

Arbeitsbericht NAB 21-22

**TBO Bözberg-2-1:
Data Report**

**Dossier IX
Rock-mechanical and
Geomechanical Laboratory Testing**

April 2022

**National Cooperative
for the Disposal of
Radioactive Waste**

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**Dossier IX
Rock-mechanical and
Geomechanical Laboratory Testing**

April 2022

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triaxial tests, oedometric tests

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Nagra Arbeitsberichte ("Working Reports") present the results of work in progress that have not necessarily been subject to a comprehensive review. They are intended to provide rapid dissemination of current information.

This NAB aims at reporting drilling results at an early stage. Additional borehole-specific data will be published elsewhere.

In the event of inconsistencies between dossiers of this NAB, the dossier addressing the specific topic takes priority. In the event of discrepancies between Nagra reports, the chronologically later report is generally considered to be correct. Data sets and interpretations laid out in this NAB may be revised in subsequent reports. The reasoning leading to these revisions will be detailed there.

This Dossier was prepared by a project team consisting of:

E. Crisci (test coordination, formal analysis, QC and writing)

S. Giger (project administration, conceptualisation and writing)

L. Laloui (review and supervision)

The present report was prepared based on numerous contractor reports, to which many people from different laboratories contributed, namely B. Bohli, K. Halvorsen, J. Stenebråten, R. Stankovic, V. Vajdova, R. Ewy, A. Ferrari, M. Rosone, H. Baumgartner, S. Louis and J. Menningen.

Editorial work: P. Blaser and M. Unger

The Dossier has greatly benefitted from technical discussions with external and internal experts. Their input and work are very much appreciated.

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1 Introduction

1.1 Context

To provide input for site selection and the safety case for deep geological repositories for radioactive waste, Nagra has drilled a series of deep boreholes ("Tiefbohrungen", TBO) in Northern Switzerland. The aim of the drilling campaign is to characterise the deep underground of the three remaining siting regions located at the edge of the Northern Alpine Molasse Basin (Fig. 1-1).

In this report, we present the results from the Bözberg-2-1 borehole.

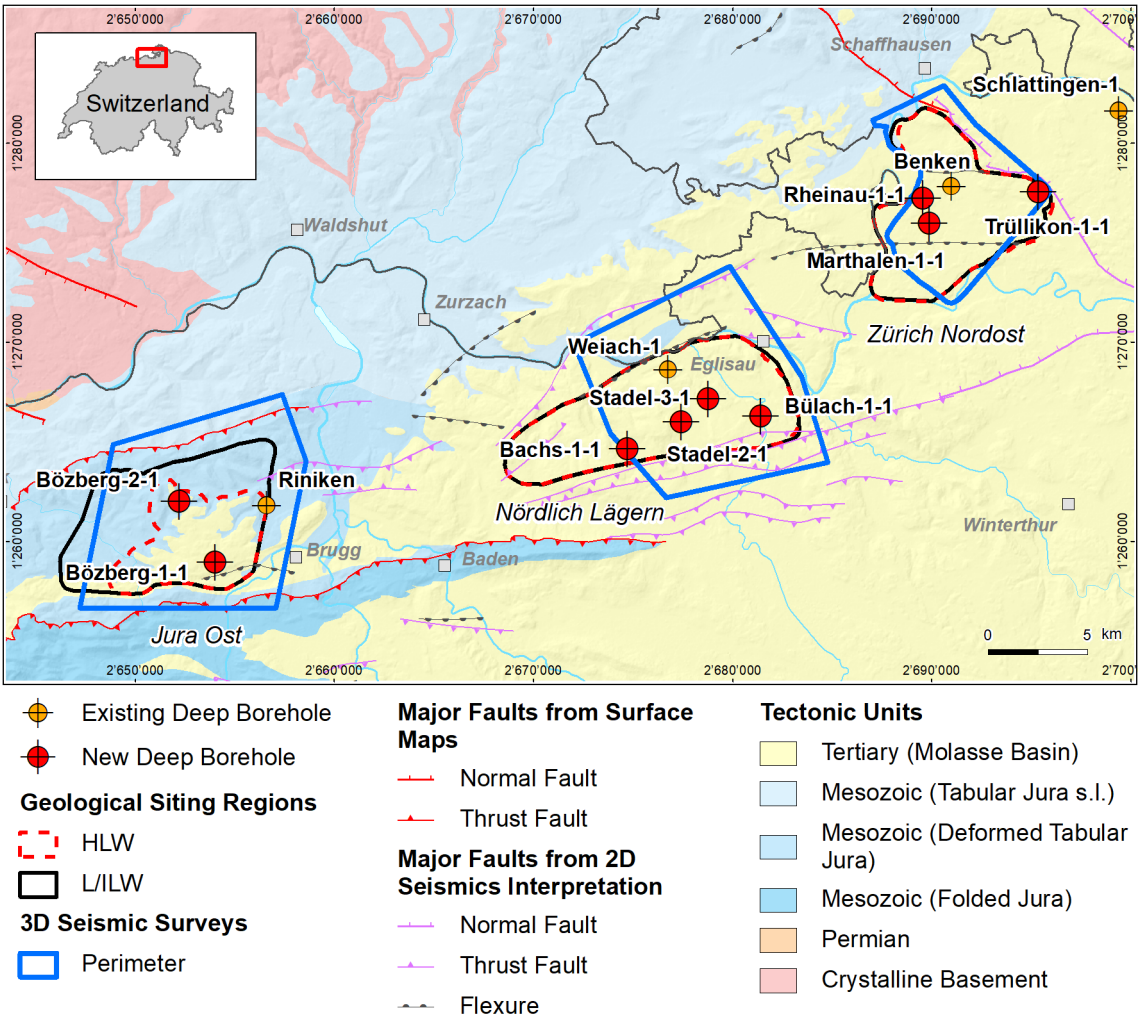


Fig. 1-1: Tectonic overview map with the three siting regions under investigation

1.2 Location and specifications of the borehole

The Bözberg-2-1 (BOZ2-1) exploratory borehole is the fifth borehole drilled within the framework of the TBO project. The drill site is located in the northern part of the Jura Ost siting region (Fig. 1-2). The vertical borehole reached a final depth of 829.11 m (MD)¹. The borehole specifications are provided in Tab. 1-1.

Tab. 1-1: General information about the BOZ2-1 borehole

Siting region	Jura Ost
Municipality	Bözberg (Canton Aargau / AG), Switzerland
Drill site	Bözberg-2 (BOZ2)
Borehole	Bözberg-2-1 (BOZ2-1)
Coordinates	LV95: 2'652'218.764 / 1'261'985.437
Elevation	Ground level = top of rig cellar: 624.33 m above sea level (asl)
Borehole depth	829.11 m measured depth (MD) below ground level (bgl)
Drilling period	11th August – 14th December 2020 (spud date to end of rig release)
Drilling company	Daldrup & Söhne AG
Drilling rig	Wirth B 152t
Drilling fluid	Water-based mud with various amounts of different components such as ² : 0 – 370 m: Bentonite & polymers 370 – 615 m: Potassium silicate & polymers 615 – 829.11 m: Pure-Bore®

The lithostratigraphic profile and the casing scheme are shown in Fig. 1-3. The comparison of the core versus log depth³ of the main lithostratigraphic boundaries in the BOZ2-1 borehole is shown in Tab. 1-2.

¹ Measured depth (MD) refers to the position along the borehole trajectory, starting at ground level, which for this borehole is the top of the rig cellar. For a perfectly vertical borehole, MD below ground level (bgl) and true vertical depth (TVD) are the same. In all Dossiers depth refers to MD unless stated otherwise.

² For detailed information see Dossier I.

³ Core depth refers to the depth marked on the drill cores. Log depth results from the depth observed during geophysical wireline logging. Note that the petrophysical logs have not been shifted to core depth, hence log depth differs from core depth.

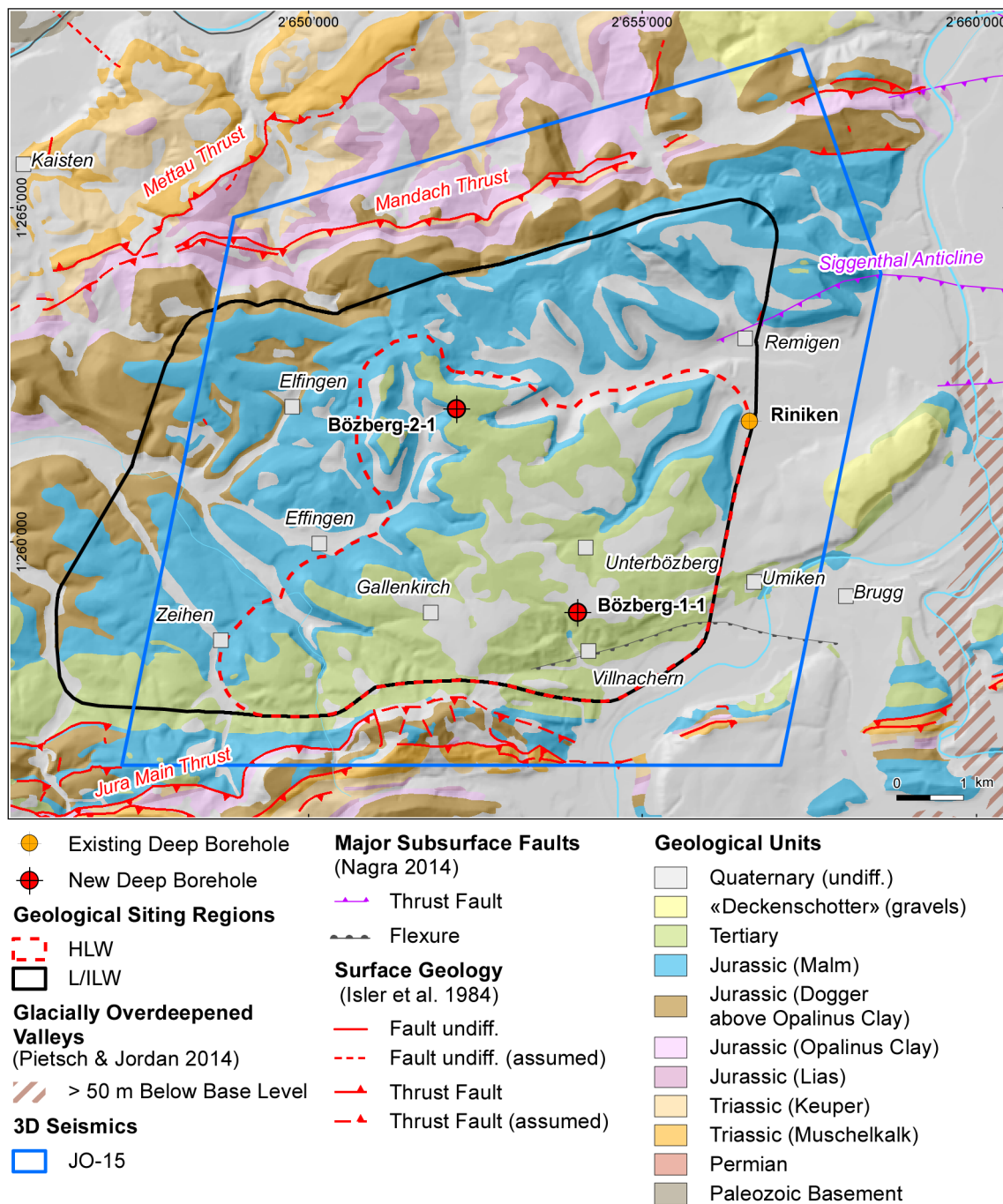


Fig. 1-2: Overview map of the investigation area in the Jura Ost siting region with the location of the BOZ2-1 borehole in relation to the boreholes Riniken and BOZ1-1

