The biaxial load cell including pressure gauges and recording equipment functions flawlessly, as verified by biaxial testing of a reference aluminium core. Functional tests of the installation tools showed no malfunction. The tool has functioned properly in all pre-installation tests, and has been cleaned after each measurement. The gauge holder of the Borre probe has been in the correct position in all tests. A control of the procedures during installation revealed no abnormities. All checklists have been followed and the same procedure used for all tests.



a) b) c)

Figure 5-5. *Photo from test: a) Type 3, b) Type 1 and c) Type 2. Strain rosette no. 1 is placed to the left, no. 2 in the middle, no. 3 to the right, in all photos.*

Finally, a check of the installation equipment (dimensions) in relation to the borehole geometry showed that there could not be any effects from the adapter tool *not* being placed in the centre of the borehole.

The quality of the glue was assessed by using a brand new batch for the final measurements on Level 2. This did not result in any differences compared to previous tests. According the manufacturer, the shelf life of the glue is several years (which is much longer than normal consumption). Possible changes in glue composition were also controlled through direct contacts with the manufacturer. The response to this was:

"We have not changed the recipe or the mode of manufacturing of the product. Furtheron we have also no information that the suppliers of the rawmaterials have changed anything."

Finally, previous experiences of using the Borre probe in inclined boreholes were investigated. Contacts with retired measurement engineers (responsible for measurements during the 1970s and 1980s), as well data from the Vattenfall Power Consultant AB case record revealed that installation in deep boreholes with wire had only been conducted in boreholes with a dip of 71° or steeper. For short boreholes (< 50 m) with less inclination, installation has been carried out using glass fibre rods, but this is not applicable to deep boreholes.

5.2.5 Measurement Level 3

In total, 5 measurements were attempted at this level. Rock conditions were good, as indicated by the photos in Appendix F. None of these measurements were judged experimentally successful. Two tests failed due to debonding, thus resulting in unrealistic strain response (test nos. 3:3:4 and 3:4:1; cf Figure B-12). For one test (3:3.2), the drill bit broke while overcoring started and damaged the probe. No overcoring data could be retrieved. In two cases (test nos. 3:1:2 and 3:5:1) the Borre probe did not release from the installation tool (adapter) for unknown reason. Two attempts were done at the position of the test no. 3:5:1 without success. Between each attempt the borehole was flushed and new methods to clean the borehole were tested. Cleaning involved both mechanical cleaning, and using (frozen) soap to clean the borehole, followed brushing the pilot hole wall with a brush, soaked with alcohol. During the following installation, a brush was placed in front of the strain gauges to brush the pilot hole wall immediately before the gauges were glued. None of these attempts lead to any improvements with respect to bonding of the strain gauges to the borehole wall.

As for the installations at Level 2, all strain gauges installed facing upwards in the pilot hole were properly glued (the glue was pressed from the surface of the strain gauges). For gauges facing downwards, large amounts of glue were remaining on the surfaces of the gauges. All gauges were very easily dismantled from the surface of the pilot hole.

5.3 Biaxial test data

All suitable overcore rock samples were tested in the biaxial cell to determine the elastic properties. Nearly all biaxial tests indicated debonding to various extent, as indicated by abnormally low strains, highly varying strain readings, non-linearity, and hysteresis. Biaxial test results were partly successful for some tests from Level 1, whereas all tests from Levels 2 and 3 had to be discarded due to debonding behaviour.

For the tests from Level 1, the strain record was checked in detail. During testing, the Borre logger is used to record strain continuously, during which pressure is applied manually. Hence, there are several strain readings for each pressure stage. For all but two tests (1:1:1 and 1:4:1), strains were unstable at each applied pressure stage. Consequently, these tests were excluded. The gauge response curves from the remaining tests (1:1:1 and 1:4:1) are shown in Appendix C. For comparison, a typical example of an unsuccessful test at Level 2 is also shown in Appendix C (Figure C-3).

For test no. 1:1:1, linearity is fair during the loading phase, whereas several gauges display very non-linear behaviour during unloading. Elastic constants could not be unambiguously determined for the unloading stage. During initial loading (1–3 MPa), somewhat stable values on the elastic constants can be derived. These findings are evidence that bonding is not optimal. For test no. 1:4:1, one rosette (no. 1) showed divergent behaviour compared to the other rosettes, in particular during loading. However, during unloading, the gauge response is fairly linear, although large hysteresis was observed. Elastic constants from the unloading stage and for a pressure range of 8–3 MPa were found to be relatively consistent. The results are presented in Table 5-4. All original data are stored in the SKB database Sicada.

In addition to these tests, biaxial tests were conducted on cleaned (by hand) overcored samples, in which the Borre probe again was installed. This was performed for tests nos. 1:5:1 and 2:3:1, from Levels 1 and 2, respectively. Both these tests indicated good bonding, with very linear and isotropic rock behaviour (Table 5-4). Also, when dismantling the strain gauges from the rock, several of the gauges broke in the actual strain gauge (rather than in the bond interface), proving the bonding to the rock was very good for these tests.

Finally, biaxial tests on overcored samples from the *Type 1* and *3* tests (of the test program) showed good strain response with very good linearity and isotropic behaviour. For the *Type 2* test, the results showed that debonding of the strain gauges occurred (Table 5-4).

It is of particular interest to compare the biaxial strain response for the overcored sample for test no. 2:7:1, which was tested both immediately after overcoring (Figure C-3) and later for a cleaned pilot hole wall and installation in dry conditions in an inclined sample (*Type 3* test; Figure C-6). The difference is dramatic, with the latter test (*Type 3*) indicating good bonding and realistic strain response. A similar comparison can be made for test no. 1:4:1, which was performed after overcoring (Figure C-2) as well as for a cleaned pilot hole and installation in borehole water (*Type 1* test; Figure C-7). The differences between these two are less dramatic, but still significant.

Table 5-4. Results from biaxial testing on overcore samples from borehole KFM07B.

Level no.	Measurement no. (pilot hole no. *)	Hole length [m]	Young's modulus, *E* [GPa]	Poisson's ratio, *v*
1	1:1:1 [1)]	67.91	83.6	0.50
1	1:4:1	71.00	53.0	0.13
1	1:5:1 [2)]	72.45	48.0	0.17
2	2:3:1 [2)]	152.83	42.4	0.17
Test 1	1:4:1 [3)]	71.00	59.8	0.30
Test 3	2:7:1 [3)]	158.66	55.4	0.18
Test 2	2–50 [4)]	213.11	–	–

*) Numbering scheme: *(measurement level : test no. : pilot hole no.).*

[1)] Values from loading stage, 1–3 MPa.

[2)] Tests after cleaning the sample and re-installating the probe/strain gauges.

[3)] Tests in the test program, 2 cores from earlier overcoring tetst have been re-used.

[4)] Extremely high (and unrealistic) values due to debonding.

5.4 In situ stress state

The in situ stress state was calculated using: (i) the measured strain response (difference between strain gauge readings after and prior to overcoring), (ii) recorded orientation of strain gauge rosettes in the borehole, and (iii) values on elastic constants determined from biaxial testing. Strain differences were determined from stable strain values before overcoring vs. stable values after completed overcoring. For tests with very stable post-overcoring response, the final strain values were taken at the end of the flushing period (just before core break) to minimize the possible influence of temperature on the strain readings (cf Appendices A and B in which the times for which strain differences were calculated are marked “OC Start” and “OC Stop”, respectively).

The mean stresses were calculated from all successful (rating *a*) and partly successful (ratings *b*) measurements at Level 1. For Levels 2 and 3 no stress calculation was performed due to debonding of strain gauges. Data on the elastic constants were taken from the biaxial test results for test no. 1.4:1, despite the relatively large scatter in strain response for this test. However, since the results from biaxial tests for test *Type 1* and *3* gave similar values of the elastic constants (with good bonding), the values of test no. 1:4:1 were judged to be realistic. Also, data from biaxial testing of cleaned samples from Levels 1 and 2 indicate similar values on the elastic constants (cf Table 5-4). Data from test 1:1:1 pointed at higher values on both Young’s modulus and Poisson’s ratio. However, these were taken from the initial loading stage and are judged less reliable.

The resulting stresses for each test, as well as the mean values for Level 1 are shown in Appendix D, and in Table 5-5, Table 5-6, and Table 5-7. All orientations are given relative to geographic north. Orientations of the principal stresses are also shown in Figure 5-6 for Level 1. All original data are stored in the SKB database Sicada.

Table 5-5. Magnitudes of principal stress as determined by overcoring in borehole KFM07B.

Level no.	Measurement no. (pilot hole no. *)	Hole length [m]	σ_1 [MPa]	σ_2 [MPa]	σ_3 [MPa]
1	1:1:1	67.91	7.3	4.6	2.0
1	1:2:1	68.94	7.8	6.4	0.1
1	1:3:1	70.09	5.8	3.0	–0.1
1	1:4:1	71.00	15.5	8.8	1.8
1	1:5:1	72.45	13.5	6.8	–1.4
1	Mean	–	7.3	6.9	2.2

*) Numbering scheme: *(measurement level : test no. : pilot hole no.).*

Table 5-6. Orientations of principal stress as determined by overcoring in borehole KFM07B.

Level no.	Measurement no. (pilot hole no. *)	Hole length [m]	σ_1 Trend/Plunge [°]	σ_2 Trend/Plunge [°]	σ_3 Trend/Plunge [°]
1	1:1:1	67.91	204/47	044/41	305/10
1	1:2:1	68.94	074/26	250/64	343/01
1	1:3:1	70.09	241/03	346/78	149/12
1	1:4:1	71.00	326/51	079/18	181/33
1	1:5:1	72.45	213/07	337/78	121/10
1	Mean	–	048/12	282/70	141/16

*) Numbering scheme: *(measurement level : test no. : pilot hole no.).*

Table 5-7. Horizontal and vertical stress components calculated from measured principal stresses in borehole KFM07B.

Level no.	Measurement no. (pilot hole no. *)	Hole length [m]	σ_H [MPa]	σ_h [MPa]	σ_v [MPa]	Trend σ_H [°]
1	1:1:1	67.91	5.8	2.1	6.0	031
1	1:2:1	68.94	7.6	0.1	6.7	073
1	1:3:1	70.09	5.8	0.0	2.9	060
1	1:4:1	71.00	10.0	5.3	10.7	107
1	1:5:1	72.45	13.4	–1.1	6.6	032
1	Mean	–	7.2	2.6	6.6	051

*) Numbering scheme: (measurement level : test no. : pilot hole no.).

Confidence intervals were calculated for the measurement results using the methodology proposed by /Walker et al. 1990/ and a newly developed computer code (described in /Lindfors et al. 2005/). Confidence intervals were determined for both magnitudes and orientations of the principal stresses at Level 1, as well as for the horizontal and vertical stress components. In this report, only the 90%-confidence intervals are presented, see Appendix G. However, neither a 90%-, nor a 95%-confidence interval for the principal stress orientations did encompass all single measurements.

Observations of core disking can be used to estimate the virgin stress state. The methodology by /Hakala 1999ab/ can be utilized for this purpose. However, this methodology is developed for overcore samples with 62 mm outer diameter (i.e. normal overcoring diameter for stress measurements). The observed core disking in KFM07B was found for an overcoring diameter of 50 mm. Since a thin-walled cylinder is more susceptible to damage, stresses would thus be overestimated if normal overcoring diameter was assumed, and no stress estimation was thus conducted.

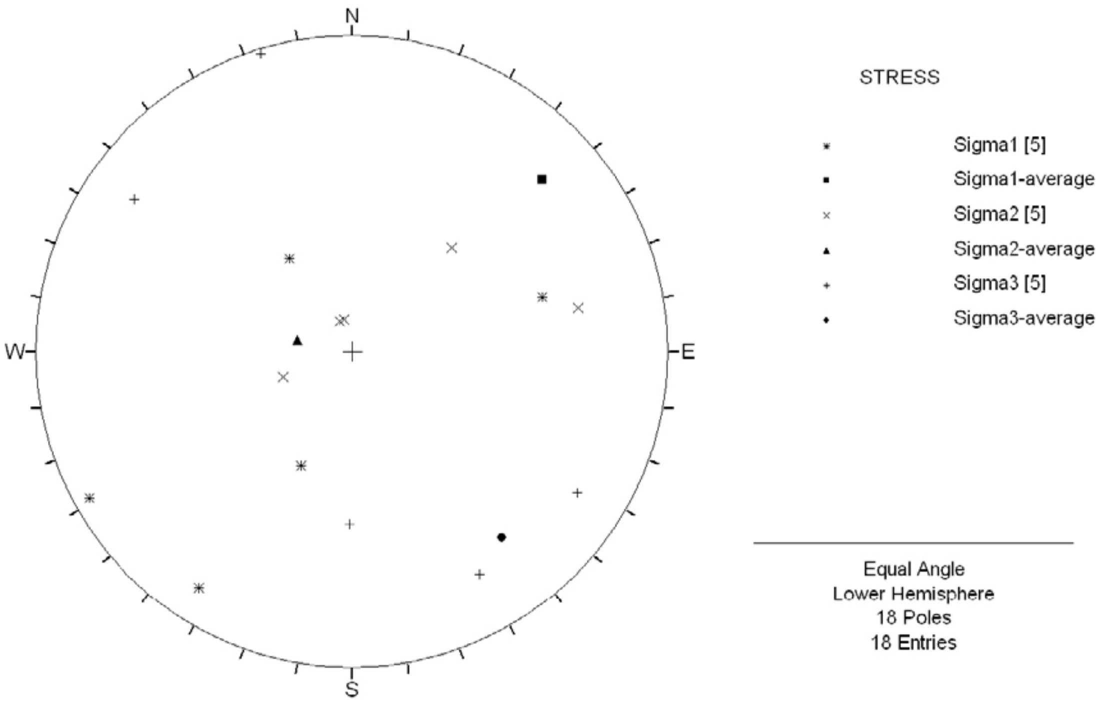


Figure 5-6. *Orientations of measured principal stresses in borehole KFM07B, Level 1, shown in a lower hemisphere projection (all measurements with rating a and b; only one measurement with rating a, cf Table 5-1).*

5.5 Discussion

The overcoring measurements in borehole KFM07B were largely unsuccessful, primarily due to problems with bonding of the strain gauges to the rock surface. The results from the additional test program (described in Section. 5.2.4), together with general observations from the ordinary stress measurements and additional quality control checks showed that:

- Installation tool and procedures were faultless.
- Glue quality and recipe was identical to previous, successful, installations at the site.
- The dip angle of the borehole does not affect the installation.
- The glue or bonding was not affected whether the installations were performed in ordinary tap water (pH 7.5–10.5) or in borehole water.
- There are difficulties to efficiently clean the pilot hole wall and the bottom of the 76 mm borehole for a borehole with low dip angle (from the horizontal) at depth.

Unreferenced information from the Client indicated that the borehole grouting cement used in this borehole could disperse at higher water pressure, which then substantially decreases the adhesiveness at the surface of the borehole. The fact that extensive grouting was conducted between measurements at Levels 1 and 2, and Levels 2 and 3, respectively, may be a contributing factor to the bonding problems. Consistent with this theory is the fact that debonding of strain gauges was more pronounced on Levels 2 and 3, compared to Level 1. Adding to this is the increased difficulties in flushing the borehole to clean out drill cuttings as the borehole becomes deeper.

The bonding problem appears to be of compound nature, being attributable both to poor adhesion and drill cuttings and/or clay materials remaining in the borehole. Obviously, the latter would be more pronounced in an inclined borehole, compared to a subvertical or vertical hole. It appears plausible that some material remained at the borehole wall, thus forcing strain gauges away from the borehole wall. It should be noted that this occurred both in actual bore-hole installations, as well as in the test program for the *Type 2* tests. However, this hypothesis cannot be fully verified based on the presently available data.

The fact that strain rosettes facing upwards in the pilot hole rosette were properly glued (the glue was pressed from the surface of the strain gauges) and rosettes facing downwards had large amounts of glue remaining on the surfaces is an indication that something prevented the rosettes (facing downwards) to be in full contact with the pilot hole wall. Also, the pressure exerted on the gauges during installation may be non-uniform, as illustrated in Figure 5-7.

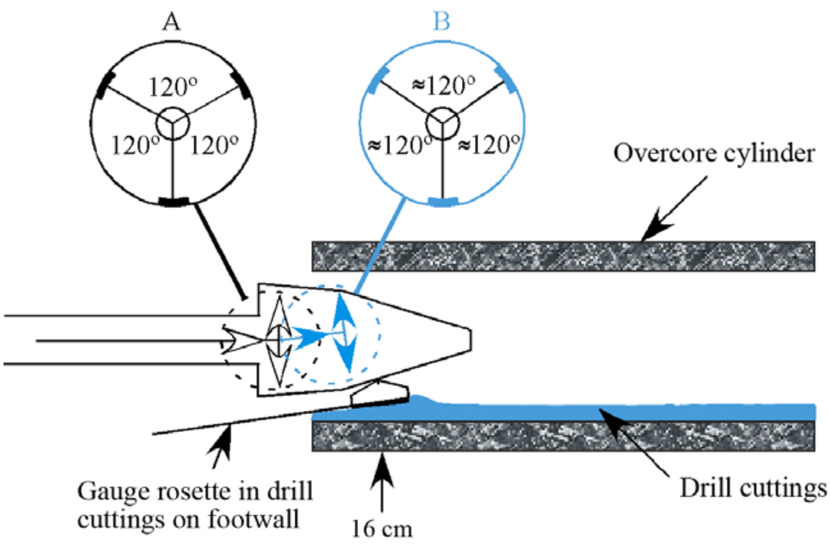


Figure 5-7. *Plausible mechanism causing suboptimal bonding of strain gauges in inclined boreholes.*

The possibly non-uniform pressure exerted on the gauges during the installation is an effect of the probe (more specifically the rod and nose cone) is forced slightly upwards due to obstructions in the pilot hole. This results in at least one of the strain rosettes being pushed against the borehole wall prematurely, which may lead to incorrect angular position of the rosette, as illustrated schematically in the Figure 5-7. Furthermore, the direction of movement of at least one rosette is not fully radial with respect to the centre of the pilot hole.