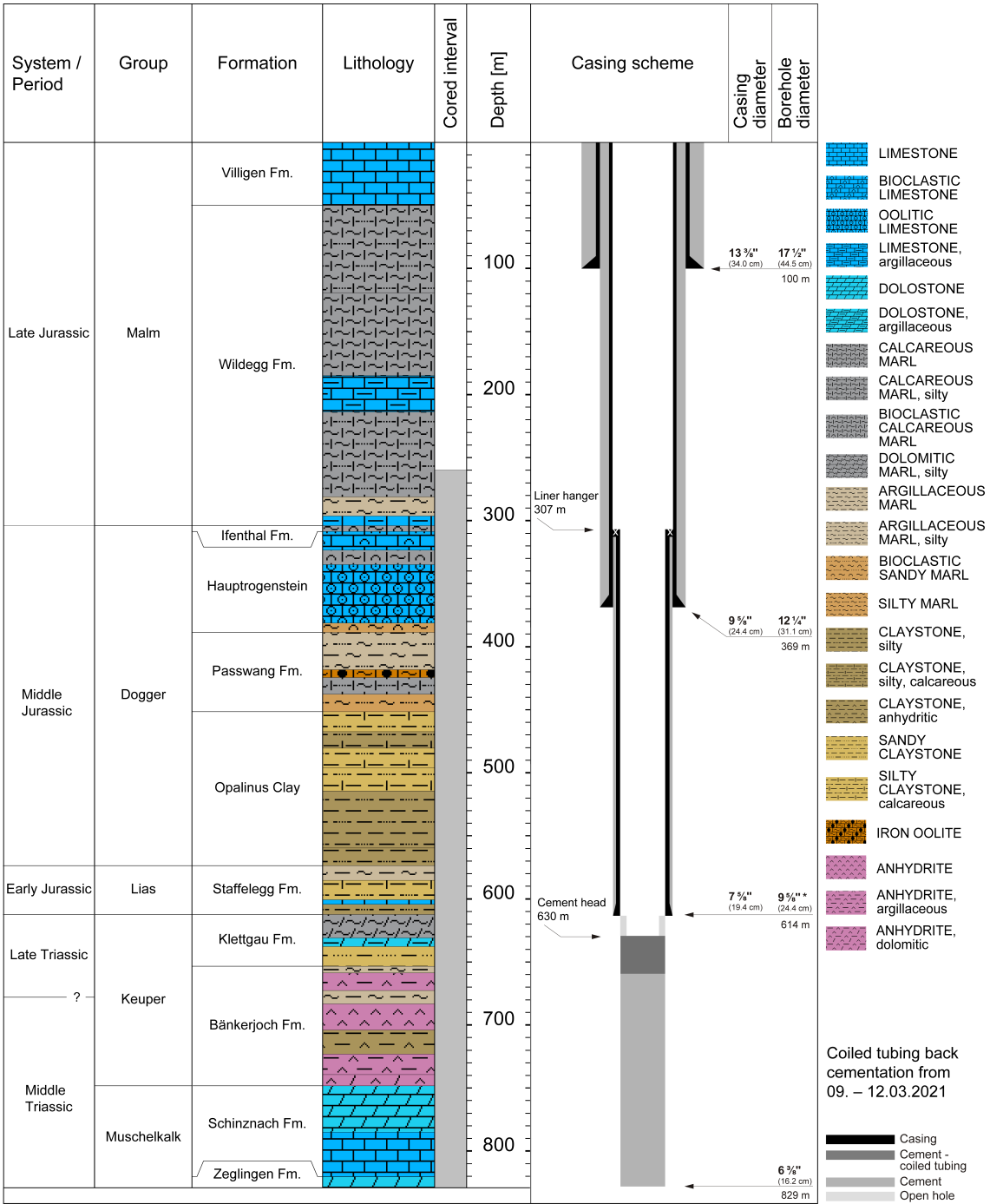


Fig. 1-3: Lithostratigraphic profile and casing scheme for the BOZ2-1 borehole⁴

⁴ For detailed information see Dossier I and III.

Tab. 1-2: Core and log depth for the main lithostratigraphic boundaries in the BOZ2-1 bore-hole⁵

System / Period	Group	Formation	Core depth in m (MD)	Log
Jurassic	Malm	Villigen Formation	50.0	—
		Wildeggen Formation	303.95	304.38 —
	Dogger	Ifenthal Formation	308.70	309.07 —
		Hauptrogenstein	388.54	388.97 —
		Passwang Formation	451.54	451.90 —
		Opalinus Clay	573.68	573.89 —
	Lias	Staffellegg Formation	612.46	612.76 —
Triassic	Keuper	Klettgau Formation	653.45	654.70 —
		Bänkerjoch Formation	748.27	749.52 —
		Schinznach Formation	820.32	821.09 —
	Muschelkalk	Zeglingen Formation	829.11	829.88 —
			final depth	

⁵ For details regarding lithostratigraphic boundaries see Dossier III and IV; for details about depth shifts (core goniometry) see Dossier V.

1.3 Documentation structure for the BOZ2-1 borehole

NAB 21-22 documents the majority of the investigations carried out in the BOZ2-1 borehole, including laboratory investigations on core material. The NAB comprises a series of stand-alone dossiers addressing individual topics and a final dossier with a summary composite plot (Tab. 1-3).

This documentation aims at early publication of the data collected in the BOZ2-1 borehole. It includes most of the data available approximately one year after completion of the borehole. Some analyses are still ongoing (e.g. diffusion experiments, analysis of veins, hydrochemical interpretation of water samples) and results will be published in separate reports.

The current borehole report will provide an important basis for the integration of datasets from different boreholes. The integration and interpretation of the results in the wider geological context will be documented later in separate geoscientific reports.

Tab. 1-3: List of dossiers included in NAB 21-22

Black indicates the dossier at hand.

Dossier	Title	Authors
I	TBO Bözberg-2-1: Drilling	P. Hinterholzer-Reisegger
II	TBO Bözberg-2-1: Core Photography	D. Kaehr & M. Gysi
III	TBO Bözberg-2-1: Lithostratigraphy	P. Jordan, P. Schürch, H. Naef, M. Schwarz, R. Felber, T. Ibele & M. Gysi
IV	TBO Bözberg-2-1: Microfacies, Bio- and Chemostratigraphic Analyses	S. Wohlgwend, H.R. Bläsi, S. Feist-Burkhardt, B. Hostettler, U. Menkveld-Gfeller, V. Dietze & G. Deplazes
V	TBO Bözberg-2-1: Structural Geology	A. Ebert, L. Gregorczyk, S. Cioldi, E. Hägerstedt & M. Gysi
VI	TBO Bözberg-2-1: Wireline Logging, Micro-hydraulic Fracturing and Pressure-meter Testing	J. Gonus, E. Bailey, J. Desroches & R. Garrard
VII	TBO Bözberg-2-1: Hydraulic Packer Testing	R. Schwarz, M. Willmann, S. Reinhardt, S.M.L. Hardie, M. Voß & A. Pechstein
VIII	TBO Bözberg-2-1: Rock Properties, Porewater Characterisation and Natural Tracer Profiles	T. Gimmi, L. Aschwanden, L. Camesi, E. Gaucher, A. Jenni, M. Kiczka, U. Mäder, M. Mazurek, D. Rufer, H.N. Waber, P. Wersin, C. Zwahlen & D. Traber
IX	TBO Bözberg-2-1: Rock-mechanical and Geomechanical Laboratory Testing	E. Crisci, L. Laloui & S. Giger
X	TBO Bözberg-2-1: Petrophysical Log Analysis	S. Marnat & J.K. Becker
	TBO Bözberg-2-1: Summary Plot	Nagra

1.4 Scope and objectives of this dossier

The dossier at hand is organised as follows:

- Chapter 2 presents the aims of the laboratory testing programmes and introduces the laboratories involved.
- Chapter 3 provides an overview of core sampling, conditioning and storage methods, and also explains the non-destructive method used to evaluate core integrity prior to shipping to the laboratories.
- Chapter 4 introduces the testing methods used in the testing programmes and provides an overview of the executed tests per formation.
- Chapter 5 documents the results of the rock-mechanical testing programme.
- Chapter 6 documents the triaxial and the oedometric test results of the geomechanical testing programme. Given the greater complexity of the testing procedure and the relevance of the test results for site evaluation, these test results are more rigorously documented than the rock-mechanical test results.
- A short discussion on the representativeness of the results is provided in Chapter 7.

Furthermore, large documentation of the performed tests is reported in the appendix, and includes:

A – Photo documentation of the rock-mechanical testing programme

B – XCT (medical X-ray tomography) cross-sections, with indication of the section used for geomechanical testing

C – Diagnostic plots of the triaxial tests (geomechanical testing programme)

D – Mineralogical analysis (geomechanical testing programme)

E – Triaxial test results (geomechanical testing programme)

F – Test results in oedometric conditions (geomechanical testing programme)

2 Aims of the study and overview of the testing programme

2.1 Aims of the study and distinction of rock-mechanical and geomechanical testing programmes

For site characterisation, rock-mechanical and geomechanical properties are used for the following applications:

1. Supporting data for the detailed analysis and interpretation of in situ micro-hydraulic fracturing tests
2. Parametrise 3D geomechanical numerical models with (sub-)formation properties to assess the spatial variability of the stress tensor
3. Design of underground repository access structures
4. Hydro-mechanical properties of the host rock Opalinus Clay and its confining units
5. Volumetric behaviour (consolidation and swelling) and hydraulic properties of the host rock Opalinus Clay and its confining units

To address points 1. to 3. «standard» rock-mechanical tests were performed on core material in the stratigraphic interval Malm to Rotliegend, except for Opalinus Clay. «Standard» here means that the tests were performed according to national and international standards, notably the suggested methods of the International Society of Rock Mechanics (*cf.* Section 4.2). Standard tests were performed within the **"rock-mechanical testing programme"**.

In contrast, laboratory testing under points 4. and 5. were conducted using specialised protocols (*cf.* Section 4.3) combining rock-mechanical and soil mechanical aspects. Specifically, these protocols account for 1) the higher requirements of the low-permeability and fluid-sensitive Opalinus Clay and its argillaceous confining units to obtain robust test results, and 2) for the greater relevance of these units to evaluate the safety of a future repository. Tests performed using the specialised protocols are hereafter assigned to the **"geomechanical testing programme"**.

2.2 Overview of testing programme and contractors

2.2.1 Rock-mechanical testing programme

The rock-mechanical testing programme with core material of the BOZ2-1 borehole comprised the following testing methods:

- Indirect tensile strength (Brazilian)
- Uniaxial compressive strength (UCS)
- Triaxial compressive strength (TRX)

The following laboratory was contracted:

- Gesteinslabor Dr. Eberhard Jahns (Germany). Main contacts were Hansjörg Baumgartner, Sarah Louis and Johanna Menningen.

2.2.2 Geomechanical testing programme

The geomechanical testing programme was specifically designed for Opalinus Clay and its confining units and comprised of the following testing methods with cores from the BOZ2-1 borehole:

- Triaxial deformation tests with various stress paths (TRX)
- High-pressure oedometric testing (OED), including for some tests constant-head permeability phases (PERM)
- One-dimensional swelling tests (OS), carried out in oedometric conditions, either allowing axial swelling in free stress conditions or at constant stress

Three laboratories were contracted for the geomechanical testing campaign:

- NGI (Norway), main contacts were Bahman Bohloli and Kristine Halvorsen
- Sintef (Norway), main contact was Jørn Stenebråten
- RSTD (USA), main contacts were Rudy Stankovic and Russ Ewy
- DI (Italy), main contact was Alessio Ferrari

Each laboratory is identified with a letter, used in the test results labelling (A = NGI, B = Sintef, C = RSTD, D = DI).

Specialised protocols were developed in recent years to evaluate hydro-mechanical properties of Opalinus Clay in both high-pressure oedometric tests (Favero 2017, Ferrari et al. 2016, Crisci et al. 2019) and triaxial deformation tests (Favero et al. 2018, Giger et al. 2018). In the case of triaxial testing, the testing procedures were further validated in a benchmarking study (Minardi et al. 2019, Minardi et al. 2020).

3 Core sampling, storage and XCT scanning

3.1 Core sampling and conditioning

Cores used for geomechanical or rock-mechanical analyses (hereafter referred to as GM cores) represent one of nine major categories sampled at the borehole. Each of these categories has special requirements to minimise potential effects on laboratory analyses, and hence special conditioning methods. Target exposure time to atmosphere was set to 20 minutes for all GM cores to allow geological description and documentation (incl. core scanner for photographic description). A complete archive of core photographs, and exposure time to atmosphere prior to embedding the cores in resin is made in Nagra's internal QA/QC documentation.



Fig. 3-1: Sampling and storage workflow of GM cores

(a) Inserting core directly into PVC tube (no plastic film). (b) Rack of PVC tubes during curing with clamp bar in core at the front row (left side). (c) Labelled PVC tubes with core and top spacer (used for clamping) embedded in epoxy resin. (d) Custom made core box used for transporting and archiving. Example pictures are from borehole Bülach-1-1 (Nagra 2021a).

The cores were then immediately inserted in PVC tubes, and axially constrained with bar clamps (Fig. 3-1). The annulus was then filled with epoxy (Sikadur-52). The annulus between the core and the PVC tube was chosen to be very small (nominal 3.2 mm) to ensure that no excessive temperature from curing of the epoxy develops⁶. Further details of the conditioning procedure are provided in the field manual (Rufer 2019).