The installation system of the Borre probe has a small, built-in, flexibility to function also in cases with small deviations in direction or size of the pilot hole, which may arise due to geological variations affecting pilot hole drilling. A rigid rod may lead to damage of the strain rosettes or the probe. It should also be noted that the adapter (installation tool) is of slightly smaller diameter than the borehole – which is a requirement for being able to hoist it down and up the borehole. A too tight fit is impractical, as effects from e.g. drill bit wear on the borehole diameter, water pressures etc, would inhibit installation.

The only tests that can be considered partly successful are those at Level 1 (rating *a* or *b*). The obtained stress state from these measurements at Level 1 (approximately 55 m vertical depth) is characterised by moderate stress magnitudes for the major principal stress. The mean major principal stress is subhorizontal and oriented NE-SW. The mean vertical stress component is 6.5 MPa, which is about four times the theoretical value corresponding to the overburden pressure. Variations between the individual measurements are relatively large, with respect to both orientation and magnitude, as manifested by the calculated confidence intervals, which are large (Appendix G).

For the measurements at Level 1, test no. 1:4:1 stands out since the strain response during overcoring and biaxial testing points at less debonding. The "drop" in strain after reaching peak values during overcoring is less pronounced for all strain gauges, including those facing downwards in the borehole. The resulting stress state from this test is thus considered the most reliable of the data from KFM07B. This test points at a maximum horizontal stress of 10 MPa, oriented WNW-ESE (107°).

It is plausible that the difficulties of cleaning a borehole increases with decreasing hole inclination. For further overcoring rock stress measurements where gluing strain gauges in the borehole is a part of the installation procedure, the following recommendations are given:

- Ordinary flushing through drill string is not always sufficient to clean the borehole from drill cuttings etc. A combination of flushing and blowing gas may result in better borehole conditions. When using gas blowing it would be useful if the nozzle of the gas hose could be guided for example to reach down into the pilot hole.
- When grouting of the borehole is necessary, only borehole grouting cement that is guaranteed to function at high water pressure without any kind of separation of the ingredients of the material should be used.

Provided that the above conditions are fulfilled, it should be possible to conduct measurements also in inclined boreholes, such as KFM07B. The equipment for overcoring stress measurements has not proven to be limited in this respect.

6 References

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Appendix A

Key measurement data

Table A-1. Key measurement data for test no. 1:1:1, 67.91 m borehole length.

Activity	Date [yy-mm-dd]	Time [hh:mm:ss]
Activation time	05-08-09	16:25:00
Mixing of glue	05-08-09	16:54:00
Application of glue to gauges	05-08-09	16:58:00
Probe installation in pilot hole	05-08-09	17:08:00
Start time for dense sampling (5 s interval)	05-08-10	07:00:00
Adapter retrieved	05-08-10	07:50:00
Adapter on surface	05-08-10	07:56:00
Drill string fed down the hole	05-08-10	08:27:00
Drill string in place	05-08-10	08:49:00
Flushing start	05-08-10	08:49:00
Rotation start	05-08-10	09:14:00
Overcoring start	05-08-10	09:15:00
Overcoring 4 cm	05-08-10	09:16:00
Overcoring 8 cm	05-08-10	09:18:00
Overcoring 12 cm	05-08-10	09:20:00
Overcoring 16 cm	05-08-10	09:22:00
Overcoring 20 cm	05-08-10	09:24:00
Overcoring 24 cm	05-08-10	09:27:00
Overcoring 28 cm	05-08-10	09:29:00
Overcoring 32 cm	05-08-10	09:31:00
Overcoring stop (100 cm)	05-08-10	09:52:00
Flushing off	05-08-10	10:09:00
Core break	05-08-10	10:32:00
Core retrieval start	05-08-10	10:57:00
Core and probe on surface	05-08-10	11:12:00
End of strain registration	05-08-10	12:34:00
Calculation of strain difference: OC Start	05-08-10	09:11:00
Calculation of strain difference: OC Stop	05-08-10	10:06:00
Overcoring advance	**Overcoring rate [cm/min]**	
0–16 cm	2.3	
16–32 cm	1.8	
32 cm – overcoring stop	3.2	

Table A-2. Key measurement data for test no. 1:2:1, 68.94 m borehole length.

Activity	Date [yy-mm-dd]	Time [hh:mm:ss]
Activation time	05-08-10	16:08:00
Mixing of glue	05-08-10	16:23:00
Application of glue to gauges	05-08-10	16:27:00
Probe installation in pilot hole	05-08-10	16:37:00
Start time for dense sampling (5 s interval)	05-08-11	07:00:00
Adapter retrieved	05-08-11	08:00:00
Adapter on surface	05-08-11	08:07:00
Drill string fed down the hole	05-08-11	08:41:00
Drill string in place	05-08-11	08:58:00
Flushing start	05-08-11	10:15:00
Rotation start	05-08-11	10:36:00
Overcoring start	05-08-11	10:38:00
Overcoring 4 cm	05-08-11	10:40:00
Overcoring 8 cm	05-08-11	10:42:30
Overcoring 12 cm	05-08-11	10:45:00
Overcoring 16 cm	05-08-11	10:47:30
Overcoring 20 cm	05-08-11	10:49:30
Overcoring 24 cm	05-08-11	10:51:00
Overcoring 28 cm	05-08-11	10:54:00
Overcoring 32 cm	05-08-11	10:56:00
Overcoring stop (100 cm)	05-08-11	11:09:00
Flushing off	05-08-11	11:26:00
Core break	05-08-11	11:43:00
Core retrieval start	05-08-11	12:00:00
Core and probe on surface	05-08-11	12:24:00
End of strain registration	05-08-11	12:43:00
Calculation of strain difference: OC Start	05-08-11	10:32:00
Calculation of strain difference: OC Stop	05-08-11	11:22:00
Overcoring advance	**Overcoring rate [cm/min]**	
0–16 cm	1.7	
16–32 cm	1.9	
32 cm – overcoring stop	5.2	

Table A-3. Key measurement data for test no. 1:3:1, 70.09 m borehole length.

Activity	Date [yy-mm-dd]	Time [hh:mm:ss]
Activation time	05-08-11	16:29:00
Mixing of glue	05-08-11	16:46:00
Application of glue to gauges	05-08-11	16:50:00
Probe installation in pilot hole	05-08-11	17:04:00
Start time for dense sampling (5 s interval)	05-08-12	07:00:00
Adapter retrieved	05-08-12	07:53:00
Adapter on surface	05-08-12	07:56:00
Drill string fed down the hole	05-08-12	08:15:00
Drill string in place	05-08-12	08:34:00
Flushing start	05-08-12	08:35:00
Rotation start	05-08-12	08:54:00
Overcoring start	05-08-12	08:56:00
Overcoring 4 cm	05-08-12	08:57:15
Overcoring 8 cm	05-08-12	08:58:30
Overcoring 12 cm	05-08-12	08:59:45
Overcoring 16 cm	05-08-12	09:01:15
Overcoring 20 cm	05-08-12	09:02:30
Overcoring 24 cm	05-08-12	09:03:45
Overcoring 28 cm	05-08-12	09:05:15
Overcoring 32 cm	05-08-12	09:06:30
Overcoring stop (100 cm)	05-08-12	09:18:45
Flushing off	05-08-12	09:38:00
Core break	05-08-12	09:54:00
Core retrieval start	05-08-12	10:10:00
Core and probe on surface	05-08-12	10:23:00
End of strain registration	05-08-12	10:45:00
Calculation of strain difference: OC Start	05-08-12	08:46:00
Calculation of strain difference: OC Stop	05-08-12	09:36:00
Overcoring advance	**Overcoring rate [cm/min]**	
0–16 cm	3.0	
16–32cm	3.0	
32 cm – overcoring stop	5.6	

Table A-4. Key measurement data for test no. 1:4:1, 71.00 m borehole length.

Activity	Date [yy-mm-dd]	Time [hh:mm:ss]
Activation time	05-08-12	17:18:00
Mixing of glue	05-08-12	17:30:00
Application of glue to gauges	05-08-12	17:33:00:
Probe installation in pilot hole	05-08-12	17:40:00
Start time for dense sampling (5 s interval)	05-08-13	07:00:00
Adapter retrieved	05-08-13	08:12:00
Adapter on surface	05-08-13	08:17:00
Drill string fed down the hole	05-08-13	08:58:00
Drill string in place	05-08-13	10:23:00
Flushing start	05-08-13	11:05:00
Rotation start	05-08-13	11:21:30
Overcoring start	05-08-13	11:22:00
Overcoring 4 cm	05-08-13	11:24:50
Overcoring 8 cm	05-08-13	11:27:10
Overcoring 12 cm	05-08-13	11:29:20
Overcoring 16 cm	05-08-13	11:31:40
Overcoring 20 cm	05-08-13	11:33:50
Overcoring 24 cm	05-08-13	11:36:05
Overcoring 28 cm	05-08-13	11:38:25
Overcoring 32 cm	05-08-13	11:40:40
Overcoring stop (70 m)	05-08-13	12:02:30
Flushing off	05-08-13	12:18:00
Core break	05-08-13	12:34:00
Core retrieval start	05-08-13	12:54:00
Core and probe on surface	05-08-13	13:10:00
End of strain registration	05-08-13	13:30:00
Calculation of strain difference: OC Start	05-08-13	10:50:50
Calculation of strain difference: OC Stop	05-08-13	12:24:30
Overcoring advance	**Overcoring rate [cm/min]**	
0–16 cm	1.7	
16–32 cm	1.8	
32 cm – overcoring stop	1.7	

Table A-5. Key measurement data for test no. 1:5:1, 72.45 m borehole length.

Activity	Date [yy-mm-dd]	Time [hh:mm:ss]
Activation time	05-08-13	19:03:00
Mixing of glue	05-08-13	19:21:00
Application of glue to gauges	05-08-13	19:24:00
Probe installation in pilot hole	05-08-13	19:31:00
Start time for dense sampling (5 s interval)	05-08-14	07:00:00
Adapter retrieved	05-08-14	08:21:20
Adapter on surface	05-08-14	08:24:30
Drill string fed down the hole	05-08-14	08:27:00
Drill string in place	05-08-14	08:47:00
Flushing start	05-08-14	08:48:00
Rotation start	05-08-14	09:10:55
Overcoring start	05-08-14	09:12:30
Overcoring 4 cm	05-08-14	09:14:40
Overcoring 8 cm	05-08-14	09:16:45
Overcoring 12 cm	05-08-14	09:19:05
Overcoring 16 cm	05-08-14	09:21:20
Overcoring 20 cm	05-08-14	09:23:40
Overcoring 24 cm	05-08-14	09:25:50
Overcoring 28 cm	05-08-14	09:28:10
Overcoring 32 cm	05-08-14	09:30:25
Overcoring stop (70 cm)	05-08-14	09:51:55
Flushing off	05-08-14	10:06:00
Core break	05-08-14	10:24:30
Core retrieval start	05-08-14	10:48:00
Core and probe on surface	05-08-14	11:02:00
End of strain registration	05-08-14	11:18:05
Calculation of strain difference: OC Start	05-08-14	09:04:30
Calculation of strain difference: OC Stop	05-08-14	10:19:55

Overcoring advance	Overcoring rate [cm/min]
0–16 cm	1.8
16–32 cm	1.8
32 cm – overcoring stop	1.8

Overcoring strain data and graphs

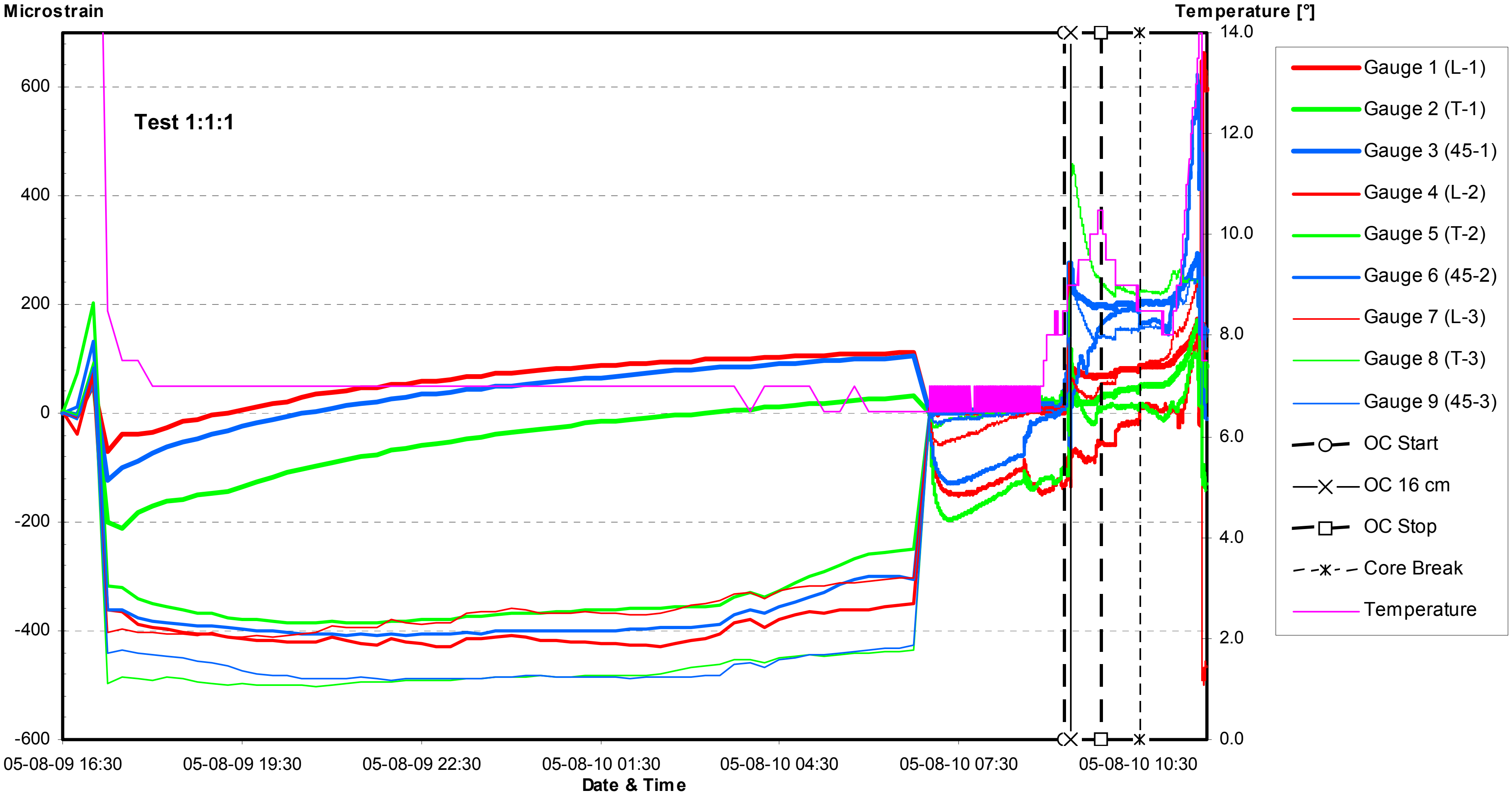


Figure B-1. *All recorded strain data and temperature from activation of probe to recovery from borehole for test no. 1:1:1, 67.91 m borehole length.*