A total of 73 GM cores with a cumulative length of 33 metres were conditioned in this way. Additional 2 cores were sampled later at the core storage facility. This was done to enable permeability testing to complement the in situ testing programme (hydraulic packer tests in the Klettgau Formation) where no conditioned core was secured, and only for hard rocks not sensitive to water exchange (drying).

3.2 Evaluation of core quality using XCT Scanning

To evaluate core integrity prior to shipping to the testing laboratories, all GM cores from Opalinus Clay and its confining units in the Upper Dogger and Lias (Staffelegg Formation) were analysed using medical X-ray computer tomography (XCT). Details of the applied XCT method can be found in Keller & Giger (2019). The obtained image data had a voxel size of $0.25 \times 0.25 \times 0.4$ mm. By stacking individual scans, a virtual cross-section could be obtained for each core (Fig. 3-2). It is noted that the CT-number is a proxy for material density. This enabled the detection of small cracks and a physical representation of the variability of material properties. These cross-sections were the basis for the selection of sub-coring for the geomechanical testing programme (Chapter 6 and Appendix B).

⁶ Maximum measured temperature in the laboratory was <27 °C.

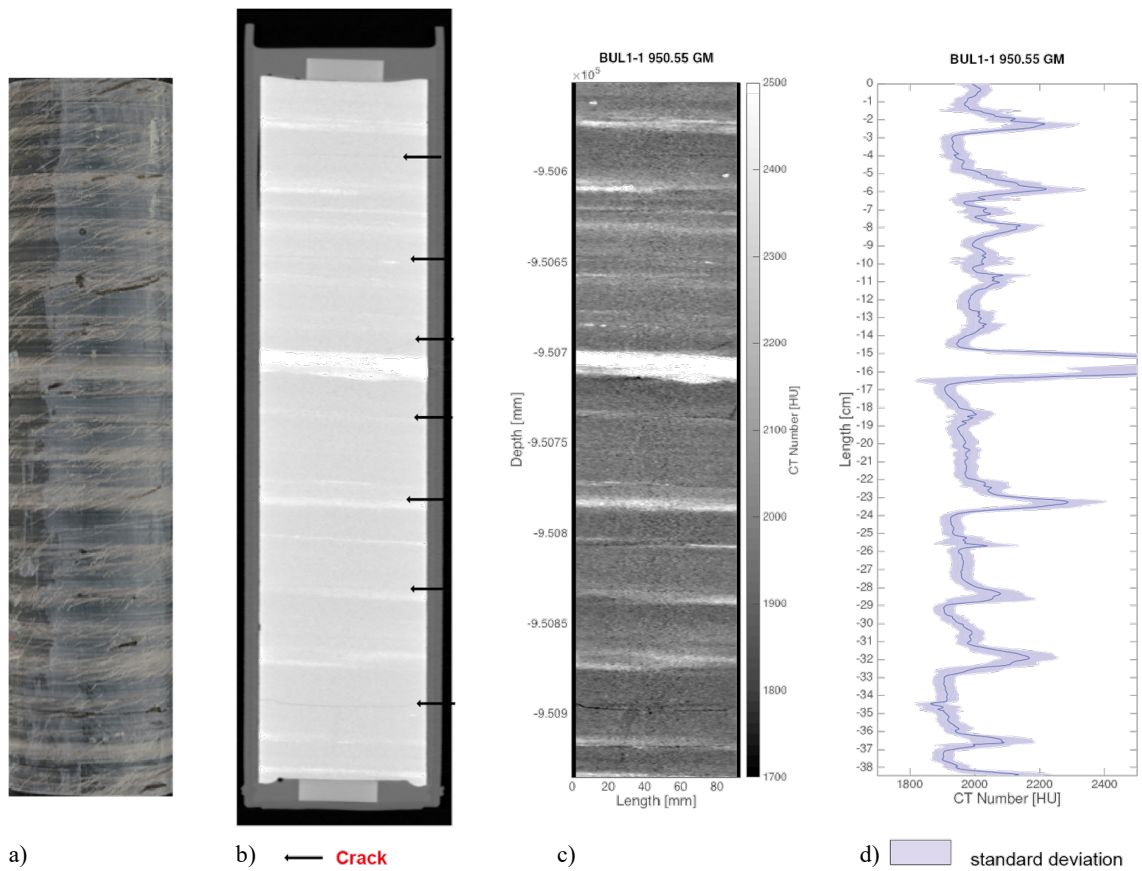


Fig. 3-2: Cross-section of XCT stack

(a) core picture; (b) entire core in PVC tube and resin (both dark grey) and embedded spacers (light grey – subhorizontal cracks are indicated by arrows); (c) optimised image for the core only; (d) vertical profile with CT number (Hounsfield Units). Example pictures are from borehole Bülach-1-1 (Nagra 2021a).

4 Testing methods and overview of executed tests

4.1 Convention of sample geometry

Sedimentary geomaterials typically display transversely isotropic mechanical properties which are related to the orientation of the bedding. To study this anisotropic response, cylindrical specimens were tested in three orientations with respect to bedding (Fig. 4-1).

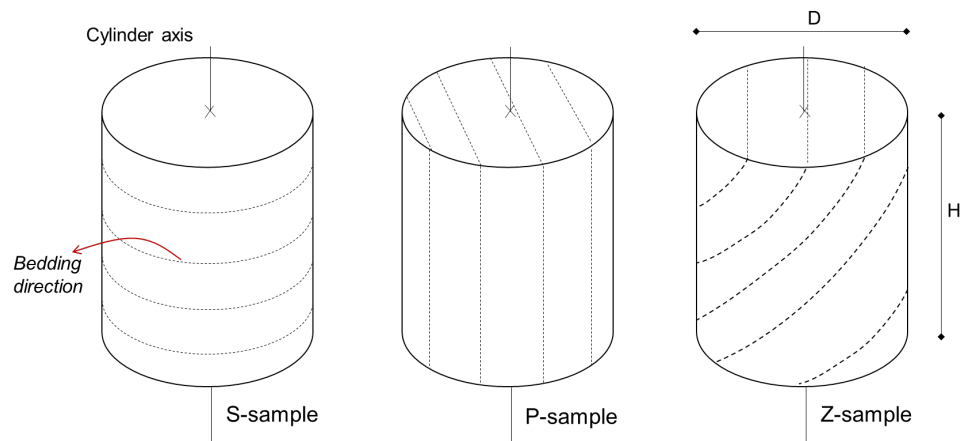


Fig. 4-1: Terminology of specimens in relation to bedding orientation

In this report, the following convention applies:

- S-samples: the cylinder axis is perpendicular to bedding direction
- P-samples: the cylinder axis is parallel to bedding direction
- Z-samples: the cylinder axis is at an angle with respect to bedding.

The convention applies to all kind of tests, however the ratio of diameter (D) to height (H) of the specimen is different. The ratio ranges from $D:H \approx 1/2$ for triaxial and uniaxial tests, to $D:H \approx 1.4$ in Brazilian tests and $D:H \approx 2.5$ for oedometric tests.

4.2 Rock-mechanical testing programme – testing methods

4.2.1 Indirect tensile strength test (Brazilian)

The Brazilian test is a uniaxial compressive strength test aimed for the indirect determination of tensile strength, and tests were done according to ASTM standard D3967-16 (ASTM 2016).

Test specimens have a diameter of 30 mm and a width of 21 mm (thickness:diameter ratio of 0.70). Testing plugs were drilled either perpendicular to bedding (so-called "S" direction) or parallel to bedding (so-called "P" direction). The plugs were drilled with a diamond tipped hollow bit. Cooling during drilling and trimming was performed with the low viscous volatile mineral oil Ilocut EDM 180 (from Castrol). Plug trimming to the required length was carried out with a diamond chop saw with slow constant velocity feeding.

During the test, cylindrical specimens are loaded perpendicular to the cylinder axis (Fig. 4-2). For clarification, it is noted that loading was always done perpendicular to the core axis. In case of the P-samples (Fig. 4-1) loading was parallel to bedding and the tensile force perpendicular to bedding. In case of the S-samples loading and tensile force are both parallel to bedding.

The constant loading rate during testing was approximately 0.30 MPa/s. In case of the P-samples (*cf.* Section 4.1) the specimen was oriented such that loading was parallel to bedding, with the tensile force, consequently, acting perpendicular to bedding. In case of the S-samples loading and tensile force are both perpendicular to bedding. The Brazilian tests were carried out on a high precision digitally controlled electromechanical testing machine with a maximum load range of 100 kN (accuracy class 0.5).

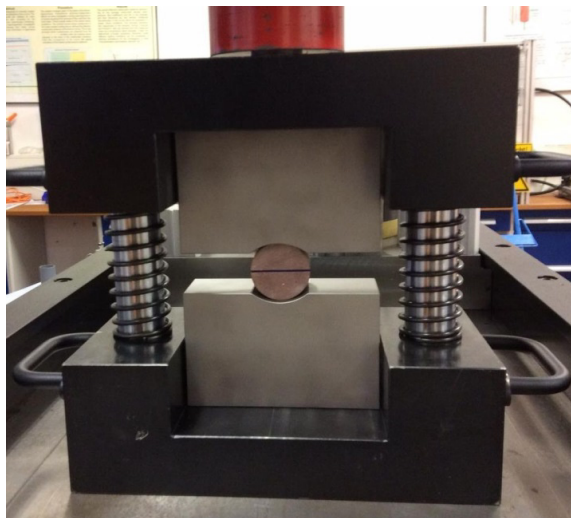


Fig. 4-2: Brazilian testing configuration with curved jaws
Plug diameter is 30 mm.

4.2.2 Unconfined compressive strength test

Unconfined compressive strength (UCS) tests were done according to ASTM standard D7012-14e1 (ASTM 2014).

Test specimens have a diameter of 25.4 mm and a length of at least 50.8 mm (length:diameter ratio of 2:1). Testing plugs were drilled either perpendicular to bedding (so-called "S" direction) or parallel to bedding (so-called "P" direction). The plugs were drilled with a diamond tipped hollow bit. Cooling during drilling and trimming was performed with the low viscous volatile mineral oil Ilocut EDM 180 (Castrol). Plug trimming to the required length was carried out with a diamond chop saw with slow constant velocity feeding. The accuracy in plane parallelism is in accordance with ASTM D4543-19 (ASTM 2019).

The UCS tests were performed on a digitally controlled, servo-hydraulic testing machine with a maximum load range of 600 kN (accuracy class 1) and at a constant strain rate of approximately 10^{-5} s^{-1} .

Axial deformation of the specimen was measured with either one or two LVDT displacement transducers. Measurements were either done directly at the specimen or corrected for load frame deformation. Radial deformation of the specimen is measured diametric with a transverse extensometer (Fig. 4-3).

Throughout this report, the strains are calculated as the ratio of the variation in height (or diameter) to the initial height (or diameter).

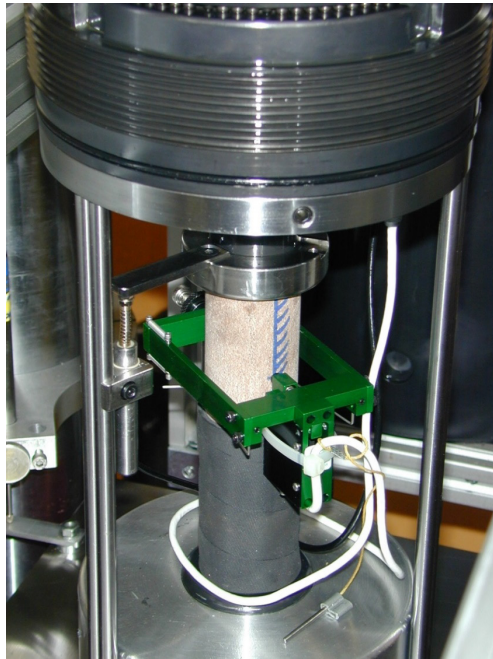


Fig. 4-3: UCS testing configuration

Note axial LVDT and transverse extensometer. Specimen diameter is 25.4 mm.

4.2.3 Triaxial deformation test

Triaxial deformation tests (TRX) were done according to ASTM standard D7012-14e1 (ASTM 2014) for single-stage procedure, but also included a hysteresis cycle (unloading/reloading) before peak strength (below).

Test specimens have the same dimensions as for the UCS tests (diameter 25.4 mm, length 50.8 mm) and were prepared in the same manner (*cf.* Section 4.2.2). The accuracy in plane parallelism is also in accordance with ASTM D4543-19 (ASTM 2019).