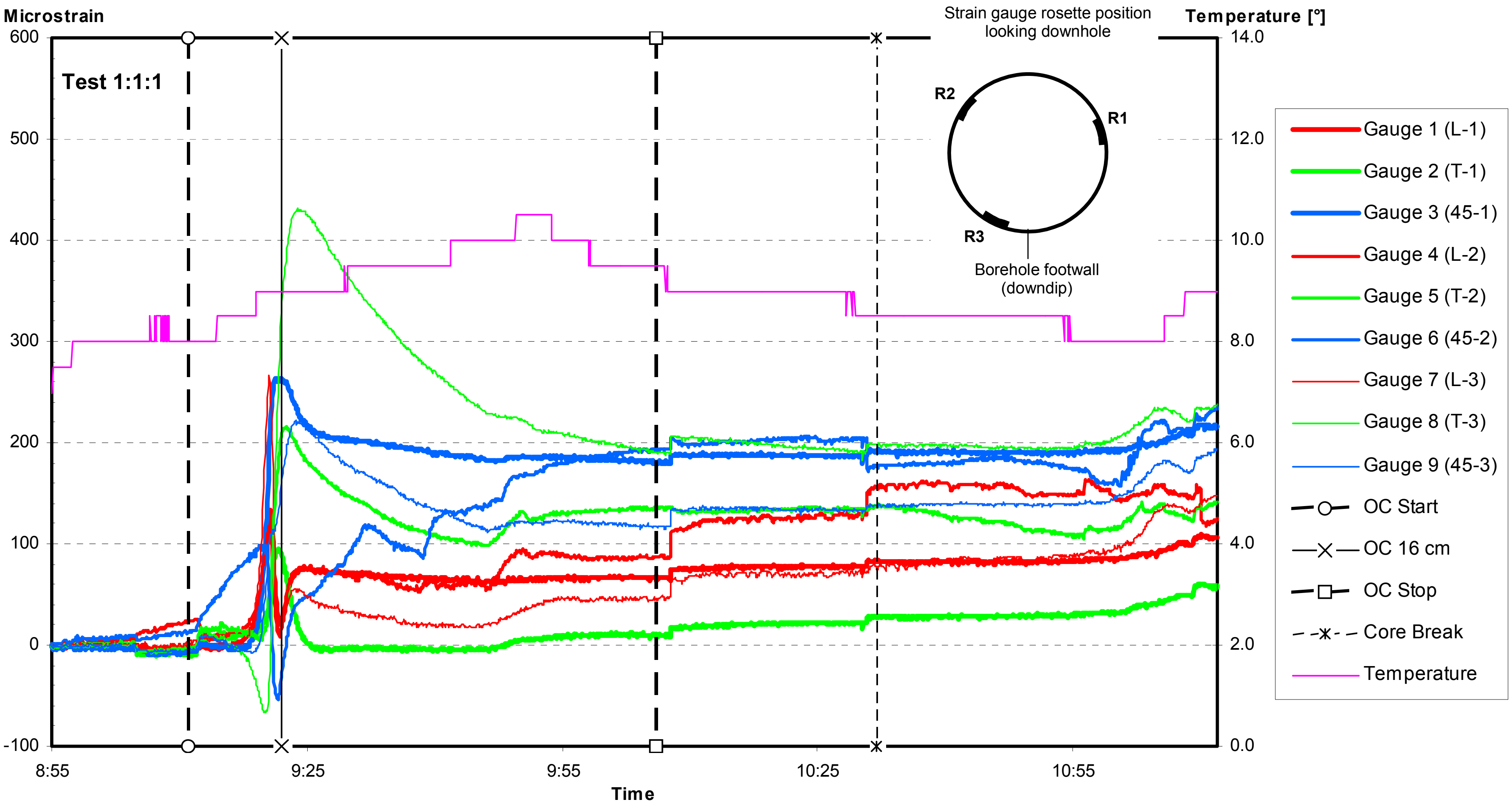


Figure B-2. *Recorded strain data and temperature during overcoring (from start to stop) for test no. 1:1:1, 67.91 m borehole length. Strain values reset to zero at 08:55.*

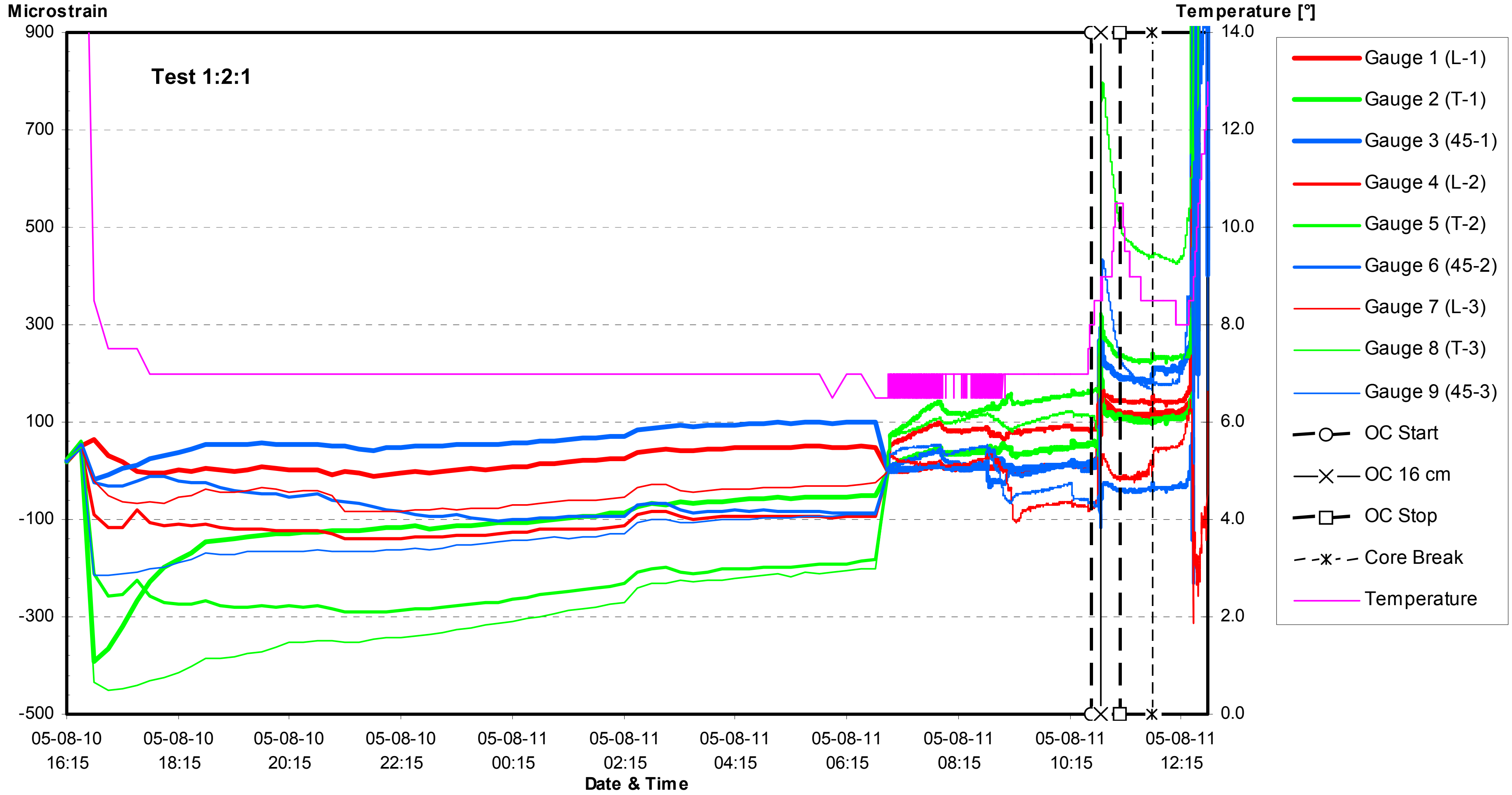


***Figure B-3.** All recorded strain data and temperature from activation of probe to recovery from borehole for test no. 1:2:1, 68.94 m borehole length.*

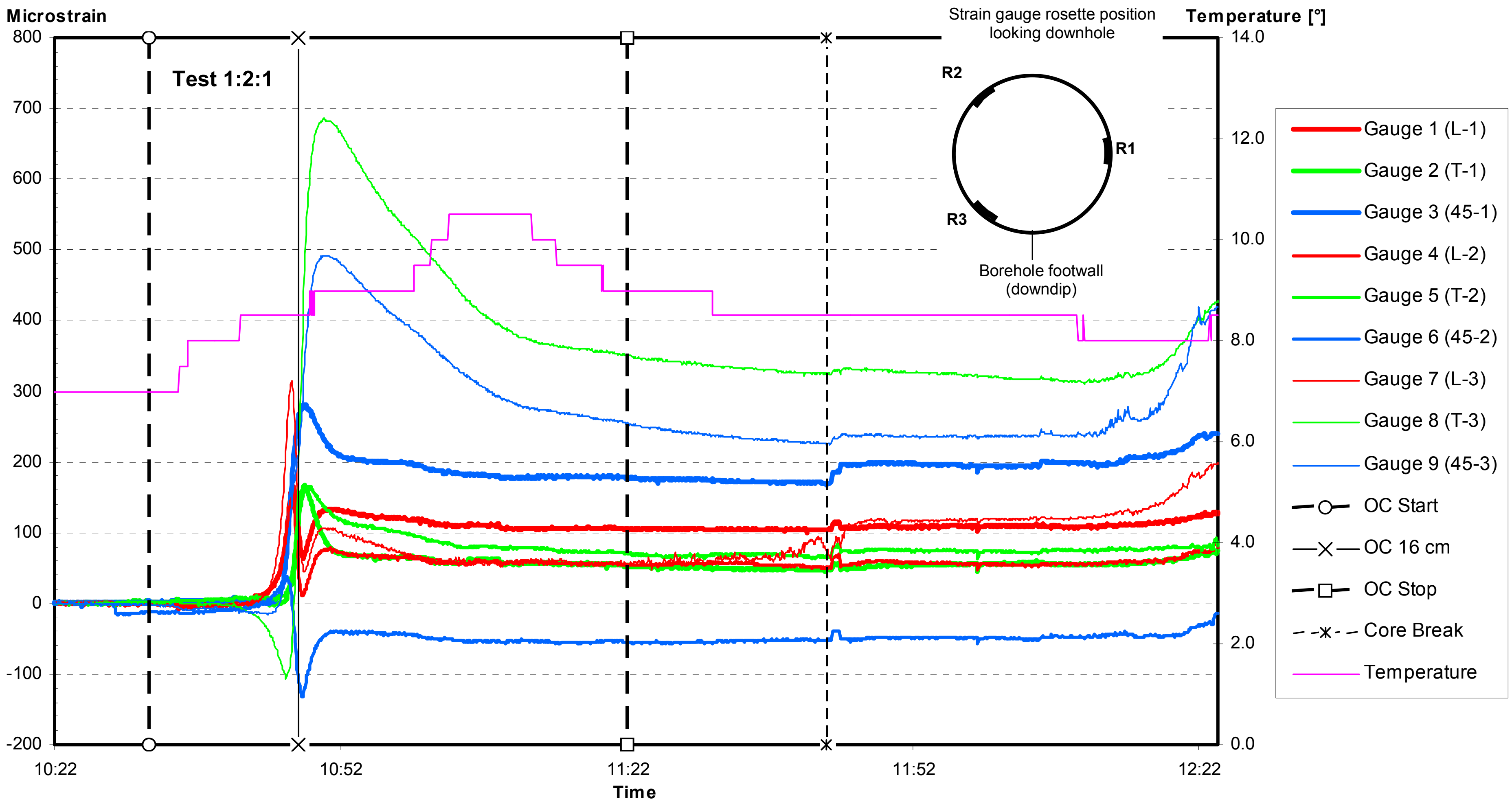


Figure B-4. *Recorded strain data and temperature during overcoring (from start to stop) for test no. 1:2:1, 68.94 m borehole length. Strain values reset to zero at 10.22.*

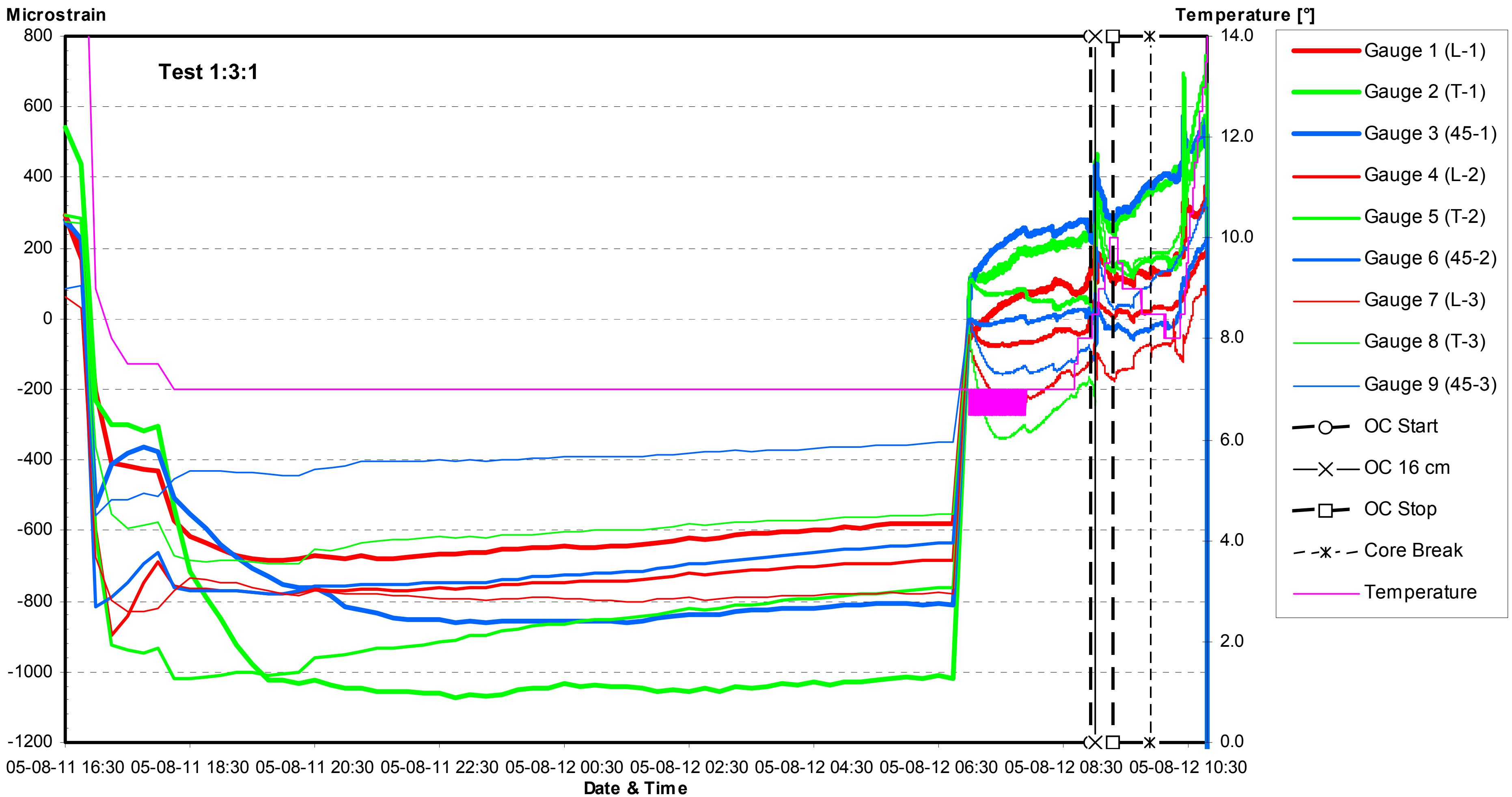


Figure B-5. *All recorded strain data and temperature from activation of probe to recovery from borehole for test no. 1:3:1, 70.09 m borehole length.*

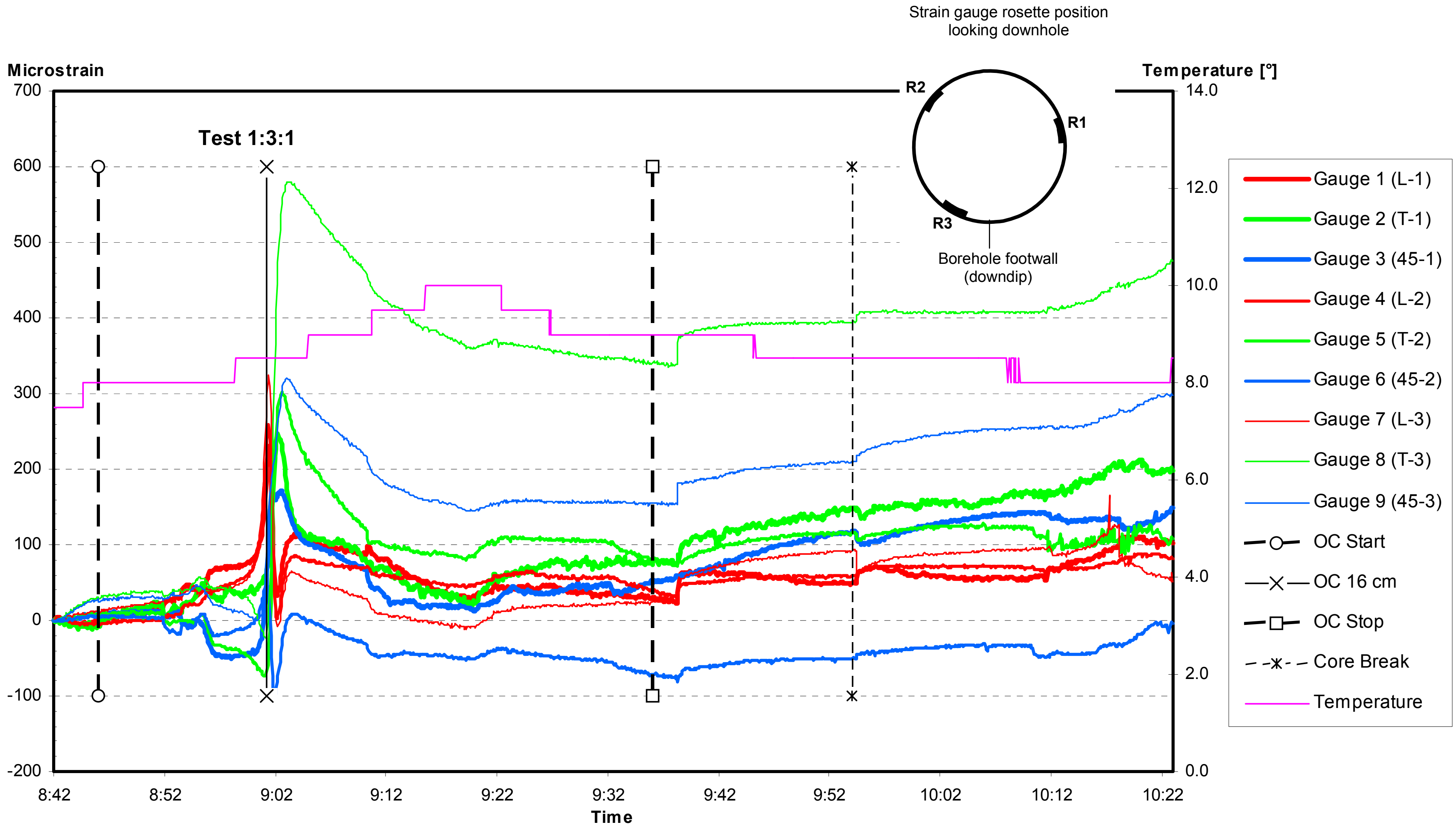


Figure B-6. *Recorded strain data and temperature during overcoring (from start to stop) for test no. 1:3:1, 70.09 m borehole length. Strain values reset to zero at 08:42.*

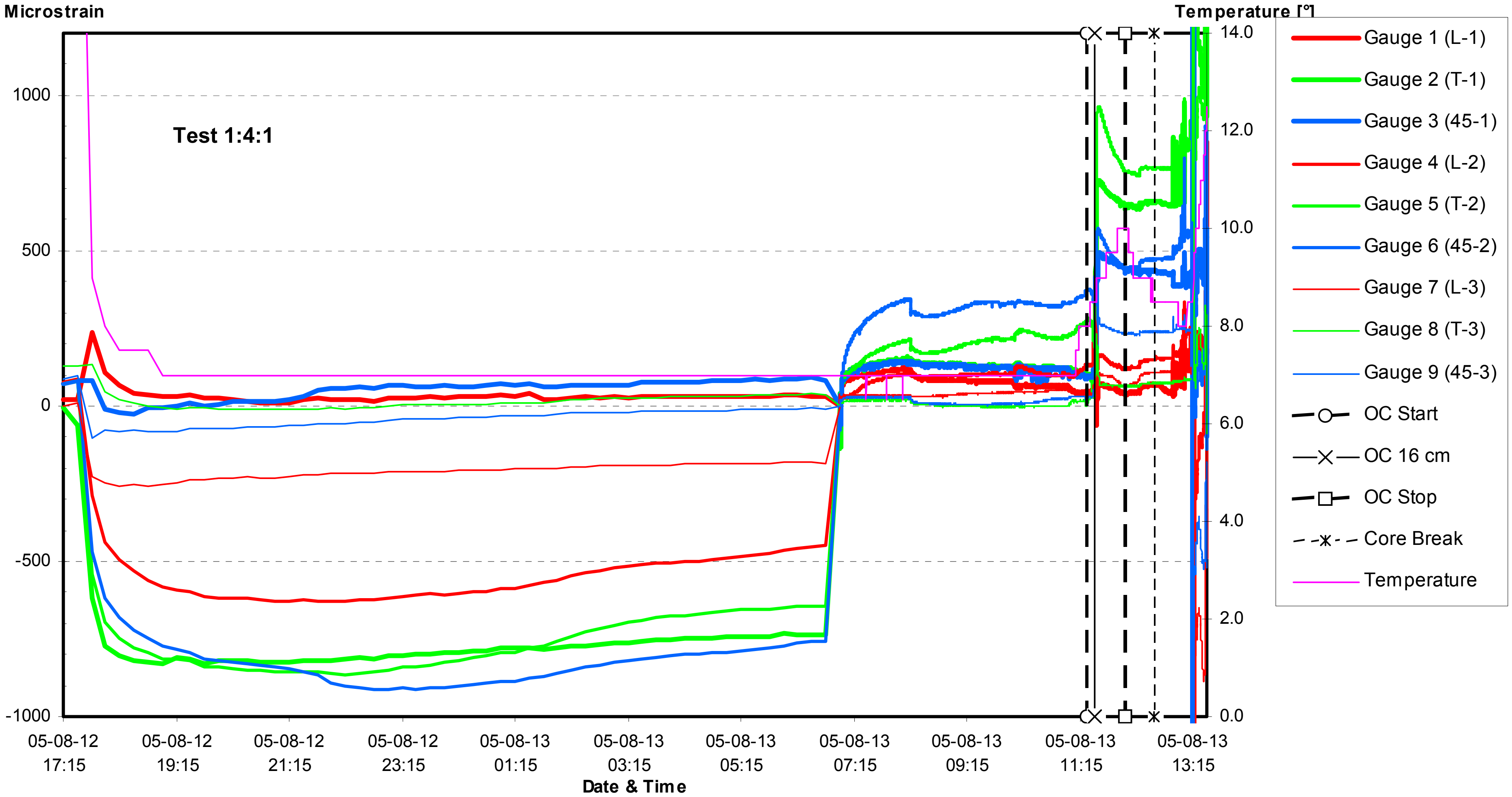


Figure B-7. *All recorded strain data and temperature from activation of probe to recovery from borehole for test no. 1:4:1, 71.00 m borehole length.*

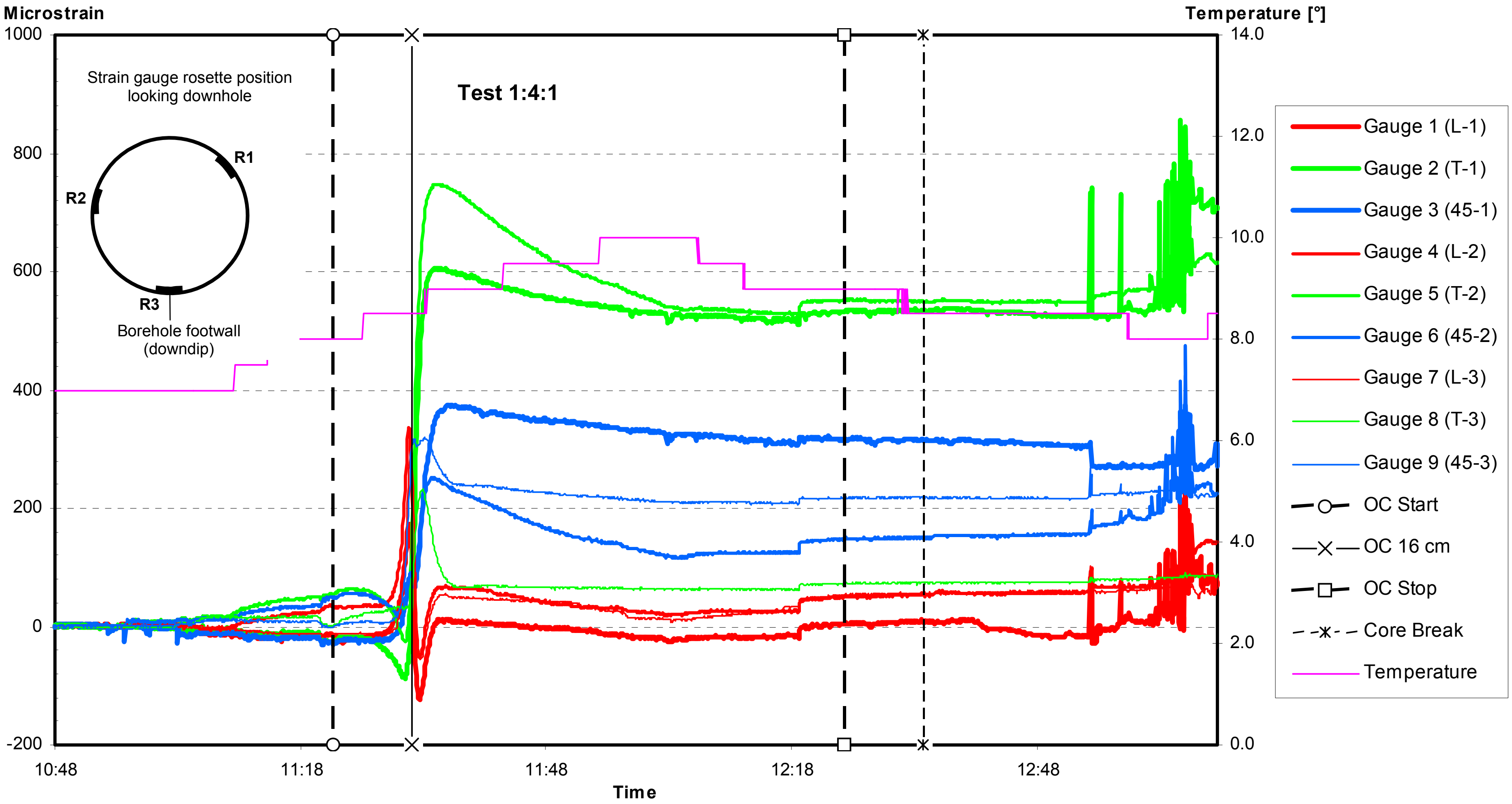


Figure B-8. *Recorded strain data and temperature during overcoring (from start to stop) for test no. 1:4:1, 71.00 m borehole length. Strain values reset to zero at 10:48.*

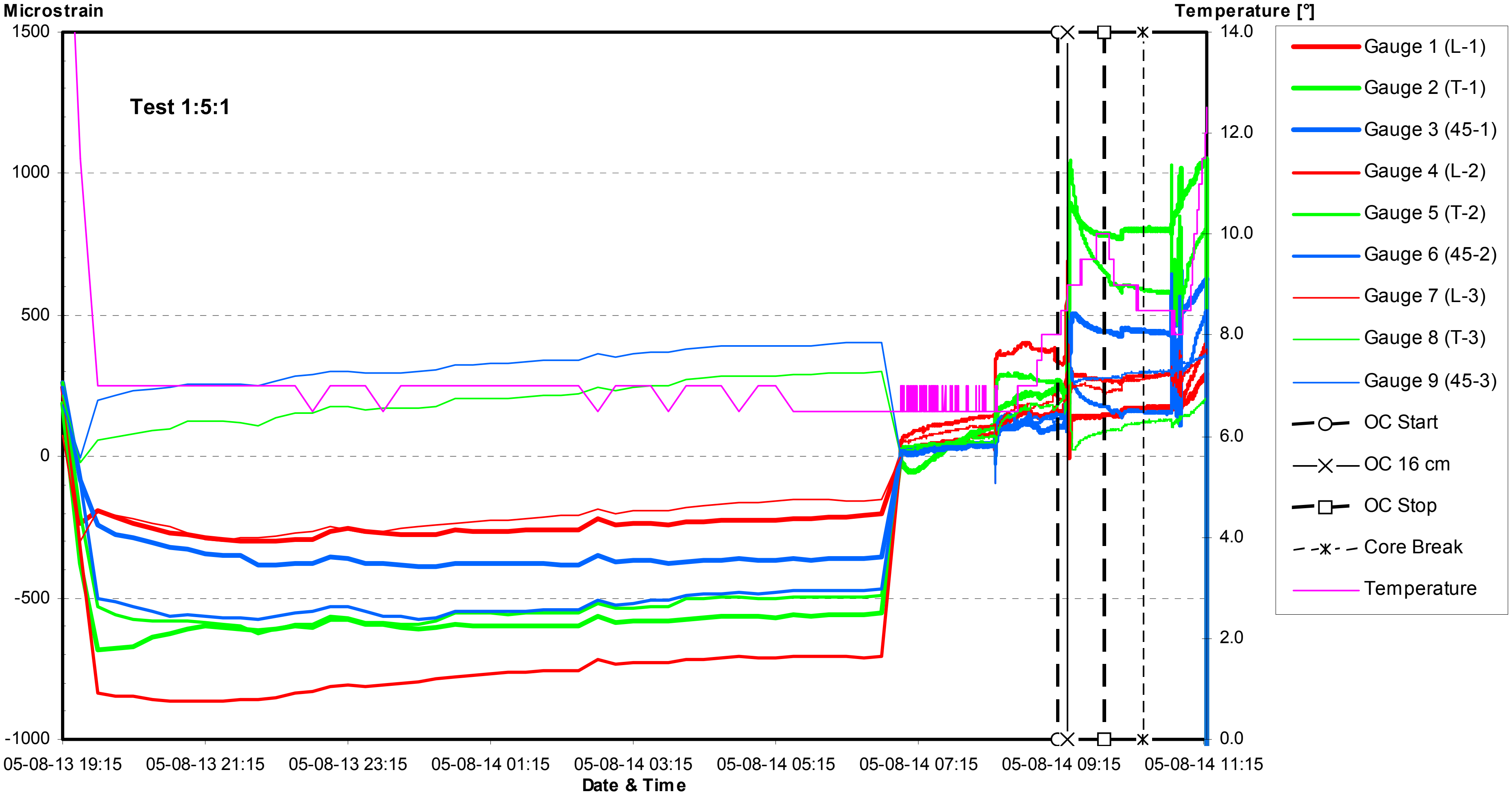


Figure B-9. All recorded strain data and temperature from activation of probe to recovery from borehole for test no. 1:5:1, 72.45 m borehole length.

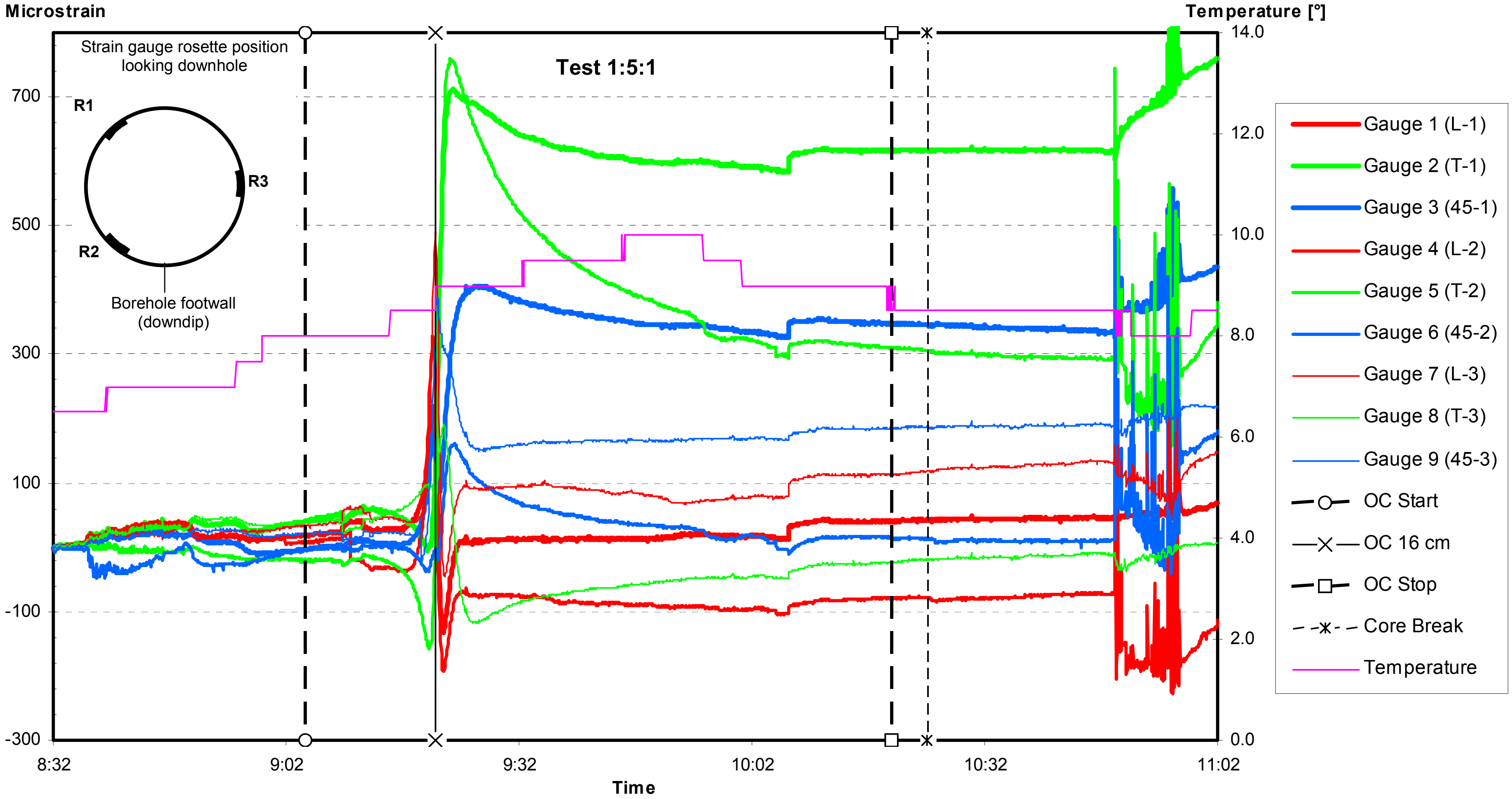


Figure B-10. *Recorded strain data and temperature during overcoring (from start to stop) for test no. 1:5:1, 72.45 m borehole length. Strain values reset to zero at 08:32.*