Axial (average of three LVDTs) and radial deformation of the specimen (diametric with one single strain gauge) were measured 'in-vessel' to avoid the load frame deformation being included in the results of the deformation of the individual specimen (Fig. 4-4). The measurement range of the LVDTs is ± 5 mm; their sensitivity in the range between 9 and 60 mV; non-linearity is 0.15% full scale. Three LVDTs were used to observe specimen distortions that may influence the strength measurements in a non-acceptable manner. The differential axial load (strain gauge) also was measured 'in vessel' with a load cell mounted directly below the specimen to eliminate the influence of piston friction effects to the stress measurement. A 600 kN load cell of accuracy class 0.5 was used for the tests.

The artificial brine was composed of demineralised water and 5 g/l NaCl. Exceptions were the anhydrite specimens in tests BOZ2-1-670TRX_S2 and BOZ2-1-696TRX_S1 for which no fluid was used. The pistons are perforated to enable drained conditions. Side drains were not used. No spherical seats were used. All the important parameters were recorded automatically with different intervals, adjusted to expected speed of changes. No smoothing or filtering algorithms were applied.

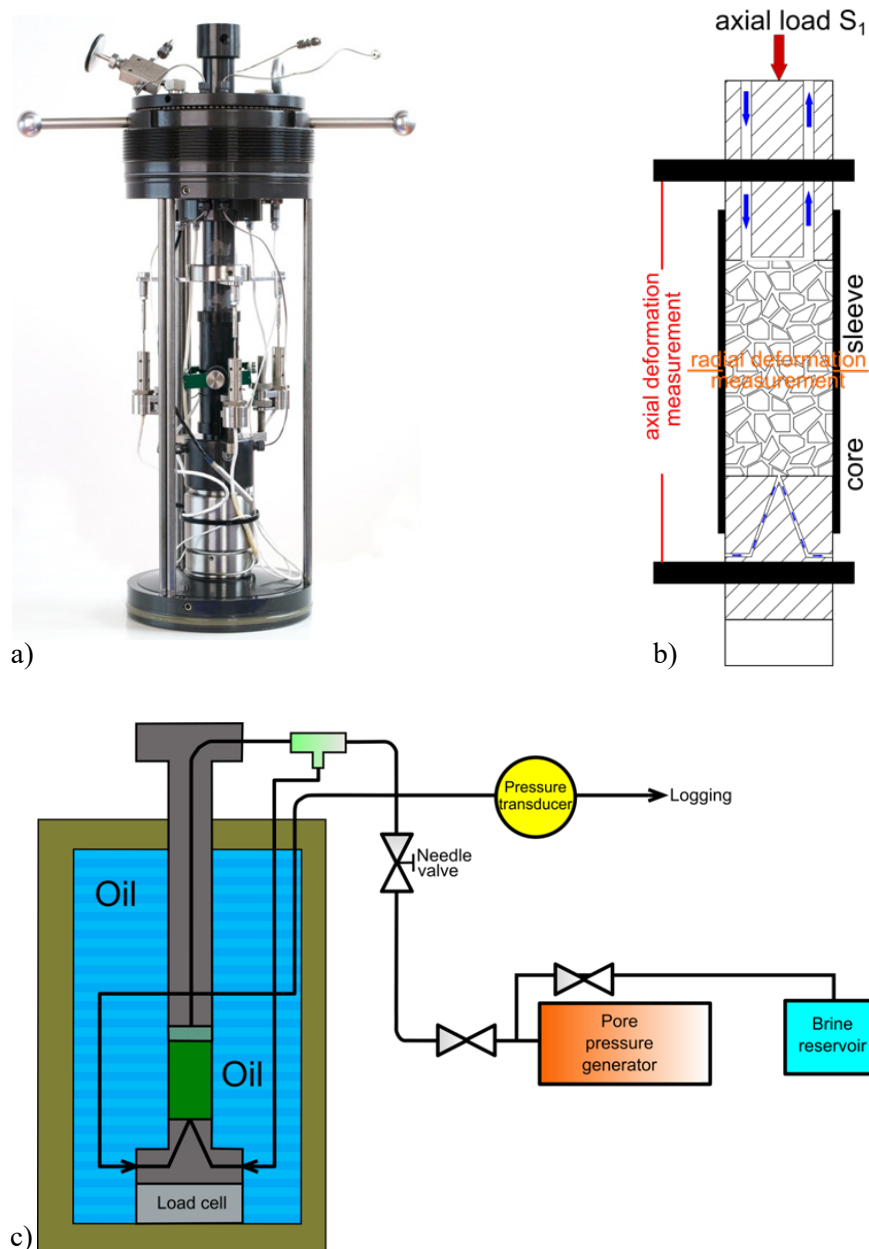


Fig. 4-4: Triaxial testing configuration used for rock-mechanical testing

Specimen in membrane with axial and radial strain sensors, pore fluid line and ultrasonics (a), schematic of the specimen (b) and the pressure cell with pore fluid system (c).

During all phases of the tests, ultrasonic velocities, both P- and S-waves, were logged and monitored according to ISRM standards (Aydin 2014). The piezometer resonance frequency was 1 MHz.

The theoretically possible stress paths in a triaxial testing configuration with two independent controls (axial and radial stress) are illustrated in Fig. 4-5 in mean total stress (p) versus deviatoric stress (q) space, where:

$$p = \frac{\sigma_a + 2\sigma_r}{3} \quad (4-1)$$

$$q = \sigma_a - \sigma_r \quad (4-2)$$

Where σ_a and σ_r are the total axial (direction of the cylinder axis) and radial (direction perpendicular to the cylinder axis) stress, respectively.

The upper part of the plane (compression part) summarises the stress paths that induce axial compression of the tested specimen. The shear path can be induced by either increasing the axial stress σ_a (CTC path), reducing the radial stress σ_r (RTC path) or increasing σ_a and reducing σ_r at the same time (TC path) keeping the mean total stress constant. The stress paths that induce an axial extension of the specimen are illustrated below the p-axis in Fig. 4-5. The axial extension can be induced by either decreasing the axial stress (RTE path), increasing the radial stress (CTE), or decreasing σ_a and increasing σ_r at the same time (TE path) keeping the mean total stress constant. Therefore, when the term 'reduce' is used to define the stress path, it means that one of the two stresses is decreased while the other is kept constant. On the other hand, when the term 'conventional' is used to define the stress path, it means that one of the two stresses is increased and the other is kept constant. It is noted that the illustrations in Fig. 4-5 are the stress paths for total stress only, so the tests can be conducted in either drained or undrained conditions. This means that the submitted loading conditions may differ based on the porewater pressure generation during undrained testing. For the triaxial tests of the rock-mechanical testing programme, only CTC stress paths were executed.

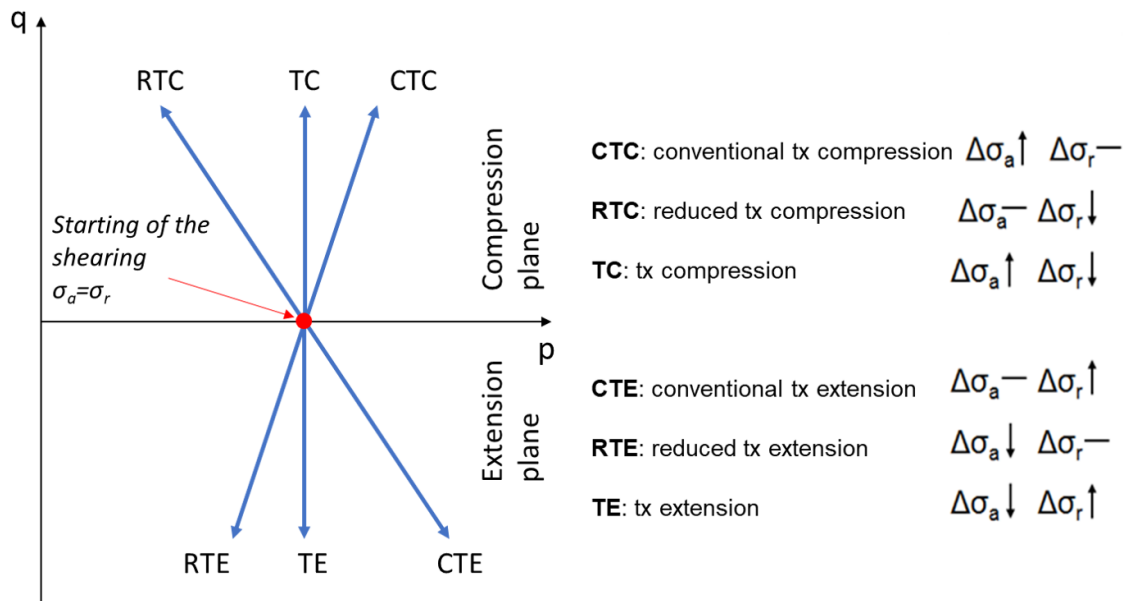


Fig. 4-5: Summary of possible stress paths that can be used to perform triaxial tests
On the right side, it is indicated which of the two stresses (axial σ_a and radial σ_r) is increased or decreased.

Test procedure

The testing procedure consisted of a maximum of four main phases:

1. Isotropic loading phase, during which the radial confining pressure and the axial load are increased simultaneously. The needle valve to the pore pressure generator is opened after the total stress has reached an equivalent value of 2 MPa. Both total mean stress (p) and fluid pressure (u_w) are then increased in concert to their respective target values: 10 to 15 MPa for p and 5 MPa for u_w .
2. *Selected tests only*: the pore-fluid-coupling parameter during isotropic loading (Skempton's B value) is evaluated in undrained conditions. During the Skempton's B test, the change in pore pressure over time (Δu_w) is determined as a function of the change in isotropic pressure increase over time (Δp) (u_w is allowed to equilibrate at least for 20 minutes up to 8–24 hours):

$$B = \frac{\Delta u_w}{\Delta p} \quad (4-3)$$

In the present case two to three Skempton's B tests were carried out per specimen with confining pressure increase Δp of 1 or 2 MPa.

3. *Selected tests only*: a consolidation phase is performed to determine the consolidation coefficient c_{vi} . An isotropic total stress increase (or decrease) is applied to the specimen and the deformations in time are recorded and analysed. The deformation evolves according to the dissipation of the porewater over- (or under-) pressure induced by the load variation. Calculation of the consolidation coefficient c_{vi} (in mm²/h) is done according to the following equation (Head 1998):

$$c_{vi} = \frac{\pi D^2}{\lambda t_{100}} \quad (4-4)$$

with D as the plug diameter and t_{100} as the theoretical time to 100% consolidation. The theoretical time t_{100} is found by extrapolating the linear portion of the volumetric strain versus square root of the experimental time curve (with time in h) to the final strain value. Lastly, λ is a constant depending on drainage boundary conditions.

4. The fourth testing phase is the shearing phase or triaxial test, applying a constant deviatoric stress or strain rate. The standard strain rate was 10^{-6} s^{-1} but was adjusted based on theoretical calculations (Head 1998) using the consolidation coefficient determined in phase 3 or considering lithology and water content.

The shearing phase of the triaxial tests was preceded in selected cases by a Skempton's B test for verification of specimen saturation and, subsequently, by a determination of the consolidation coefficient c_v as base for strain rate calculation. However, in the rock mechanics programme of BOZ2-1 cores, consolidation coefficients were not determined. Instead, strain rates were chosen based on lithological criteria (rock type, water content and mechanical properties based on UCS test results) and previous experiences (*cf.* Nagra 2021a and Nagra 2021b).

Generally, clay-rich rocks, such as clay- and siltstones or marls were tested at lower strain rates than limestones, sandstones and anhydrites. The strain rate of the single-stage triaxial tests ranged between 10^{-5} s^{-1} (2TRX tests), 10^{-6} s^{-1} (9TRX tests) and $2 \cdot 10^{-7} \text{ s}^{-1}$ (3 TRX tests).

4.3 Geomechanical testing programme – testing methods

4.3.1 Synthetic pore fluid

The artificial porewater (APW) used in the geomechanical tests is based on the recipe derived from the investigations in the Schlattingen borehole (Mäder in Wersin et al. 2013), and the composition is reported in Tab. 4-1. This recipe defines a porewater saturated with respect to calcite and dolomite under atmospheric CO₂ partial pressure (lab conditions).