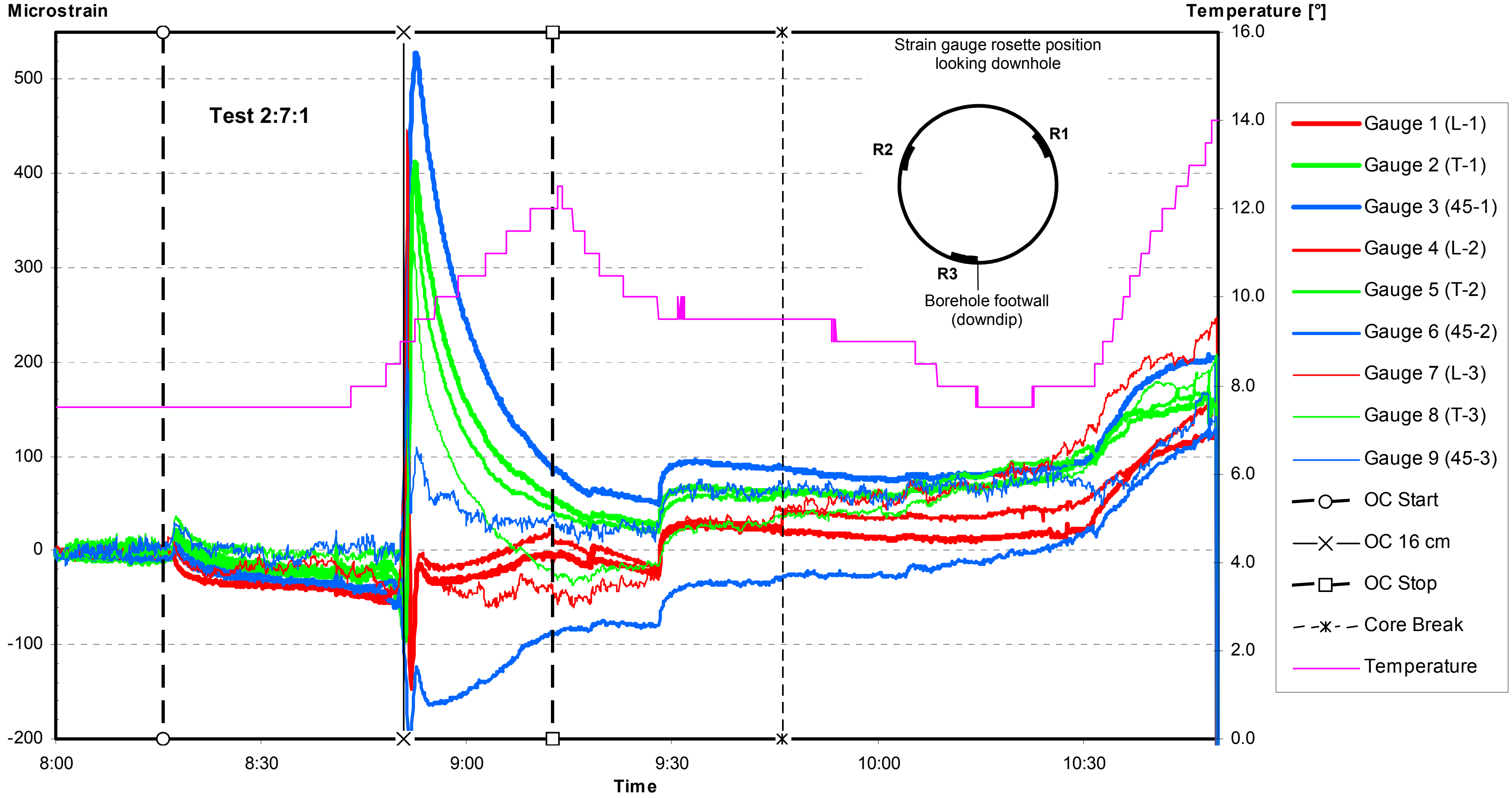


Figure B-11. *Recorded strain data and temperature during overcoring (from start to stop) for test no. 2:7:1, 158.66 m borehole length. Strain values reset to zero at 08:00. Test rated as failed (rating c).*

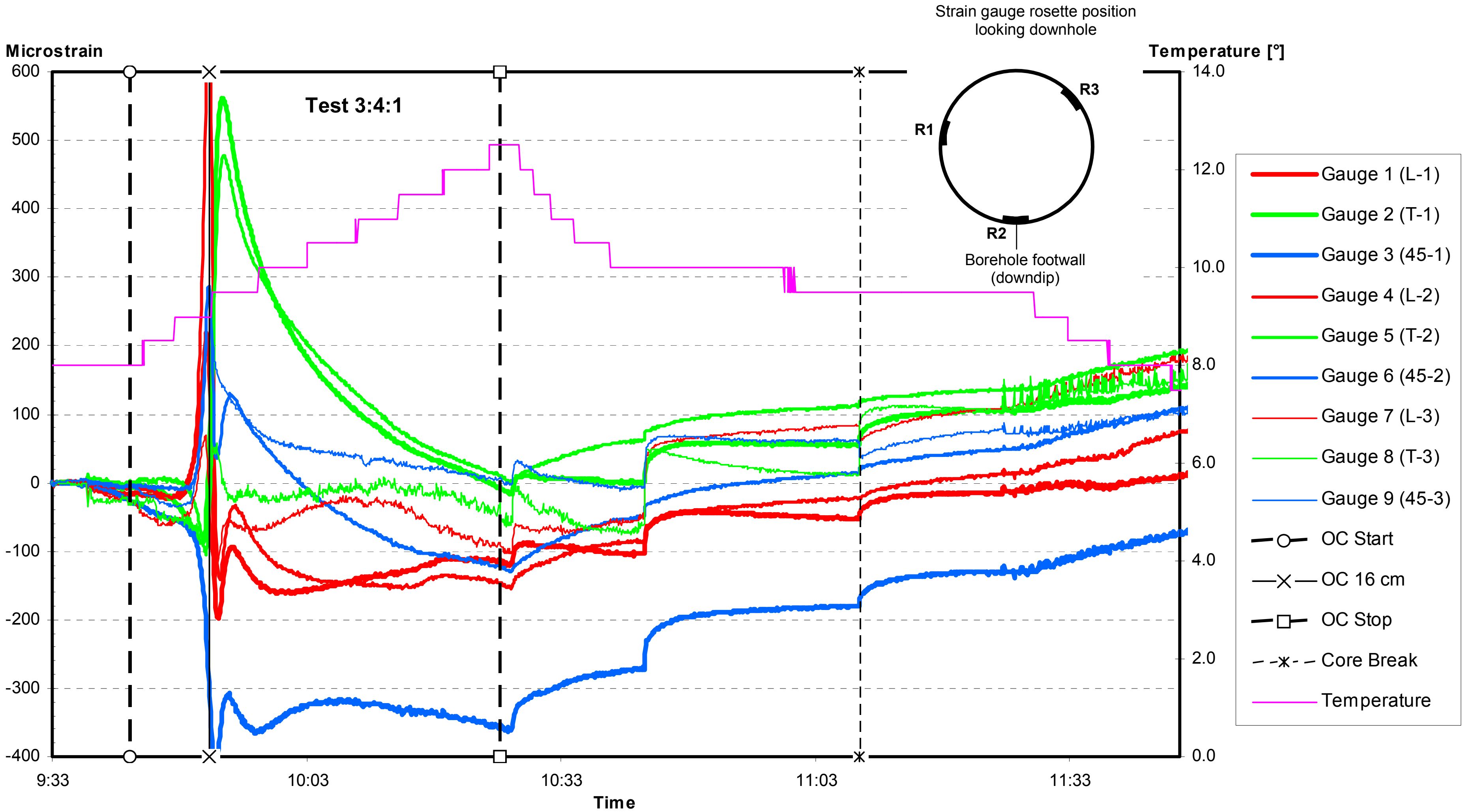


Figure B-12. *Recorded strain data and temperature during overcoring (from start to stop) for test no. 3:4:1, 248.19 m borehole length. Strain values reset to zero at 09:33. Test rated as failed (rating c).*

Biaxial test data, including data from test program

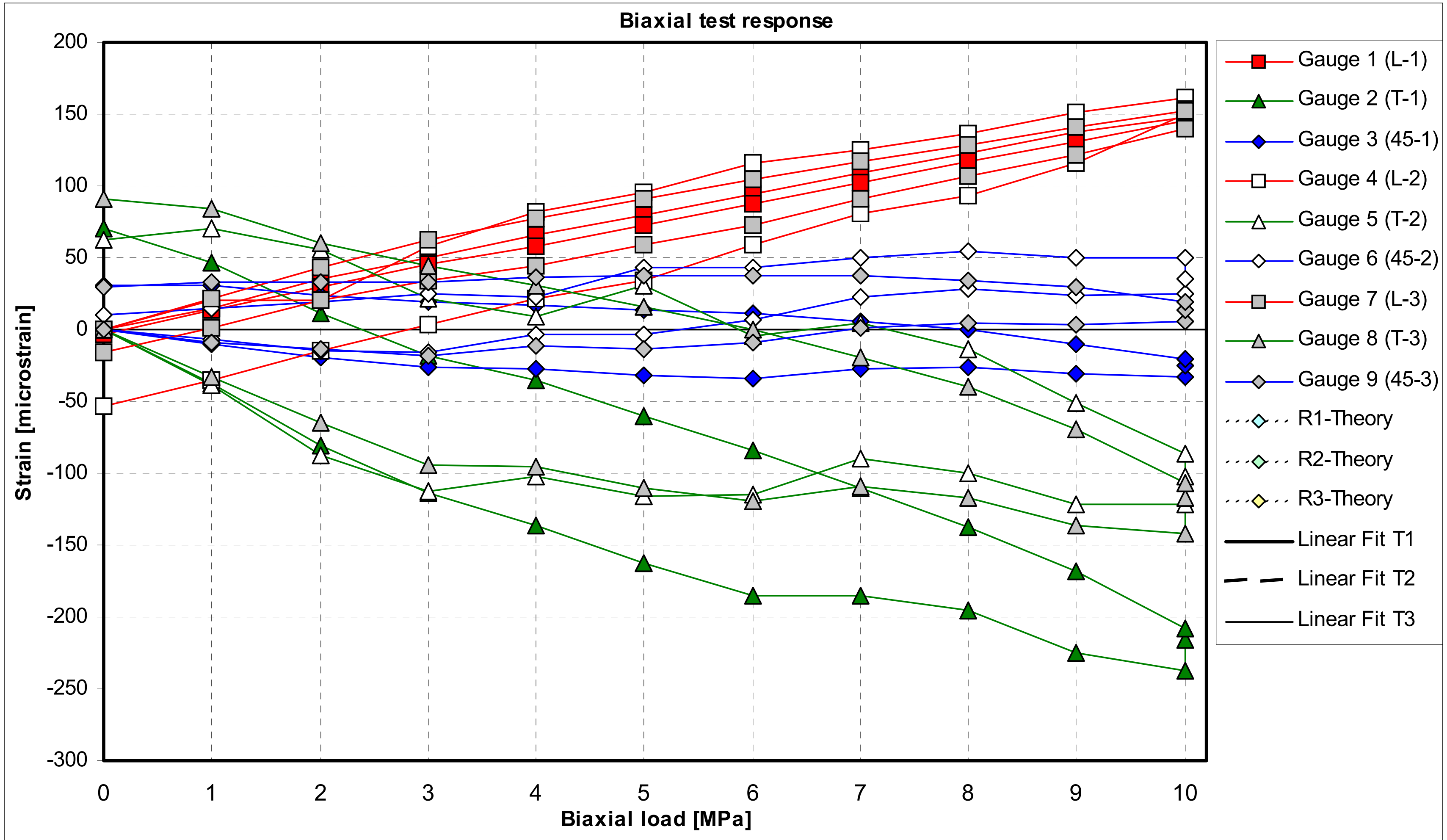


Figure C-1. *Results from biaxial testing of test no. 1:1:1, 67.91 m borehole length.*

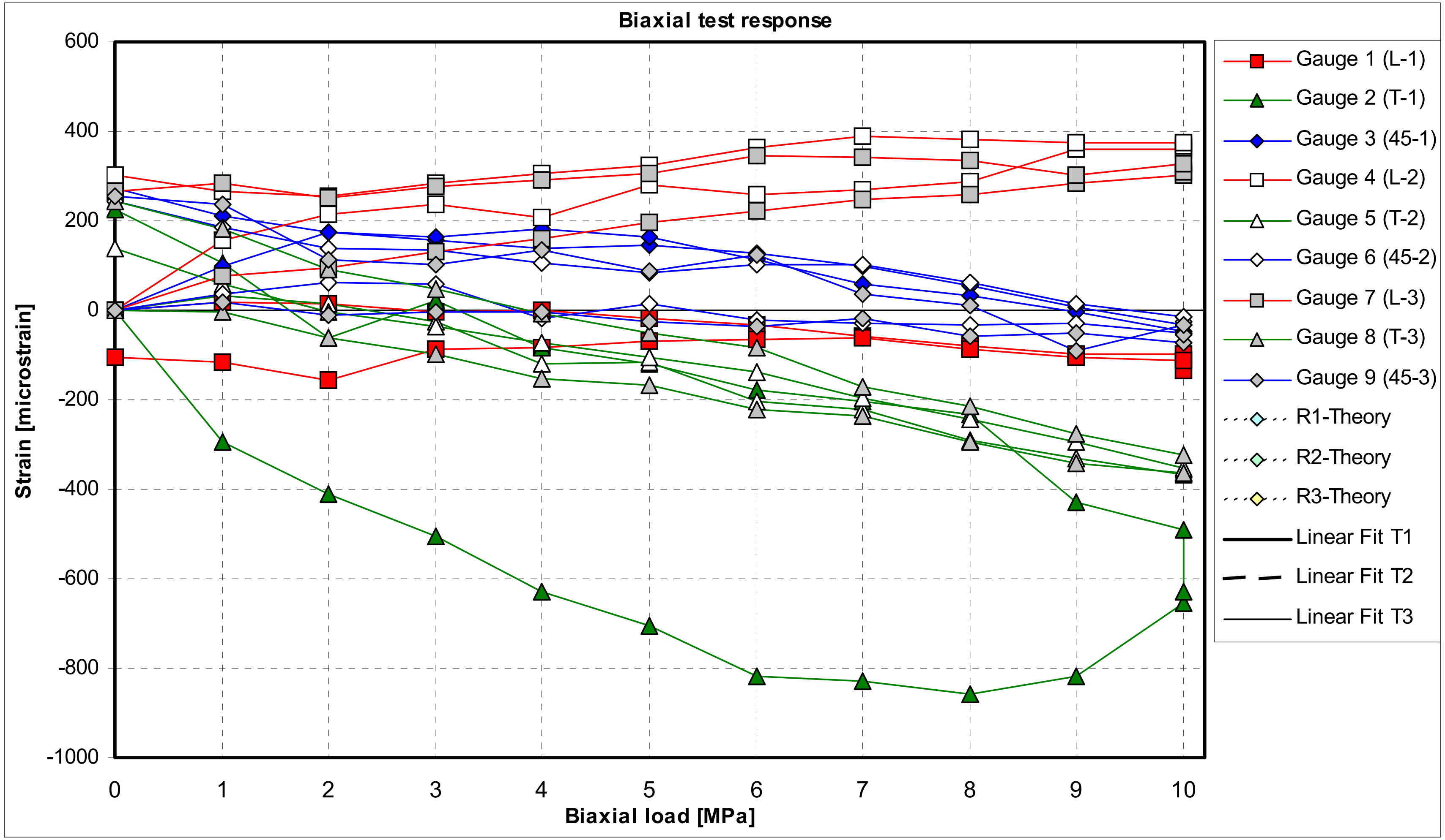


Figure C-2. *Results from biaxial testing of test no. 1:4:1, 71.00 m borehole length.*

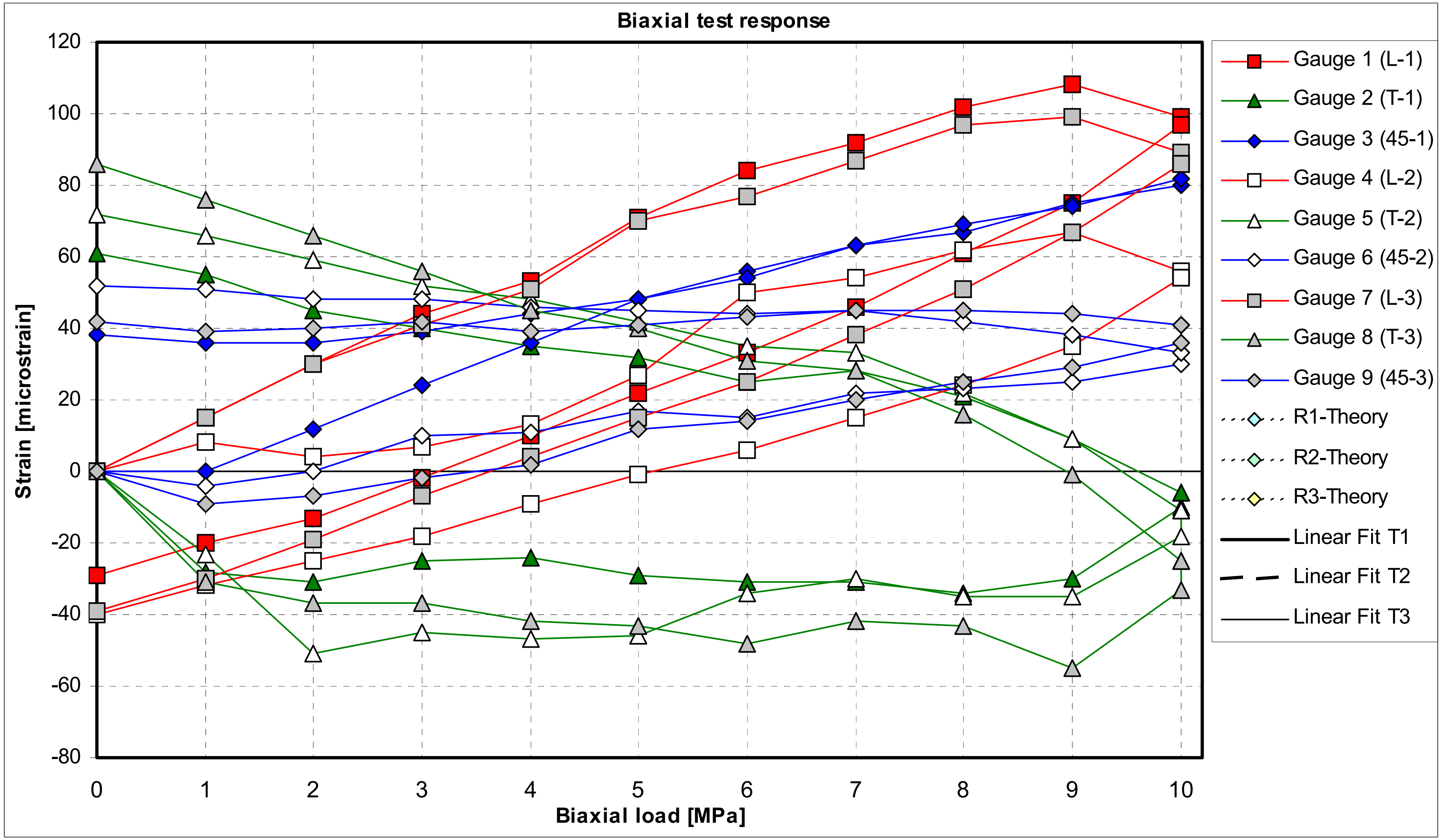


Figure C-3. *Results from biaxial testing of test no. 2:7:1, 158.66 m borehole length. Test rated as failed (rating c).*

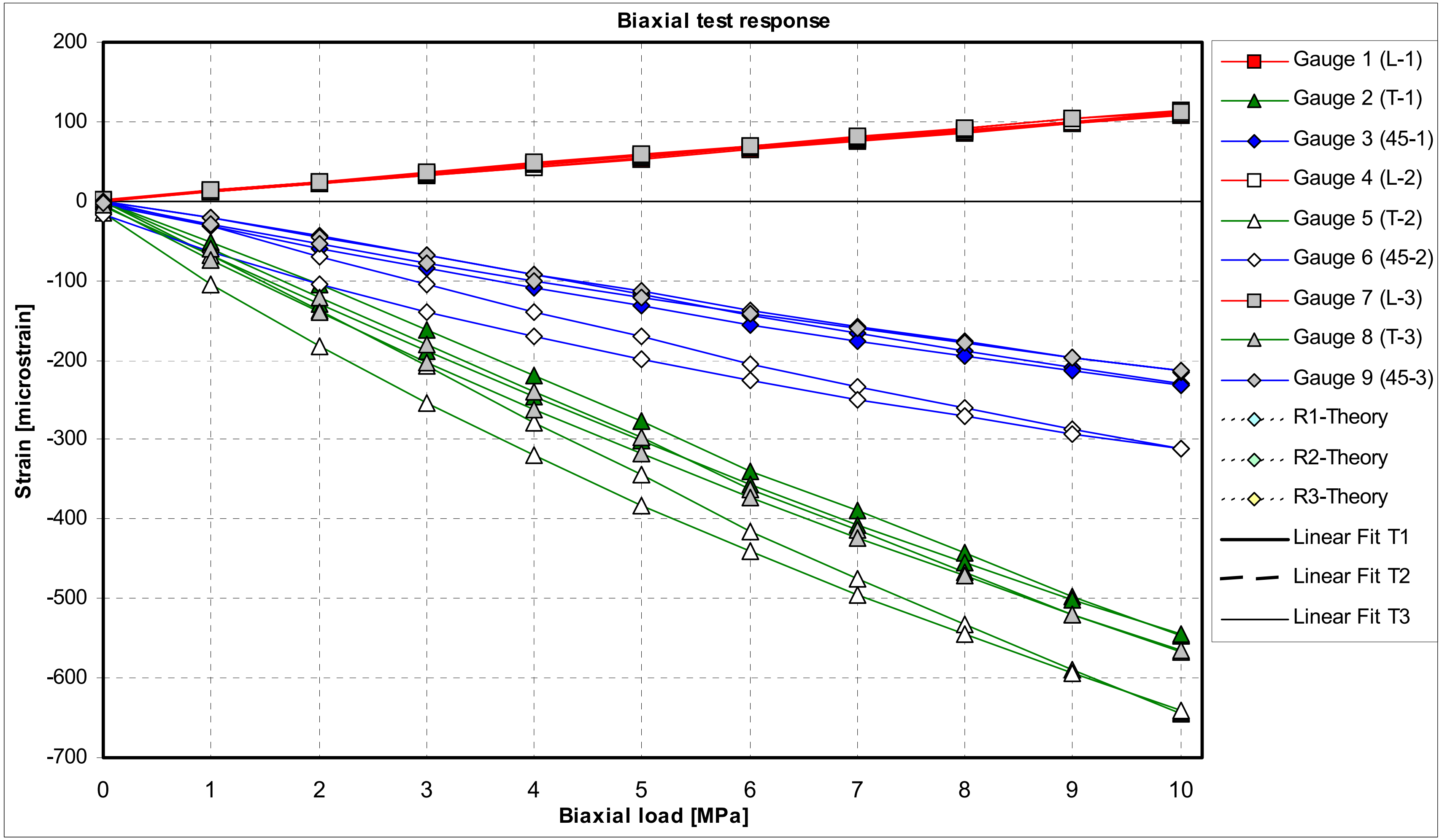


Figure C-4. *Results from biaxial testing of test no. 1:5:1, 72.45 m borehole length – after cleaning of overcored sample.*

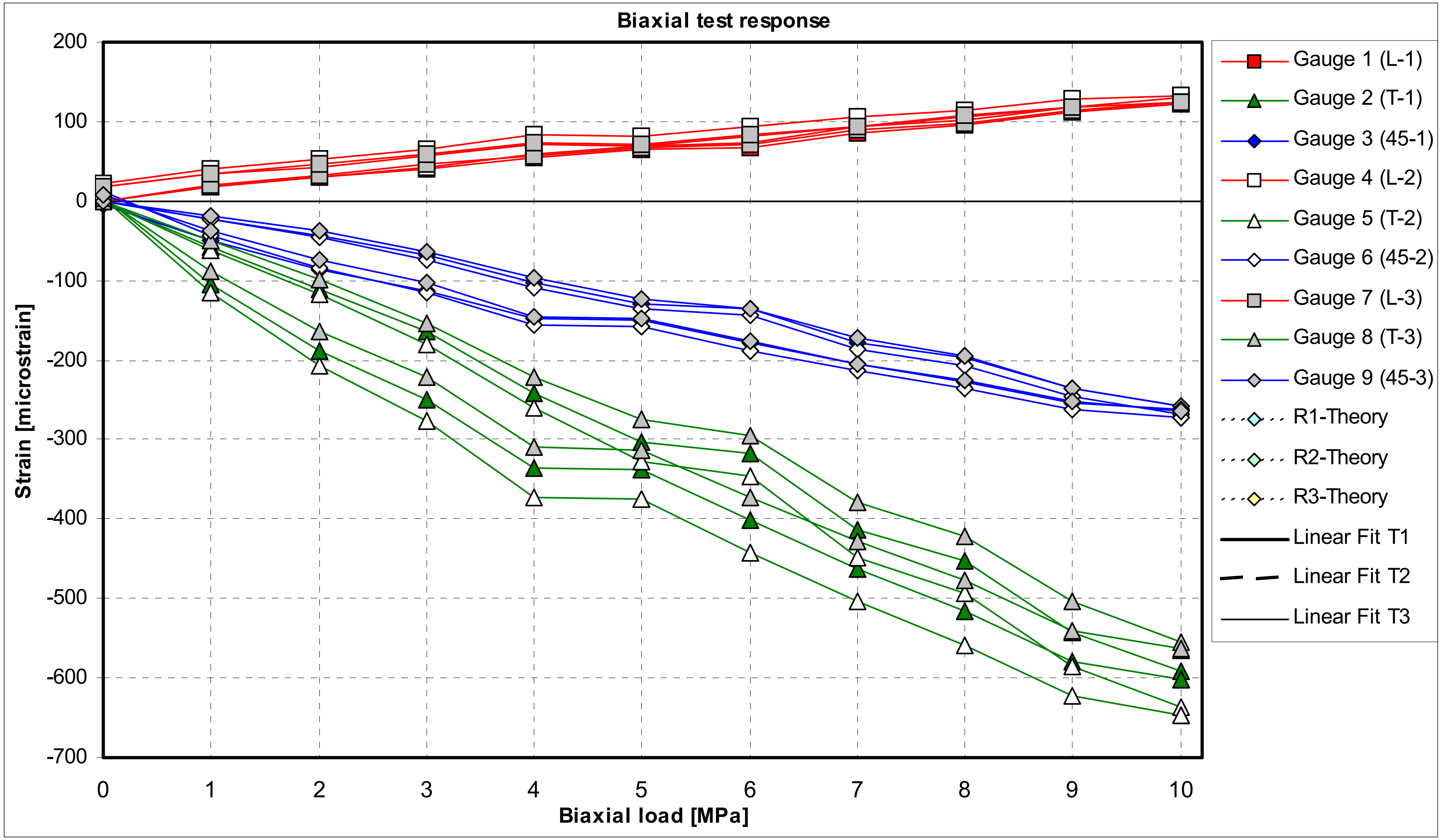


Figure C-5. *Results from biaxial testing of test no. 2:3:1, 152.83 m borehole length – after cleaning of overcored sample.*

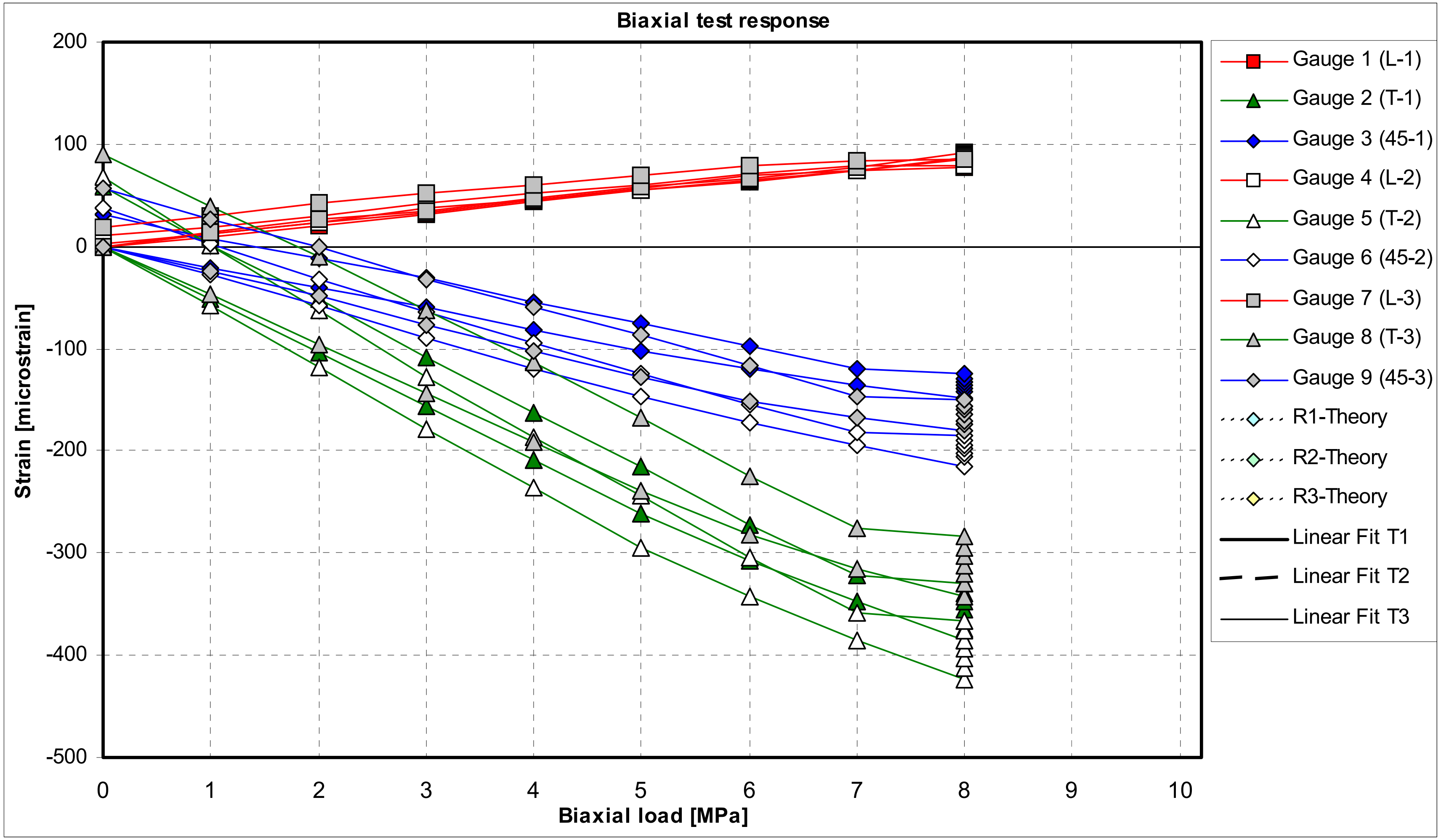


Figure C-6. *Results from biaxial testing with maximum load of 8 MPa, performed on core (2:7:1) with the Borre probe installed according to test Type 3.*

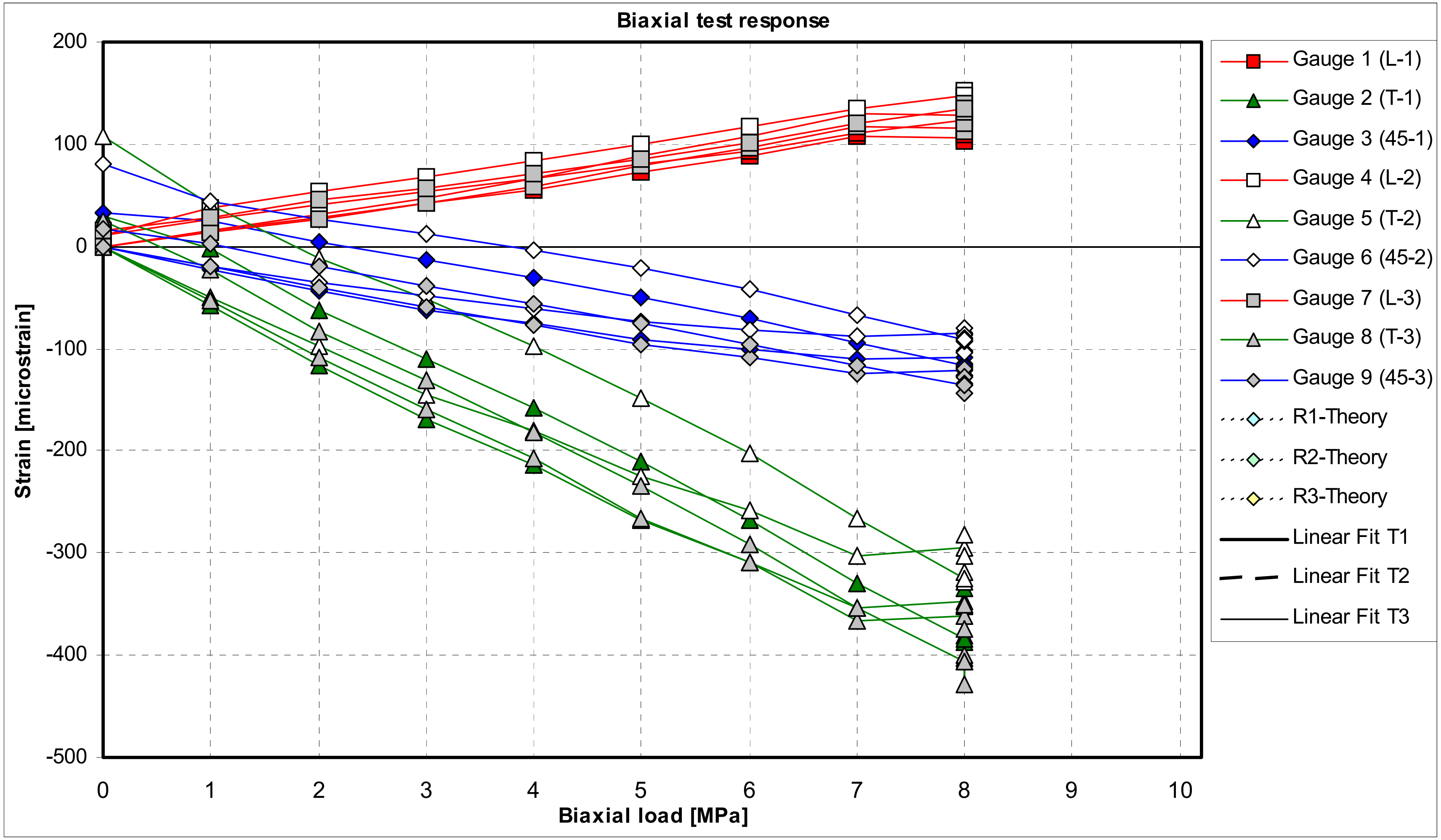


Figure C-7. *Results from biaxial testing with maximum load of 8 MPa, performed on core (1:4:1) with the Borre probe installed according to test Type 1.*