Towards the end of the geomechanical testing programme, the porewater chemistry was also constrained for the BOZ2-1 core material (cf. Dossier VIII). These investigations confirm the general Na-Cl water type. The salinities in the Dogger section are lower than in the APW; e.g. chloride concentrations in Opalinus Clay are about 2.5 g/L and in the Passwang Formation between 1.5 and 2.5 g/L (APW: 6.7 g/L). Towards the base of the Staffelegg Formation, the chloride contents decrease to about 0.4 g/L. In addition to saturation with carbonate minerals, the investigations suggest saturation with respect to the sulphate mineral celestite. But the APW was not changed for the final geomechanical tests, to be consistent with earlier tests. Finally, the slightly higher ionic strength in the porewater found in the BOZ2-1 core is not anticipated to have a significant effect on hydromechanical properties (Witteveen et al. 2013, Ewy 2014, Tuttolomondo 2021).

Tab. 4-1: Recipe used for the preparation of the APW

Compound	mmol/kg _{H2O}	g/kg _{H2O}
NaCl	115.26	6.7356
NaHCO ₃	0.54	0.0456
CaCl ₂ 2H ₂ O	11.91	1.7510
KCl	2.55	0.1902
MgCl ₂ 6H ₂ O	9.17	1.8635
Na ₂ SO ₄	24.00	3.4089

4.3.2 Triaxial deformation test (specialised protocol)

To assess the mechanical properties of the Opalinus Clay and confining units, dedicated testing protocols were established (Minardi et al. 2019).

The extraction of the specimens was carefully performed in order to minimise water content loss during the operation. All involved laboratories used a drilling machine. All labs used hydrocarbons as cooling fluids during the drilling of the specimens.

Computed tomography of the cores after drilling was used to identify the most suitable sections for extracting test specimens (cf. Appendix A). The target zones were selected upon Nesol's and Nagra's guidance.

The conventional testing procedure indicated by Nagra to carry out triaxial tests foresaw the following steps (Fig. 4-6a):

1. An initial isotropic total stress (0.5 – 1 MPa) is applied to the specimen to ensure contact with the axial piston. The saturation of the specimen is then performed at constant volume to minimise specimen disturbance (i.e. fissure opening during resaturation); axial and radial stresses are progressively increased to keep the specimen's volume constant while it is put in contact with fluid at low back pressure. Next, the fluid back-pressure is increased to at least 2 MPa (the total stresses are also increased to keep the effective stress constant) (*ss1*), to dissolve possible air remaining in the tubing or the material. This procedure allows the determination of the axial and radial swelling pressures. The confining stress is then set equal to the axial stress (*ss2*). A pore pressure increment step is performed either at this stage (*ss3*) or before the shearing phase in order to reach the target confinement
2. The assessment of the specimens' saturation is carried out by measuring the Skempton's B coefficient (B check test). Two to three isotropic undrained loadings are performed. More steps are applied when unsatisfactory values are obtained.
3. Drained consolidation or swelling of the specimen is performed to reach the target consolidation stress; consolidation effective stresses range between 7 and 13 MPa. The pore fluid pressure is kept constant to 8 – 10 MPa during consolidation.
4. The final stage is the shearing of the specimens at constant axial strain rate. An unloading/reloading loop is performed, then the specimen is sheared until the specimen's failure and achievement of the post-peak constant deviatoric stress, in undrained or drained conditions.

This conventional testing procedure is adopted by Lab B. Test 12 by Lab B adopted a modification on the saturation procedure: the sample was exposed to RH 96%, then saturation was completed in the triaxial cell at constant load.

A different procedure was generally used by Lab C and is referred to as «alternative procedure» (Fig. 4-6b). This alternative procedure foresees the equalisation of the specimen to different relative humidity values (between 85% and 96%) in desiccators before testing in order to achieve different saturation conditions. After that, the specimens were mounted in the rig, and an initial undrained loading was carried out until an increase of the pore pressure was detected. At this stage, the specimen was assumed to have achieved the fully saturated condition; B check test was then performed in three steps. A pressure transducer was placed inside the vessel very close to the specimen to monitor the evolution of the pore fluid pressure during the application of the external mechanical stress. When this testing procedure is adopted, no artificial pore fluid is added to the specimen.

In tests with IDs from C7 to C14 (see Section 6.2 for details on the ID notation), performed by Lab C, variations to the alternative procedure were introduced. In 4 tests (C9, C10, C13, C14), Lab C imposed a positive pore pressure with brine exposure to saturate the specimens (active saturation). Also, in 5 tests (C7 to C14), a drained reverse consolidation (unloading, sample swelling) was performed.

The laboratories involved in the triaxial testing programme with specialised protocols, prepared cylindrical specimens respecting the diameter (*D*) to height (*H*) ratio $D:H \approx 0.5$. In particular, the specimen nominal diameters are:

- Lab B: $D = 25.0$ mm
- Lab C: $D = 19.1$ mm

The labs used two drainage systems: Lab B used both radial drainage and drainage at the two edges, while Lab C used radial drainage and drainage at one edge of the cylinder. The strain rates to apply during shearing were defined according to the drainage conditions and the specimen dimensions (i.e., drainage length). Water content after testing was determined by oven-drying at 105 °C for several days until constant weight.

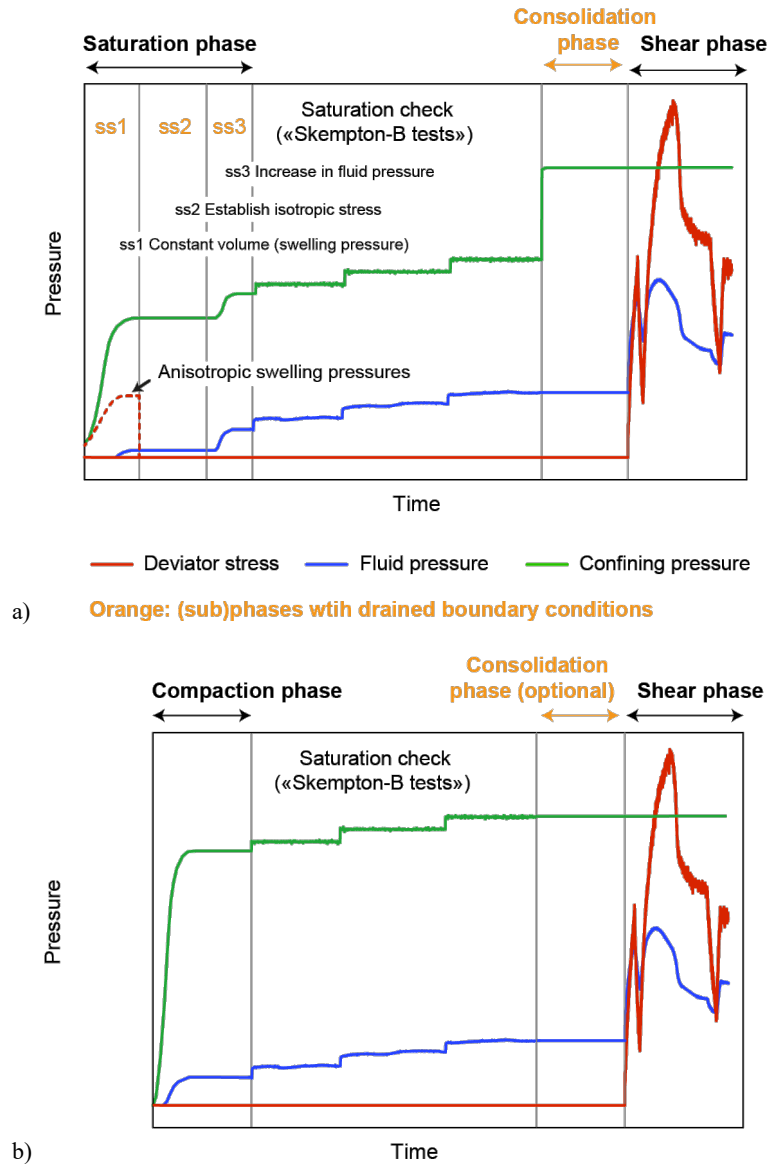


Fig. 4-6: Pressure – time sequences of triaxial deformation tests (specialised protocols)
(a) conventional and (b) alternative testing procedures for undrained boundary conditions during the shear phase.

4.3.3 Oedometric test (high-pressure, specialised protocol)

Specimens for oedometric testing are of cylindrical shape, with a diameter (D) to height (H) ratio $D:H \geq 2.5$. The nominal dimensions of the specimens are:

- Lab D: $D = 35.0$ mm; $H = 12.5$ mm

The operators cut a pre-defined section of the core with a saw, through the PVC tube to minimise exposure of the geomaterial to the atmosphere. Then, the obtained slice is cut into a smaller piece to be handled within a lathe machine. No air nor water is used during the sawing process. Planarity and parallelism of the bases are verified, and the dimensions of sawn specimens are measured. In addition, Lab A covered the cut parts with a hydrocarbon oil and performed lathing at high humidity to limit the humidity gradient between the specimen and the laboratory atmosphere. After the final specimen diameter was reached, the specimen was wiped free of oil (using oil-only absorbent).

The specimen is then put into the oedometric ring, a rigid metallic ring to constrain the radial strains; silicon grease was placed on the internal surface of the ring to reduce the friction between the specimen and the metallic ring.

The specimen disks are loaded axially, and deformation is recorded with time.

Specimens are resaturated within the apparatus in isochoric conditions. The axial deformations are kept constant by increasing the axial stress. Pore pressure is applied from the bottom side of the specimen at 50 kPa. When the swelling pressure generated by saturation at isochoric conditions stabilises, pore pressure equal to 50 kPa is applied at the top side of the specimen. Displacements are monitored throughout this stage of the test. Once the axial stress has stabilised, the mechanical loading phase of the test can start.

The loading is performed in steps, starting from the axial swelling stress attained at the end of the resaturation phase. The incremental loading steps are performed by doubling the axial stress reached during the previous step. Each step lasted at least 24 hours. A few doubling steps (depending on the swelling stress) are performed to achieve an axial stress of 10 – 15 MPa. For selected tests, a constant-head permeability test (PERM) is performed at this stage, increasing the pore pressure at the bottom side and measuring the fluid flow through the specimen. The axial stress and pressure gradient are kept constant during the permeability test until steady-state conditions are achieved. Then, the bottom fluid pressure is reduced back to 50 kPa. Enough time is given for the displacement to stabilise, a minimum of 24 hours. An unloading/reloading phase follows. The specimen is then loaded in steps, up to a maximum stress of 60 MPa. Finally, an unloading phase is performed in steps to achieve an axial stress of approximately 7 MPa.

After completion of the test, the oedometer cell is dismantled, and the specimen is dried in the oven to measure the water content (oven-drying at 105 °C for several days until constant weight).

4.3.4 Complementary tests

In this section, complementary sample permeability tests (PERM) performed within the context of the geomechanical testing campaign are described.

Constant-head permeability tests were performed on two of the specimens tested at predefined stages during one-dimensional compression tests, at constant vertical total stress. An additional constant-head test was carried out in oedometric configuration (core 645.97/25-GM, Test ID D1_PERM_BOZ2_1) at 10 MPa effective stress (axial stress of 15 MPa, pore pressure equal to 5 MPa).

In addition, a constant-head permeability test was performed on one specimen (core 635.75/23-GM, Test ID A1_PERM_BOZ2_1) in triaxial conditions at 10 MPa effective stress (constant radial and axial stress of 17 MPa, pore pressure equal to 7 MPa) using cylindrical samples of 25 mm diameter and 25 mm length.

A pore pressure gradient between the top and bottom side of the specimen was applied via two independent pressure/volume controllers, and the volumes of water flowing in and out of the specimen were measured. Once the flow reached a stable value (after a few days), this was used to compute the hydraulic conductivity adopting Darcy's law. After completion of the permeability phase, the oedometric test continued as described in the previous section.

4.4 Lithostratigraphy and test overview

4.4.1 Lithostratigraphy of tested core material

A brief summary is provided here on lithological characteristics of the formations of which cores were used in geomechanical testing. Further details on lithology can be found in Dossier III (TBO Bözberg-2-1: Lithostratigraphy).