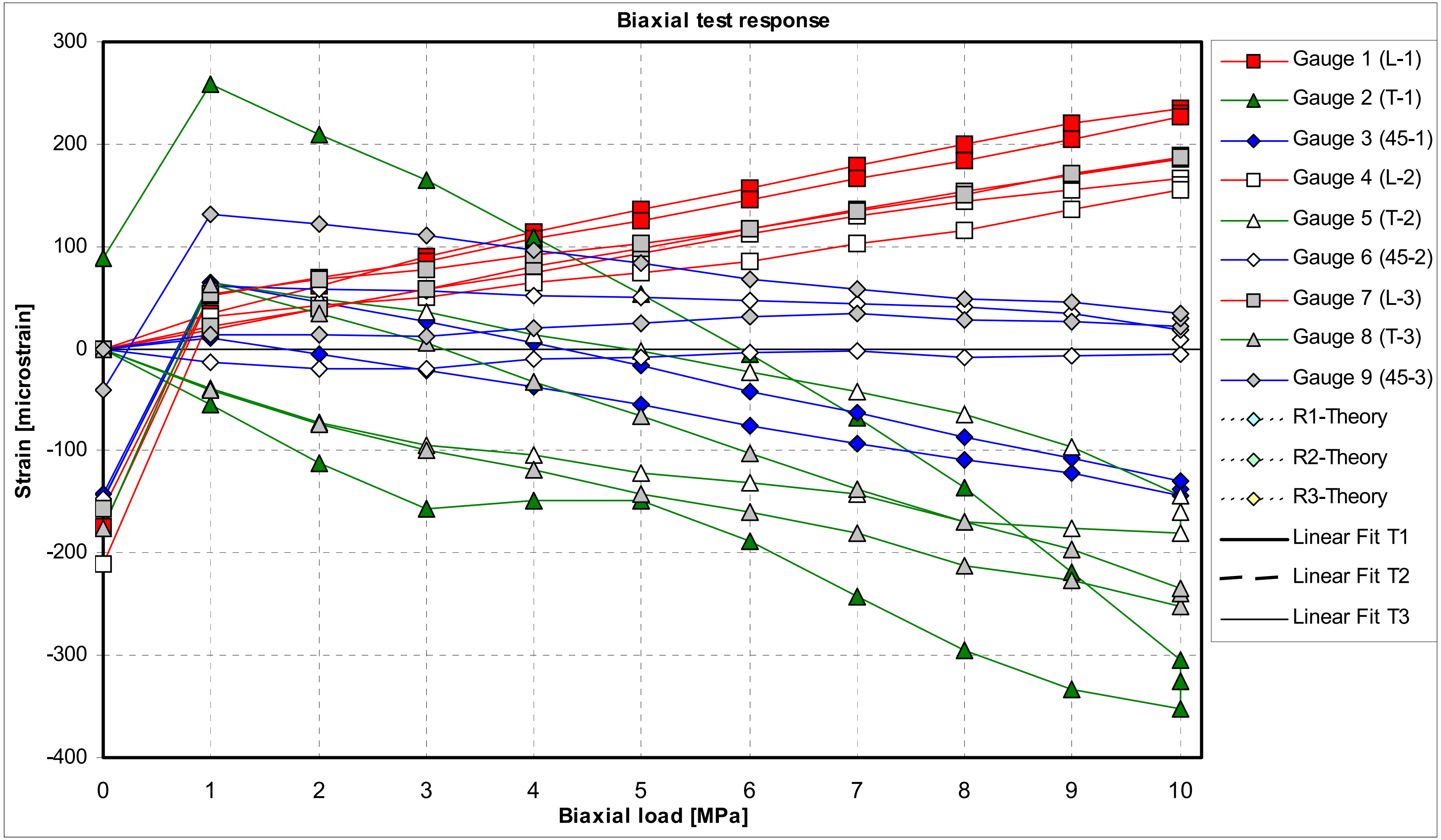


Figure C-8. *Results from biaxial testing with maximum load of 8 MPa, performed on core (2–50) with the Borre probe installed according to test Type 2.*

Appendix D

Stress calculation input data and results

Table D-1. Measured and average in situ stresses for borehole KFM07B, Level 1, test nos. 1:1:1, 1:2:1, 1:3:1, 1:4:1 and 1:5:1.

SwedPower

OVERCORING STRESS MEASUREMENTS

Project Description : Forsmark KFM07B
Measurement Level : KFM07B Level 1
Date : 2005-12-22

(values for gauge and resistance factor are always 2 and 1, respectively)

Input Data

Depth [m]	Hole dip [º]	Hole bearing [º]	Bearing (ball) - X [º]	Young's modulus [GPa]	Poisson's ratio	Needle bearing [º]	Overcoring Time [hh:mm:ss]	[hh:mm:ss]
67.91	52.9	135.7	350	53.0	0.13	-	Start=09:11:00	Stop=10:06:00
68.94	52.9	135.7	0	53.0	0.13	-	Start=10:32:00	Stop=11:22:00
70.09	52.9	135.7	345	53.0	0.13	-	Start=08:46:00	Stop=09:36:00
71.00	52.9	135.7	330	53.0	0.13	-	Start=10:50:50	Stop=12:24:30
72.45	53	135.6	240	53.0	0.13	-	Start=09:04:30	Stop=10:19:55

Strains

Depth [m]	ε_{L1} (gauge no. 1) [μstrain]	ε_{T1} (gauge no. 2) [μstrain]	ε_{45_1} (gauge no. 3) [μstrain]	ε_{L2} (gauge no. 4) [μstrain]	ε_{T2} (gauge no. 5) [μstrain]	ε_{45_2} (gauge no. 6) [μstrain]	ε_{L3} (gauge no. 7) [μstrain]	ε_{T3} (gauge no. 8) [μstrain]	ε_{45_3} (gauge no. 9) [μstrain]
67.91	69	20	188	64	139	182	44	198	124
68.94	102	48	173	54	67	-45	58	347	256
70.09	29	84	43	43	73	-77	12	310	128
71.00	0	532	311	48	549	147	52	72	216
72.45	22	576	352	-87	330	19	79	-63	164

Calculated Principal Stresses

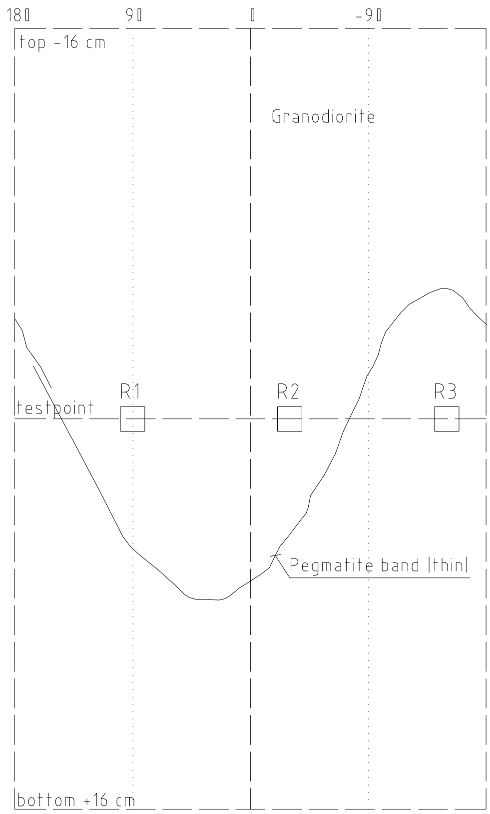
Depth [m]	σ_1 [MPa]	σ_1 - Dip [º]	σ_1 - Bearing [º]	σ_2 [MPa]	σ_2 - Dip [º]	σ_2 - Bearing [º]	σ_3 [MPa]	σ_3 - Dip [º]	σ_3 - Bearing [º]
67.91	7.3	46.9	203.8	4.6	41.3	43.7	2.0	10.0	304.7
68.94	7.8	25.7	73.6	6.4	64.2	250.3	0.1	1.3	343.0
70.09	5.8	3.2	240.5	3.0	77.8	345.7	-0.1	11.7	149.9
71.00	15.5	51.0	325.6	8.8	17.7	78.8	1.8	33.4	181.0
72.45	13.5	6.9	213.0	6.8	77.7	336.9	-1.4	10.1	121.8
Mean	*7.3*	*12.1*	*48.1*	*6.9*	*70.1*	*281.9*	*2.2*	*15.5*	*141.5*

Calculated Horizontal and Vertical Stresses

Depth [m]	Major stress σ_A [MPa]	σ_A - Bearing [º]	Minor stress σ_B [MPa]	σ_B - Bearing [º]	Vertical stress σ_z [MPa]	Error (sum of squares)	Strains re-calculated?
67.91	5.8	31.1	2.1	121.1	6.0	11800.9	No
68.94	7.6	73.1	0.1	163.1	6.7	1888.9	No
70.09	5.8	60.2	0.0	150.2	2.9	7802.5	No
71.00	10.0	106.9	5.3	16.9	10.7	2176.1	No
72.45	13.4	32.3	-1.1	122.3	6.6	16749.2	No
Mean	*7.2*	*51.3*	*2.6*	*141.3*	*6.6*		

Overcore logging sheets

OVERCORE SAMPLE LOG
Borehole no., test no., depth : **KFM07B, Test no. 1:1:1, 67.91 m depth**



Angle clockwise in borehole direction
rosette 1 =+90 degrees
rosette 2 =-30 degrees
rosette 3 =-150 degrees

GEOLOGY

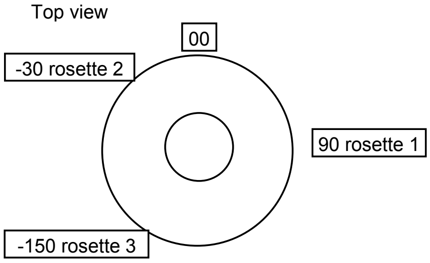
Grandiorite

STRUCTURES (JOINTS)

Thin pegmatite band.

Mark any observed fractures

Top view

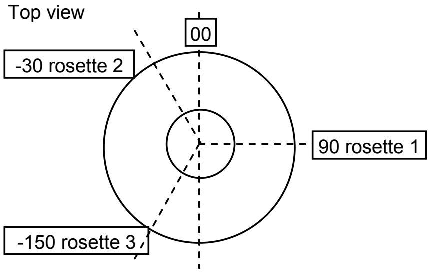


COMMENTS

Strain gauge orientation OK.

Control of strain gauge orientation

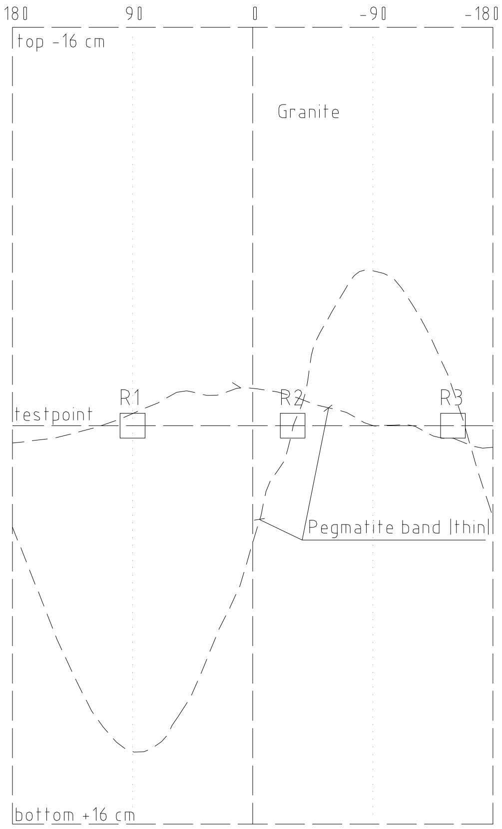
Top view



Use special tool to check that strain gauges are 120 degrees apart. Mark any deviations in the figure.

OVERCORE SAMPLE LOG

Borehole no., test no., depth : KFM07B, Test no. 1:2:1, 68.94 m depth



Angle clockwise in borehole direction
rosette 1 =+90 degrees
rosette 2 =-30 degrees
rosette 3 =-150 degrees

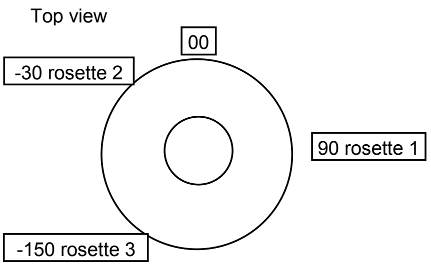
GEOLOGY

Granite

STRUCTURES (JOINTS)

Thin pegmatite bands.

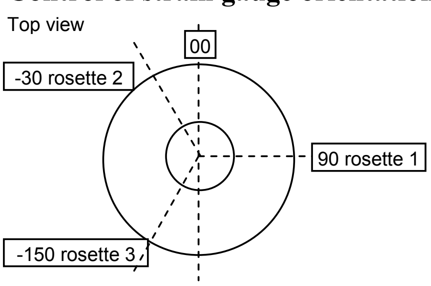
Mark any observed fractures



COMMENTS

Strain gauge orientation OK.

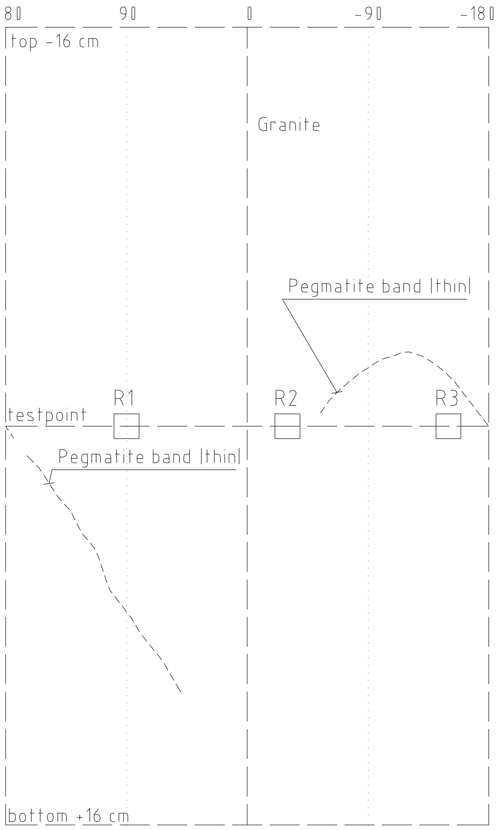
Control of strain gauge orientation



Use special tool to check that strain gauges are 120 degrees apart. Mark any deviations in the figure.

OVERCORE SAMPLE LOG

Borehole no., test no., depth : **KFM07B, Test no. 1:3:1, 70.09 m depth**



Angle clockwise in borehole direction
rosette 1 =+90 degrees
rosette 2 =-30 degrees
rosette 3 =-150 degrees

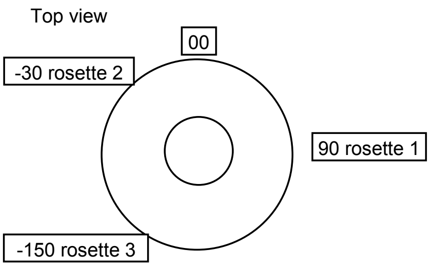
GEOLOGY

Granite

STRUCTURES (JOINTS)

Thin pegmatite bands.

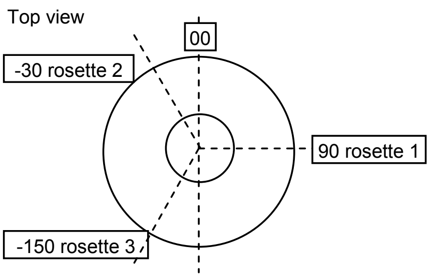
Mark any observed fractures



COMMENTS

Strain gauge orientation OK.