- **Wildegge Formation:** Calcareous marl with interlayers of limestone
- **Hauptrogenstein:** Bioclastic, calcareous and argillaceous marl with interlayers of bioclastic limestone (324 m). Oolitic limestone with dark, argillaceous seams (350 and 380 m).
- **Passwang Formation:** Bioclastic argillaceous marl with thin interbeds of limestone (394 m). Calcareous claystone (427 m) to calcareous marl (433 m).
- **Opalinus Clay:** Silty claystone with silty to sandy lenses. The following subdivision was specified:
 - **451.54 – 480.56 m Subunit 1: «Sub-unit with silty calcareous beds» (29.02 m):** Claystone to silty claystone with discrete heterogeneities, in particular silty calcareous beds and nodules.
 - **480.56 – 496.09 m Subunit 2: «Upper silty sub-unit» (15.53 m):** Claystone to silty claystone with frequent lenses, typically centimetres wide and several millimetres thick (flaser structure).
 - **496.09 – 559.75 m Subunit 3: «Mixed clay-silt-carbonate sub-unit» (63.66 m):** Silty claystone, devoid of marked characteristics typical for the other subunits.
 - **559.75 – 573.68m Subunit 4: «Clay-rich sub-unit» (13.93 m):** Homogeneous claystone with high clay-mineral content (mostly > 60 wt.-%).
- **Staffellegg Formation:** Argillaceous siltstone with lenticular bedding, lenses and thin beds of siltstone. The tested intervals belong to the Frick Member (585 m).
- **Klettgau Formation:** Thin-bedded alternation of dolomitic marl and argillaceous marl (631 m). Dolostone with up to cm-wide vugs and druses, partly filled with dolomite crystals (635 m). Alternation of argillaceous marl, sandy marl and silty marl (642 m). Argillaceous sandstone, wavy to flaser bedding, alternating with sandy claystone and sandstone (645 m). The tested intervals are from the Gansingen Member (631 and 635 m) and the Ergolz Member (642 and 645 m), respectively.
- **Bänkerjoch Formation:** Alternation of anhydrite, formed by anhydrite veins (inclined and horizontal), layers of nodules, in claystone matrix and argillaceous marl (670 m). Massive anhydrite and claystone (696 m).
- **Schinznach Formation:** Dolostone, with small irregularly shaped anhydrite nodules (763 m). Limestone, laminated by claystone drapes (816 m).
- **Zeglingen Formation:** Dolostone, porous with chert nodules.

4.4.2 Test overview

A total of 89⁷ rock-mechanical and geomechanical tests were conducted on a total of 24 cores from borehole BOZ2-1 (Tab. 4-2). The number of tests in the geomechanical testing programme is smaller than in the rock-mechanical testing programme. However, typical testing times in the geomechanical programme were 12 to 30 days for TRX+ tests and 20 to 35 days for OED+ tests. This is one order of magnitude longer than the typical TRX test in the rock-mechanical testing programme.

Cores without proper initial conditioning (PVC = 0 in Tab. 4-2) were generally only used for lithologies not sensitive to water exchange, i.e. without any macroscopic indication of damage at the time of sampling in the storage facility.

⁷ The 2 constant-head permeability tests (PERM) performed as part of the oedometric tests (OED+) are not counted separately in the total number of tests, but they are listed as such in Tab. 4-2 for overview.

Tab. 4-2: Overview of performed tests

The red border illustrates the clay-mineral rich interval of Opalinus Clay (focus of geo-mechanical testing programme). PVC indicates whether cores were conditioned in resin and core barrel on site (1) or later wrapped in aluminium foil off-site (0). TRX = triaxial test, UCS = unconfined compressive strength test, TS = indirect tensile strength test (Brazilian), TRX+ = TRX with specialised protocols, OED+ = Oedometric test with specialised protocols (high-pressure), PERM = constant-head permeability tests in OED+ tests or triaxial configuration.

Core-ID	Formation	Top	Length	Bottom		Rock-mechanical testing programme			Geomechanical testing programme		
						Standard rock-mechanical tests			Special protocols		Other
		[m]	[cm]	[m]	PVC	TRX	UCS	TS	TRX+	OED+	PERM
BOZ2-1											
273.27/50-GM	Wildeggen	273.27	50	273.77	1	1	2	2			
324.05/50-GM	Hauptrogenstein	324.05	50	324.55	1	1	3	2			
350.68/50-GM		350.68	50	351.18	1	1	2	2			
380.83/48-GM		380.83	48	381.31	1	1	3	2			
394.48/40-GM	Passwang	394.48	40	394.88	1	1	1	2			
427.89/50-GM		427.89	50	428.39	1				1		
433.50/50-GM		433.5	50	434	1	1	1	2			
453.09/50-GM	Opalinus Clay	453.09	50	453.59	1				2		
464.07/50-GM		464.07	50	464.57	1					2	1
504.58/44-GM		504.58	44	505.02	1				8		
515.49/46-GM		515.49	46	515.95	1				3		
519.03/50-GM		519.03	50	519.53	1				5		
529.52/48-GM		529.52	48	530.00	1					5	1
566.20/43-GM		566.20	43	566.63	1				6		
585.26/45-GM	Staffellegg	585.26	45	585.71	1	1	1	2			
631.19/45-GM	Klettgau	631.19	45	631.64	1	1	3	2			
635.75/23-GM		635.75	23	635.98	0						1
642.43/49-GM		642.43	49	642.92	1	1	1	2			
645.97/25-GM		645.97	25	646.22	0						1
670.50/50-GM	Bänkerjoch	670.50	50	671.00	1	1	1	2			
696.50/45-GM		696.50	45	696.95	1	1	2	2			
763.84/48-GM	Schinznach	763.84	48	764.32	1	1	2	2			
816.50/42-GM		816.50	42	816.92	1	1	2	2			
825.77/35-GM	Zeglingen	825.77	35	826.12	1	1	1	2			
Total					24	14	25	28	25	7	4

5 Rock-mechanical testing

5.1 Indirect tensile strength test (Brazilian)

A total of 25 Brazilian tests were performed (Tab. 5-1). The splitting tensile strength (MPa) is calculated according to the following formula (curved jaws):

$$S_z = \frac{1272 * F}{\pi * d * l} \quad (5-1)$$

with the compressive force F (in kN); the specimen diameter d (in mm) and the specimen length l (in mm). It is noted that the values of S_z are negative.

Tab. 5-1: Test results from indirect tensile strength tests

For specimen geometry see Fig. 4-1.

Test-ID	Specimen geometry	Average depth	Bulk density	Water content	Tensile strength
		[m]	[g/cm ³]	[wt.-%]	[MPa]
BOZ2-1_273TS_P1	P	273.66	2.567	2.99	-1.5
BOZ2-1_273TS_S1	S	273.71	2.545	3.17	-2.0
BOZ2-1_324TS_P1	P	324.40	2.583	1.91	-2.1
BOZ2-1_324TS_S1	S	324.45	2.604	1.96	-2.3
BOZ2-1_350TS_P1	P	350.81	2.533	4.02	-1.6
BOZ2-1_350TS_S1	S	350.87	2.516	3.96	-1.8
BOZ2-1_380TS_S1	S	381.18	2.575	3.23	-3.1
BOZ2-1_380TS_P1	P	381.19	2.572	2.93	-2.2
BOZ2-1_394TS_S1	S	394.58	2.527	4.53	-3.4
BOZ2-1_394TS_P1	P	394.59	2.530	4.22	-2.3
BOZ2-1_433TS_S1	S	433.88	2.511	3.90	-3.7
BOZ2-1_433TS_P1	P	433.91	2.498	4.31	-2.6
BOZ2-1_585TS_S1	S	585.61	2.508	3.61	-3.0
BOZ2-1_585TS_P1	P	585.62	2.502	3.55	-2.3
BOZ2-1_631TS_S1	S	631.48	2.661	2.15	-3.8
BOZ2-1_631TS_P1	P	631.55	2.641	3.01	-2.5
BOZ2-1_642TS_S1	S	642.82	2.693	2.41	-2.3
BOZ2-1_642TS_P1	P	642.84	2.653	3.13	-2.5
BOZ2-1_670TS_S1	S	670.78	2.558	5.56	-1.6
BOZ2-1_696TS_S1	S	696.63	2.845	1.32	-3.1
BOZ2-1_696TS_P1	P	696.65	2.873	0.90	-2.5
BOZ2-1_763TS_S1	S	763.96	2.545	5.43	-3.8
BOZ2-1_763TS_P1	P	763.98	2.426	6.78	-2.6
BOZ2-1_816TS_S1	S	816.66	2.683	0.18	-2.8
BOZ2-1_816TS_P1	P	816.67	2.281	0.08	-3.9

The test results yielded values from -3.8 MPa to -1.6 MPa for S-samples and -3.9 MPa to -1.5 MPa for P-samples. Most TS specimens failed along primary central tensile fractures. Photographs of the specimens before and after testing can be found in Appendix A.

5.2 Unconfined compressive strength tests (UCS)

A total of 25 UCS tests were performed by two laboratories (Tab. 5-2). Photographs of the specimens before and after testing can be found in Appendix A.

At the linear portion of the axial load cycle, an unloading/reloading cycle was performed by reducing the axial stress to 1/3 of the actual load, and hysteresis was observed. The cycle was performed for determining the elastic properties of the rock. The Young's modulus E (in GPa) was determined as an average reload modulus using the slope of the rising portion of the hysteresis as the ratio between the axial load change $\Delta\sigma_a$ (in MPa) and the induced axial strain $\Delta\epsilon_a$ (dimensionless) according to the equation:

$$E = \frac{\Delta\sigma_a}{\Delta\epsilon_a} \quad (5-2)$$

The Poisson's ratio (ν) is calculated as the negative ratio between the delta in radial $\Delta\epsilon_r$ and axial strain $\Delta\epsilon_a$:

$$\nu = -\frac{\Delta\epsilon_r}{\Delta\epsilon_a} \quad (5-3)$$

An example of calculation of tangent E modulus is reported in Fig. 5-1.

Following the hysteresis, the axial load was again increased until peak strength was reached, and the specimen was allowed to fail. The compressive peak strength was derived from the peak value of the axial load.

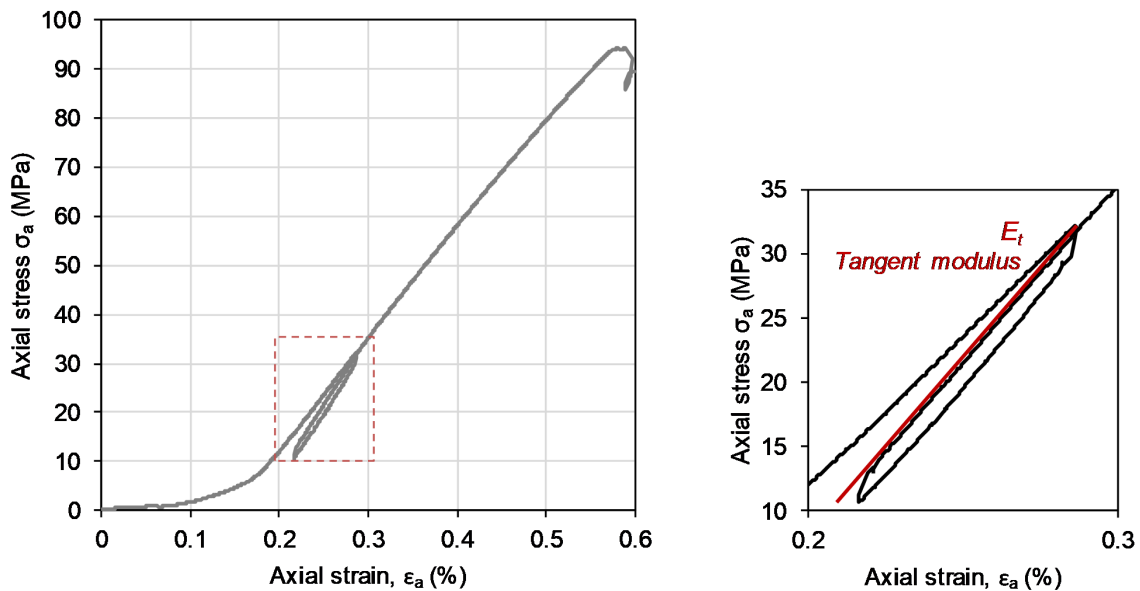


Fig. 5-1: Stress – strain diagram for UCS test

On the right zoom into the unloading/reloading loop, and the definition of tangent and secant Young's moduli. Example from test BUL1-1_661UCS_S1 (Nagra 2021a).

Tab. 5-2: Test results from UCS tests

Young's modulus refers to E_{50} . For specimen geometry see Fig. 4-1.

Test-ID BOZ2-1	Specimen geometry	Average depth	Bulk density	Water content	Young's modulus	Poisson's ratio	Peak strength	Strain at peak strength
		[m]	[g/cm ³]	[wt.-%]	[GPa]	[-]	[MPa]	[%]
273UCS_S1	S	273.44	2.598	2.31	15.90	0.18	68.0	0.91
273UCS_S2	S	273.74	2.582	2.94	12.74	0.30	57.6	0.90
324UCS_S2	S	324.10	2.553	2.94	7.81	0.14	26.4	0.55
324UCS_P1	P	324.46	2.605	2.19	16.69	0.21	34.3	0.29
324UCS_S1	S	324.52	2.549	2.92	7.40	0.13	20.5	0.52
350UCS_S1	S	350.73	2.485	4.34	19.61	0.20	39.7	0.31
350UCS_P1	P	350.77	2.518	3.90	15.74	0.18	23.3	0.42
380UCS_S2	S	380.99	2.599	2.82	8.06	0.20	18.7	0.34
380UCS_P1	P	381.23	2.615	2.20	17.95	0.18	38.4	0.33
380UCS_S1	S	381.28	2.613	1.87	18.58	0.17	49.0	0.40
394UCS_S1	S	394.52	2.535	3.95	8.36	0.22	28.3	0.71
433UCS_S1	S	433.97	2.513	4.33	8.45	0.18	36.6	0.75
585UCS_S1	S	585.68	2.517	3.28	10.86	0.17	44.4	0.63
631UCS_S2	S	631.23	2.682	2.41	18.95	0.11	70.5	0.43
631UCS_S3	S	631.33	2.658	2.98	19.90	0.24	62.0	0.48
631UCS_S1	S	631.61	2.622	3.84	15.41	0.23	18.4	0.21
642UCS_S1	S	642.89	2.674	2.74	21.44	0.19	78.7	0.59
670UCS_S1	S	670.71	2.577	5.36	9.86	0.25	23.6	0.47
696UCS_S1	S	696.56	2.880	0.89	31.63	0.17	58.6	0.26
696UCS_S2	S	696.82	2.878	0.57	35.13	0.12	63.5	0.26
763UCS_S1	S	764.04	2.629	3.40	33.17	0.30	112.9	0.52
763UCS_S2	S	764.10	2.529	4.95	25.98	0.42	76.6	0.55
816UCS_S2	S	816.56	2.704	0.08	48.06	0.21	211.9	0.53
816UCS_S1	S	816.75	2.697	0.16	41.96	0.34	138.8	0.41
826UCS_S1	S	826.10	2.319	8.80	18.52	0.38	48.4	0.45

The relatively large lithologic variability of tested specimens is reflected by the test results, ranging just over one order of magnitude both for Young's moduli and strength.

5.3 Triaxial deformation tests

A total of 14 triaxial tests were performed. Photographs of the specimens before and after testing can be found in Appendix A.

Basic properties and test conditions are provided in Tab. 5-3. The water content reported refers to the final, post-test measurement. With some exceptions, tests were conducted undrained with an initial fluid pressure of either 7 or 10 MPa. The anhydrite samples BOZ21_670TRX_S2 and BOZ2-1_696TRX_S1 were carried out "dry" without the pore-fluid system and at a strain rate of $1 \times 10^{-5} \text{ s}^{-1}$. Confining pressure in all tests was 15 MPa except in the two "dry" tests (10 MPa).

Skempton's B values were constrained in 5 tests⁸.

Ultrasonic velocities were recorded throughout the tests, and the tabulated values in Tab. 5-3 were constrained at the start of the shear phase. S-wave signals could not be determined for one sample (BOZ2-1_670TRX_S2).

During shearing in test 324 TRX S1, the sample exhibited a plastic, dilatant response up to 3% axial deformation. The sample did not reach peak shear strength within this strain range and was therefore unloaded (Fig. 5-2).

The core material of this test sample consists of an alternation of bioclastic calcareous marl and bioclastic limestone. It is speculated that the marly interlayers buffer the expected brittle response, and lead to significant yielding without strain-softening.

⁸ The tabulated values in Tab. 5-3 are not corrected for potential equipment compliance.

Tab. 5-3: Basic properties and triaxial test results from consolidation and saturation stage
For specimen geometry see Fig. 4-1.

Test-ID	Specimen geometry	Average depth	Bulk density	Water content	Pore pressure	Confining pressure	Skempton's B	P-wave velocity	S-wave velocity
		[m]	[g/cm ³]	[wt.-%]	[MPa]	[MPa]	[-]	[m/s]	[m/s]
BOZ2-1_273TRX_S1	S	273.74	2.57	3.99	7.0	15.0	0.52	4'193	2'398
BOZ2-1_324TRX_S1	S	324.52	2.56	4.07	7.0	15.0	0.71	4'607	2'512
BOZ2-1_350TRX_S1	S	350.73	2.49	5.90	10.0	15.0	-	4'976	2'611
BOZ2-1_380TRX_S1	S	381.28	2.62	2.98	10.0	15.0	-	5'254	2'943
BOZ2-1_394TRX_S1	S	394.52	2.54	4.69	7.0	15.0	-	3'724	2'264
BOZ2-1_433TRX_S1	S	433.97	2.51	5.33	7.0	15.0	0.68	3'773	2'438
BOZ2-1_585TRX_S1	S	585.68	2.50	4.83	7.0	15.0	0.60	4'088	2'429
BOZ2-1_631TRX_S1	S	631.61	2.64	4.09	7.0	15.0	0.55	4'839	2'630
BOZ2-1_642TRX_S1	S	642.89	2.69	3.45	7.0	15.0	-	5'050	2'900
BOZ2-1_670TRX_S2	S	670.55	2.73	3.03	dry	10.0	-	5'382	-
BOZ2-1_696TRX_S1	S	696.56	2.83	1.53	dry	10.0	-	5'438	2'722
BOZ2-1_763TRX_S1	S	764.04	2.58	5.56	10.0	15.0	-	5'734	2'878
BOZ2-1_816TRX_S1	S	816.72	2.70	1.03	10.0	15.0	-	3'895	2'229
BOZ2-1_826TRX_S1	S	826.07	2.29	11.16	10.0	15.0	-	4'674	2'113

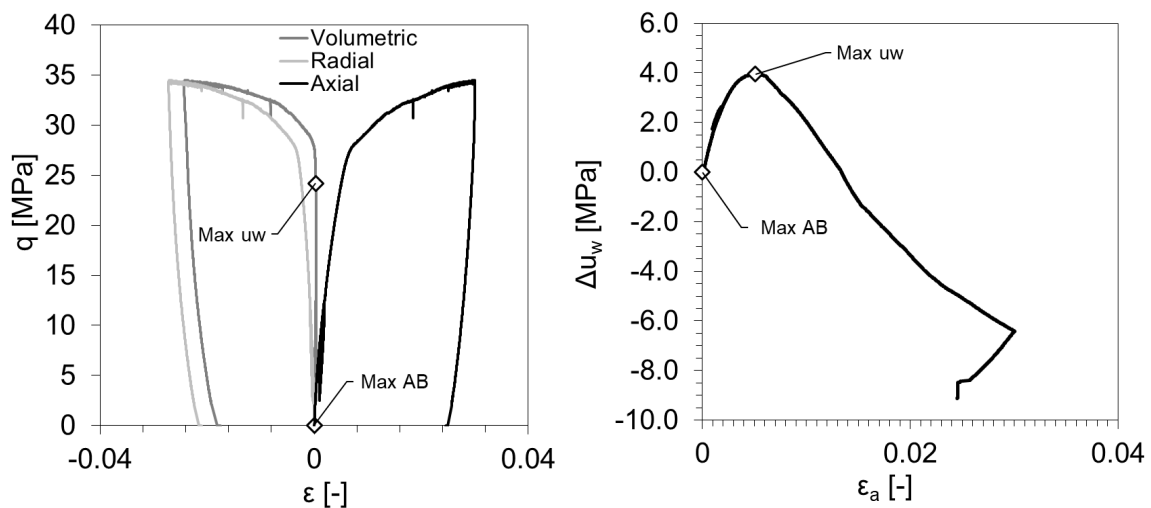


Fig. 5-2: Sample with highly dilatant response

Test BOZ2-1_324_TRX_S1

Tab. 5-4: Triaxial test results from the shear phase

^a Switch from undrained to drained during the test (cf. Fig. 5-2).

Test-ID	Stress path	Strain Rate	Young's modulus	Poisson's ratio	Deviatoric stress at peak ($q = \sigma_1 - \sigma_3$)	Radial total stress at peak (σ_3)	Pore pressure at peak	Axial strain at peak	Post-peak q	Pore pressure at post-peak
BOZ2-1		[1/s]	[GPa]	[-]	[MPa]	[MPa]	[MPa]	[%]	[MPa]	[MPa]
273TRX_S1	CTCU	1E-06	5.2	0.57	56.3	15	12.1	1.62	41.1	9.1
324TRX_S1	CTCU ^a	1E-06	8.11	0.46	-	15	-	-	-	-
350TRX_S1	CTCU	1E-06	33.5	0.60	56.0	15	5.7	0.73	61.6	0.5
380TRX_S1	CTCU	1E-06	17.7	0.25	76.5	15	6.4	1.09	55.6	0.50
394TRX_S1	CTCU	2E-07	6.9	0.56	26.6	15	10.5	0.84	20.6	7.9
433TRX_S1	CTCU	2E-07	7.0	0.66	29.3	15	11.1	0.85	21.1	5.2
585TRX_S1	CTCU	2E-07	9.2	0.38	65.6	15	0.0	1.56	35.7	1.0
631TRX_S1	CTCU	1E-06	16.7	0.25	68.0	15	7.2	0.98	53.1	0.5
642TRX_S1	CTCU	1E-06	29.1	0.53	103.9	15	9.6	1.08	62.9	4.4
670TRX_S2	CTC	1E-05	18.1	0.63	48.8	10	-	0.58	30.8	-
696TRX_S1	CTC	1E-05	23.5	0.22	64.2	10	-	0.57	37.8	-
763TRX_S1	CTCU	1E-06	20.9	0.46	115.6	15	8.9	0.70	61.0	0.5
816TRX_S1	CTCU	1E-06	41.3	0.24	231.6	15	4.1	0.72	76.9	0.5
826TRX_S1	CTCU	1E-06	18.1	0.50	72.3	15	8.2	0.66	45.7	8.21

6 Geomechanical testing programme

In the BOZ2-1 geomechanical testing campaign, 25 triaxial tests were performed with specialised protocols. Two geometries (Section 5.1) were selected: S- and P-samples.

Tests with IDs C1, C2, C3, C5 and C11 (see Section 6.2 for ID details) showed an anomalous lower strength with respect to the majority of the results. It was suspected that damage in samples from Lab C may have been induced by the swelling happening during pre-conditioning at high relative humidity (alternative procedure). Hereafter, those results are indicated as damaged tests. Tests from C1 to C6 follow the alternative procedure, while in the following tests from C7 to C14 some modifications to the procedure were introduced to further investigate the potential damage induced by the swelling.

In tests C7 to C14, the samples were intentionally loaded to a higher stress level (17 – 18 MPa) than the target for shearing, except for tests C9 and C10, which were loaded even higher to 25 MPa and 30 MPa respectively.

In tests C9, C10, C12, C13 and C14 samples were put in contact with brine. Active saturation was applied (backpressure was applied to the brine in the porewater lines during saturation) in those tests, except test C12.

Also, test B12 from Lab B included a modification on the saturation procedure: the sample was exposed to a relative humidity of 96%, in a closed dessicator for ~ 6 weeks. Evolution of weight and dimensions during this period were monitored. X-ray computer tomography scans of the sample were taken before and after the exposure to the high relative humidity, and showed that microfissures had developed within the desiccator. Then, the sample was mounted in the triaxial rig and put in contact with the brine under constant load of 9.4 MPa (pore pressure 3 MPa).

In addition, 7 one-dimensional compression tests (including 2 constant-head permeability tests) were performed in oedometric conditions. Two additional permeability tests were performed in oedometric conditions.

In the following sections, the test results of the experimental campaign are presented. First, the main geotechnical and intrinsic properties are reported (Section 6.1). Then, in Sections 6.2 and 6.3, the results of tests in triaxial and oedometric conditions are reported.

6.1 Geotechnical and intrinsic properties of tested cores

6.1.1 Water content and Native activity

The laboratories involved in the testing campaign also determined basic properties of the tested specimens. The water content of the specimens before and after testing was determined, and the results are reported in Fig. 6-1.

For the triaxial tests, the first phase of each test consisted in imposing saturated conditions on the specimen, either (i) by injecting water in isochoric conditions, measuring the generated swelling pressure (conventional testing procedure), or (ii) by isotropically compressing the specimen until a positive pore pressure is developed (alternative testing procedure; *cf.* Fig. 4-6).

When the conventional testing procedure is used, the water content before and after the tests generally differs, and in the case of undrained boundary conditions, the difference may primarily be attributed to resaturation in the rig. This is the case for results from Lab B. Using the alternative testing procedure (Lab C), no fluid is added to the specimen whilst in the rig, but a minimum part

of the pore fluid is potentially being squeezed out of the sample during consolidation. Nonetheless, the water content before and after the test is expected to be approximately the same. Additional sources of discrepancy between the water content before and after the tests can be attributed to the handling of the specimen when dismantling the tests (e.g., loss of solid mass while removing the specimen from the sleeve, drained unloading phases which allow further swelling and water content increase).