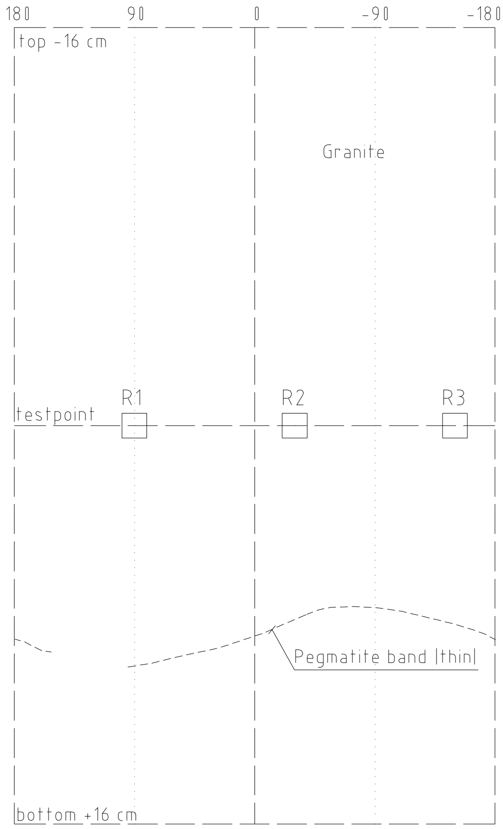
Control of strain gauge orientation



Use special tool to check that strain gauges are 120 degrees apart. Mark any deviations in the figure.

OVERCORE SAMPLE LOG

Borehole no., test no., depth : **KFM07B, Test no. 1:4:1, 71.00 m depth**



Angle clockwise in borehole direction
rosette 1 =+90 degrees
rosette 2 =-30 degrees
rosette 3 =-150 degrees

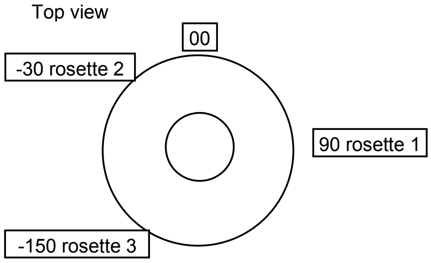
GEOLOGY

Granite

STRUCTURES (JOINTS)

Thin pegmatite band.

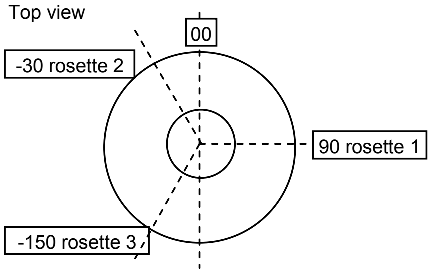
Mark any observed fractures



COMMENTS

Strain gauge orientation OK.

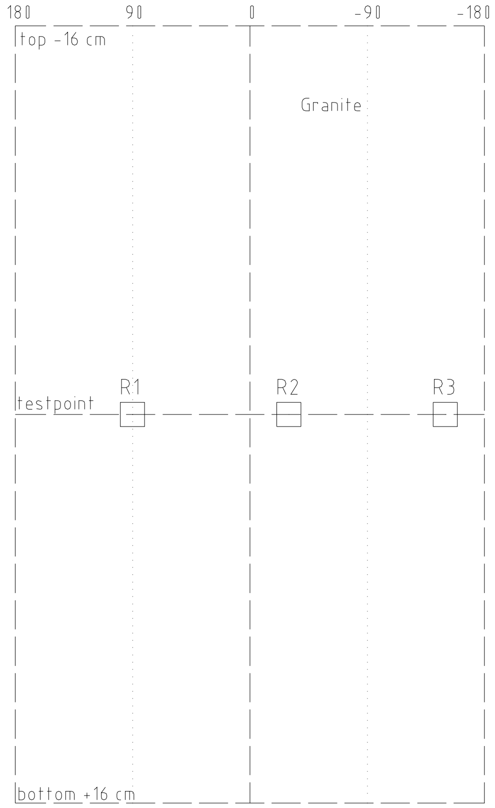
Control of strain gauge orientation



Use special tool to check that strain gauges are 120 degrees apart. Mark any deviations in the figure.

OVERCORE SAMPLE LOG

Borehole no., test no., depth : **KFM07B, Test no. 1:5:1, 72.45 m depth**



Angle clockwise in borehole direction
rosette 1 =+90 degrees
rosette 2 =-30 degrees
rosette 3 =-150 degrees

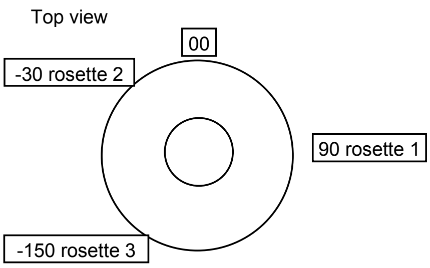
GEOLOGY

Granite

STRUCTURES (JOINTS)

No fractures before or after biaxial testing.

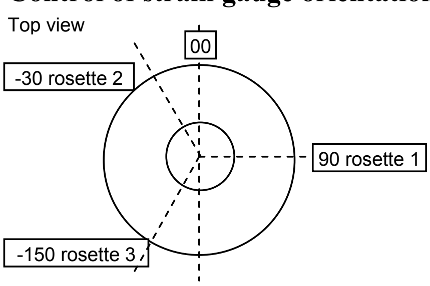
Mark any observed fractures



COMMENTS

Strain gauge orientation OK.

Control of strain gauge orientation

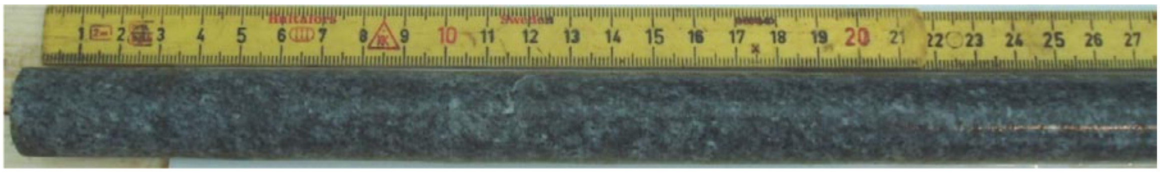


Use special tool to check that strain gauges are 120 degrees apart. Mark any deviations in the figure.

Appendix F

Photos of core samples

1:1:1, 67.91 m – pilot core



1:1:1, 67.91 m – overcore sample

1:2:1, 68.94 m – pilot core

1:2:1, 68.94 m – overcore sample

Figure F-1. *Photos of pilot core and overcore sample for borehole KFM07B, Level 1.*

1:3:1, 70.09 m – pilot core

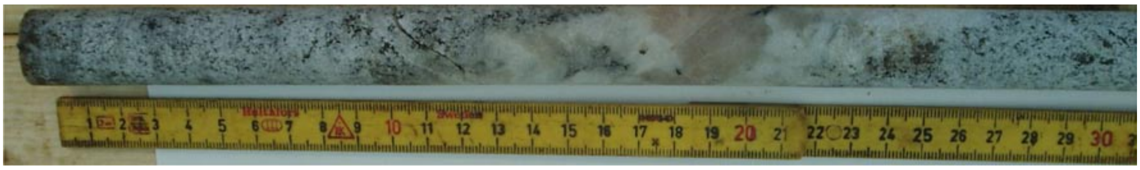
1:3:1, 70.09 m – overcore sample

1:4:1, 71.00 m – pilot core

1:4:1, 71.00 m – overcore sample

Figure F-1. (Continued.)

1:5:1, 72.45 m – pilot core



1:5:1, 72.45 m – overcore sample

Figure F-1. *(Concluded.)*

2:1:2, 150.91 m – pilot core

2:1:2, 150.91 m – overcore sample

2:2:1, 151.80 m – pilot core

2:2:1, 151.80 m – overcore sample (30 cm)

2:3:1, 152.83 m – pilot core

2:3:1, 152.83 m – overcore sample

Figure F-2. *Photos of pilot core and overcore sample for borehole KFM07B, Level 2.*

2:4:1, 153.74 m – pilot core

2:4:1, 153.74 m – overcore sample (30 cm)

2:5:1, 156.53 m – pilot core

2:5:1, 156.53 m – overcore sample

2:6:1, 157.53 m – pilot core

2:6:1, 157.53 m – overcore sample

Figure F-2. *(Continued.)*

2:7:1, 158.66 m – pilot core

2:7:1, 158.66 m – overcore sample

2:8:1, 159.64 m – pilot core

2:8:1, 159.64 m – overcore sample

Figure F-2. *(Concluded.)*

3:1:1, 221.11 m – pilot core

3:2:2, 225.49 m – pilot core (30 cm)

3:2:2, 225.49 m – overcore sample

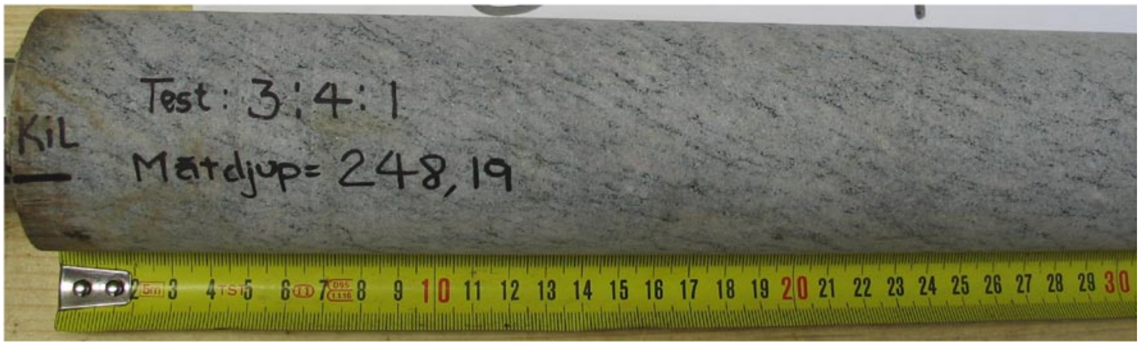
3:3:4, 247.18 m – pilot core

3:3:4, 247.18 m – overcore sample (30 cm)

Figure F-3. *Photos of pilot core and overcore sample for borehole KFM07B, Level 3.*

3:4:1, 248.19 m – pilot core

3:4:1, 248.19 m – overcore sample



3:5:1, 251.89 m – pilot core

3:5:1, 251.89 m – overcore sample

Figure F-3. *(Concluded.)*

Appendix G

Confidence intervals for measured stresses

Table G-1. 90%-confidence intervals for the principal stresses as determined from overcoring measurements in borehole KFM07B.

Level		Magnitude and Trend/Plunge of principal stresses					
		σ_1		σ_2		σ_3	
		[MPa]	[°]	[MPa]	[°]	[MPa]	[°]
Level 1	Average	7.3	048/12	6.9	282/70	2.2	141/16
	90% lower	6.0	*)	1.5	*)	–5.2	*)
	90% upper	15.7		10.5		4.2	

*) Orientation data not presented since neither 90% nor 95% confidence intervals could encompass all single measurements.

Table G-2. 90%-confidence intervals for the horizontal and vertical stress components as determined from overcoring measurements in borehole KFM07B.

Level		σ_H [MPa]	σ_h [MPa]	σ_v [MPa]	Trend σ_H [°]
Level 1	Average	7.3	2.6	6.6	051
	90% lower	3.7	–4.0	–0.2	*)
	90% upper	13.8	6.0	13.4	

*) Orientation data not presented since neither 90% nor 95% confidence intervals could encompass all single measurements.

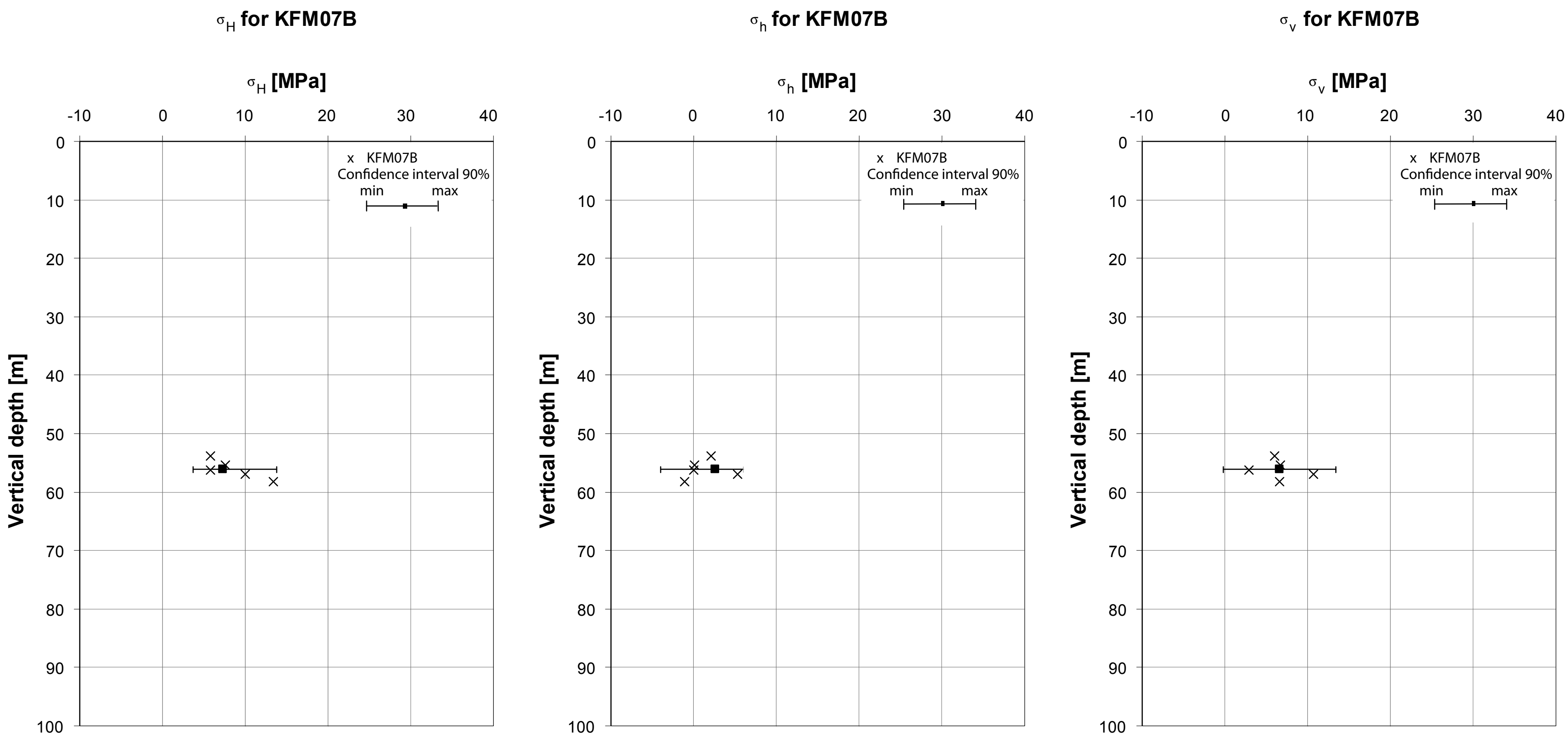


Figure G-1. Average values (■-markers) and 90%-confidence intervals (├──┤) for the horizontal and vertical stress components, shown together with measured values for each measurement level (x-markers) in borehole KFM07B.

Appendix H

Quality operating procedures for overcoring measurements

The following quality operating procedures are adhered to when conducting overcoring rock stress measurements using the Borre probe. A complete description of each procedure with adjoining checklists, can be obtained (on request) from the measurement contractor.

Pre-mobilization equipment assembly and checking

- Strain gauges assembly.
  – Visual check of geometry.
  – Check of glued parts.
  – Visual check of wires and resistance measurement.
- Glue test on new batches.
- Computer and software.
- Packing and transport.
  – Equipment.
  – Consumable supplies.

Mobilization

- Mobilization on site.
- Drilling contractor contacts, instructions for operation, etc.
- Function test of the Borre probe.
- Function test of biaxial load cell and pump.
- Function test of installation tool (adapter).
- Function test of computer and computer programs.
- Glue test (if required by the client).
- Function test and control of drilling equipment.

Overcoring stress measurement procedure

- Pilot hole drilling and examination.
  – Planing and drilling of pilot hole.
  – Examination of pilot core and decision on installation (or not).
  – Flushing and checking the pilot hole with dummy probe.
- Preparation of the Borre-cell.
  – Attaching strain gauges, including resistance check and geometry check.
  – Function test of Borre probe with attached gauges.
- Installation of Borre probe.
  – Function test of installation tool (adapter).
  – Glue application including thickness and application check.
- Overcoring.
  – Check glue hardening time.
  – Check that no activity is on-going in the borehole.
  – Retrieval of adapter.
  – Drill string in place and marked every 4 cm (0–32 cm).
  – Flushing and overcoring activities according to specification list.
  – Retrieval of drill string and Borre probe.

- Recovery of the Borre probe.
  – Orientation of probe installation recorded.
  – Data collection (transfer to computer from logger).
- Logging and photography of overcore sample.
- Biaxial testing of the overcore sample.
  – Test setup and programming of logger (Borre probe).
  – Biaxial testing.
  – Data collection (transfer to computer from logger).
  – Logging of overcore sample after biaxial testing.

Evaluation and analysis

- Plotting of overcoring and biaxial test data on computer.
- Data assessment (reliability, sources of error, rating).
- Stress calculation for successful measurements; average stresses calculated for each measurement level.
- Continuous reporting to client.

Demobilization

- Packing and transport.

Final reporting

- Complementary data assessment and rating of tests.
- Final stress calculation.
- Transient strain analysis on selected tests.
- Calculation of final stress averages.
- Final reporting to client.