The water content and the Native activity of the material were also measured on trimming pieces from a part of the section from which testing specimens were extracted. The Native activity of a specimen corresponds to the value of relative humidity in equilibrium with the specimen's native state, with no variation of the initial water content⁹.

The measurements were done by placing a piece of freshly cut material within a closed container and measuring the resulting (relative) humidity generated within the container (Ewy 2015) by the use of a psychrometer.

Results are reported in Fig. 6-2. All cores exhibit high Native activity, above 70%, indicating excellent preservation conditions.

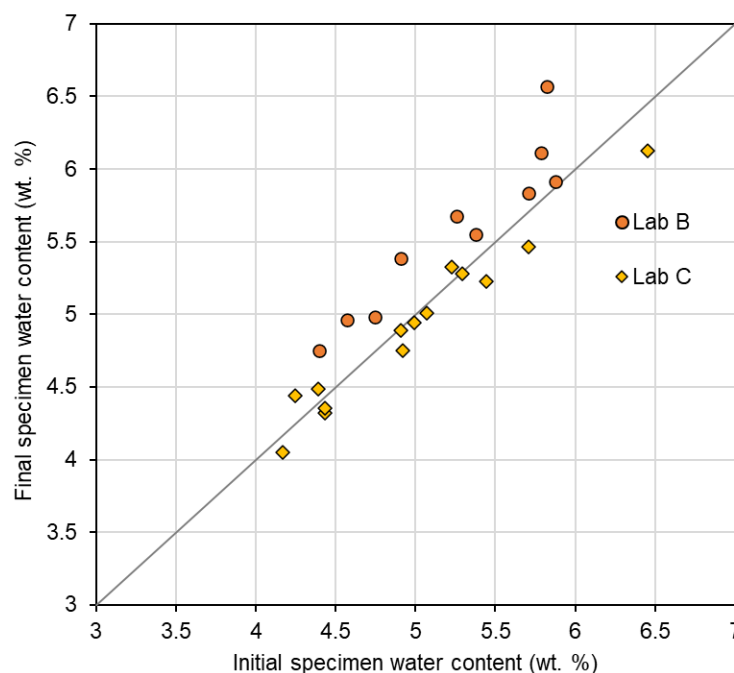


Fig. 6-1: Initial (at test) versus final water content of specimens in triaxial tests (Opalinus Clay)

⁹ In a specimen in contact with controlled relative humidity, if water content increases, then that relative humidity value is greater than the Native activity value of the shale. Conversely, if there is a water content decrease, then that relative humidity value is less than the Native activity.

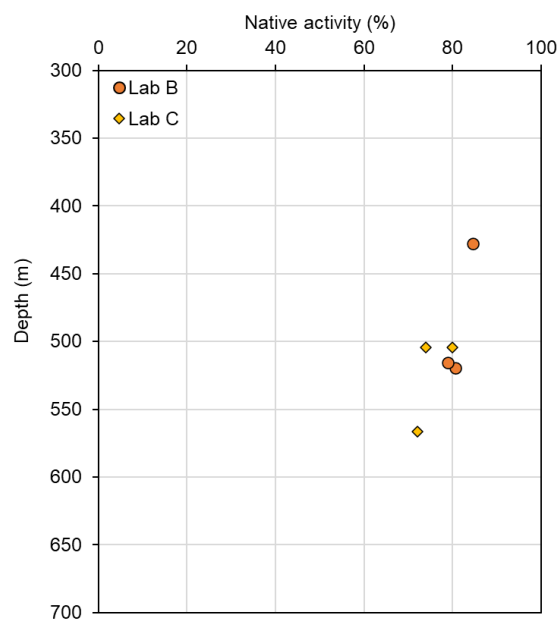


Fig. 6-2: Native activity of trimming material versus depth of collection
Results grouped by laboratory.

6.1.2 Atterberg limits, plasticity index, grain size distribution

In the context of the oedometric testing campaign Lab D performed geotechnical characterisation of the tested cores. They determined Atterberg limits, plasticity index and grain size distribution.

Atterberg limits were determined according to ASTM D4318-17 (ASTM 2017a); the material was manually crushed with a rubber-tipped pestle. Only the portion with grain dimension lower than 0.425 mm was used.

Grain size distributions were determined according to ad-hoc procedures developed by the laboratories, in line with Nagra's indications. The main aspects of the procedure of Lab D are here summarised. Lab D adopted a procedure implemented during previous projects involving Opalinus Clay and which is based on the ASTM D6913-17 (ASTM 2017b) and D7928-17 (ASTM 2017c); a gentle pre-crushing was performed manually with a rubber-tipped pestle, to separate the aggregates avoiding the breakage of individual particles. Before the test, the material was submerged in distilled water for 24 hours and sieved using water. Grain size distribution was determined by wet sieving for particles larger than 0.075 mm, and by sedimentation (by the use of a hydrometer) for the smaller particles.

Atterberg limits and granulometric fractions are summarised in Tab. 6-1. The results of the granulometric fractions show a clay fraction comparable with the clay mineralogical content determined by XRD for core BOZ2-1-464.07/50-GM (38 wt.-%). In the case of core BOZ2-1-529.52/48-GM, the results show higher discrepancies (clay mineralogical fraction is 64 wt.-%; Appendix D).

Granulometric fractions (sand, silt and clay) are distinguished (as by standard) on the dimension of the particles. It has to be pointed out that there could be particles in the silt granulometric fraction which are clay-mineral particles or aggregates with a larger size than the clay – silt threshold; on the other hand, there may be particles in the clay granulometric fraction which are minerals other than clays having fine particles dimension. All the previous considerations contribute to the difference between granulometric and mineralogical clay fractions.

Tab. 6-1: Atterberg limits and grain size fractions for the tested cores

Core ID	Lab	Core interval	w_L	w_P	PI	Gravel	Sand	Silt	Clay
		[cm]	[-]	[-]	[-]	[%]	[%]	[%]	[%]
BOZ2-1-464.07/50-GM	D	22 – 26	0.28	0.19	0.09	7.2	9.3	50.3	33.2
BOZ2-1-529.52/48-GM	D	24 – 29	0.40	0.27	0.13	0.0	4.5	55.5	40.0

6.2 Triaxial tests with specialised protocols

An overview of the performed tests is presented in Tab. 6-2. Each test is labelled with an ID indicating the main features of the test.

For example, the triaxial test ID B1_BOZ2_1_519_28_S7CTCU indicates the laboratory that performed the test (B), a testing sequential number (1), the borehole name (BOZ2-1), the specimen depth (519.28 m), the specimen geometry (S), effective confinement before shearing (7 MPa), the stress path (CTCU).

It is reported in Tab. 6-2 for each tested specimen:

- Specimen ID, as described above
- Core depth [m]
- Geological formation, as presented in Section 4.4.1
- Specimen geometry
- Total confining stress, p_0 [MPa] at the beginning of the shearing phase
- Pore pressure [MPa] at the beginning of the shearing phase
- Effective confining stress p'_0 [MPa] at the beginning of the shearing phase
- Stress path, as presented in Fig. 4-5
- Indication of shearing in drained conditions (d)
- Initial void ratio, computed using a reference solid density¹⁰ of 2.70 g/cm³
- Initial porosity, computed using a reference solid density of 2.70 g/cm³
- Initial and final water content.

The initial part of the ID (hereafter Specimen ID), including the laboratory and the sequential number is afterwards used as short code to quickly identify a specific test point in the entire set of results.

¹⁰ Solid density measurements were conducted on specimens used for mineralogical analysis, and are available in Appendix D.

Tab. 6-2: Conducted triaxial tests

Specimen ID, shearing phase characteristics, specimen initial (and final) conditions.

Specimen ID	Specimen location and geometry		Specimen geometry	Shearing phase characteristics				Specimen initial conditions			Final water content, w_f [%]
	Core depth [m]	Formation		Total confining stress, p_0 [MPa]	Pore pressure, u_{p0} [MPa]	Effective confining stress p'_0 [MPa]	Stress path	Initial void ratio, e_0 [-]	Initial porosity, n_0 [-]	Initial water content, w_0 [%]	
B7_BOZ2_1_427_95P7CTCU	427.95	Pass-wang	P	16	9	7	CTCU	0.140	0.123	5.72	6.06
B8_BOZ2_1_453_16S7CTCU	453.16	Opalinus Clay	S	16	9	7	CTCU	0.124	0.110	4.57	4.96
B9_BOZ2_1_453_16S13CTCU	453.16		S	22	9	13	CTCU	0.126	0.112	4.75	4.98
C6_BOZ2_1_504_78S13CTCU	504.78		S	22	9	13	CTCU	0.113	0.102	4.43	4.35
C11_BOZ2_1_504_78S7CTCU	504.78		S	16	9	7	CTCU	0.122	0.109	4.25	4.44
C12_BOZ2_1_504_78S7CTCU	504.78		S	16	9	7	CTCU	0.103	0.093	4.17	4.05
C5_BOZ2_1_504_78S8CTCU	504.78		S	16	8	8	CTCU	0.113	0.102	4.43	4.32
C9_BOZ2_1_504_95S13CTCU	504.95		S	22	9	13	CTCU	0.118	0.106	4.39	4.49
C7_BOZ2_1_504_95S8CTCU	504.95		S	16	8	8	CTCU	0.123	0.109	4.92	4.75
C1_BOZ2_1_504_95S7CTCU	504.95		S	16	9	7	CTCU	0.129	0.114	4.91	4.89
C2_BOZ2_1_504_95S13CTCU	504.95		S	22	9	13	CTCU	0.131	0.116	5.07	5.01
B10_BOZ2_1_515_60P7CTCU	515.60		P	16	9	7	CTCU	0.123	0.109	4.91	5.38
B11_BOZ2_1_515_91P7CTCU	515.91		P	16	9	7	CTCU	0.130	0.115	5.26	5.67
B11b_BOZ2_1_515_91P7CTCU	515.91		P	16	9	7	CTCU	0.109	0.099	4.40	4.75
B5_BOZ2_1_519_23P7CTCU	519.23		P	16	9	7	CTCU	0.145	0.126	5.88	5.91
B1_BOZ2_1_519_28_S7CTCU	519.28		S	16	9	7	CTCU	0.140	0.123	5.79	6.11
B2_BOZ2_1_519_30S13CTCU	519.30		S	22	9	13	CTCU	0.136	0.119	5.70	5.83
B12_BOZ2_1_519_28S13CTCU_RH	519.30		S	16	9	7	CTCU	0.149	0.130	5.82	6.57
B6_BOZ2_1_519_39P7CTCU	519.41		P	16	9	7	CTCU	0.117	0.105	5.38	5.55
C4_BOZ2_1_566_28S13CTCU	566.28		S	22	9	13	CTCU	0.139	0.122	4.99	4.94
C8_BOZ2_1_566_28S7CTCU	566.28		S	16	9	7	CTCU	0.133	0.117	5.44	5.23
C10_BOZ2_1_566_28S7CTCU	566.28		S	16	9	7	CTCU	0.133	0.118	5.23	5.33
C3_BOZ2_1_566_28S7CTCU	566.28		S	16	9	7	CTCU	0.145	0.127	5.71	5.46
C13_BOZ2_1_566_28P7CTCU	566.28		P	16	9	7	CTCU	0.141	0.123	5.29	5.28
C14_BOZ2_1_566_58P7CTCU	566.58		P	16	9	7	CTCU	0.158	0.136	6.45	6.13

6.2.1 Saturation and consolidation phase

6.2.1.1 Swelling pressure

In the conventional triaxial procedure (adopted by Lab B), the specimen saturation was conducted imposing isochoric conditions and monitoring the evolution of the axial and radial stress. The effective stress reached at the end of the saturation phase is called swelling pressure, and the results (grouped by S- and P-geometries, respectively) are reported in Fig. 6-3 versus the specimen initial water content (before saturation). For specimens with S-geometry, the radial direction corresponds to the one of the bedding, while the axial direction is perpendicular to it. Swelling pressure was found to be higher in the axial direction.

On the other hand, in P-samples, the axial direction corresponds to the bedding direction, while the radial stress is obtained by maintaining close to zero the average of the deformation in the two radial directions, perpendicular and parallel to bedding.

It has to be noted that the experimental configuration adopted by Lab B, does not allow to sustain a confining pressure higher than the axial pressure. In BOZ2-1 saturation tests, P-samples showed a tendency of the confining pressure to rise above the axial pressure. Hence, the axial pressure was adjusted to the confining value, and the two values coincide in Fig. 6-3.

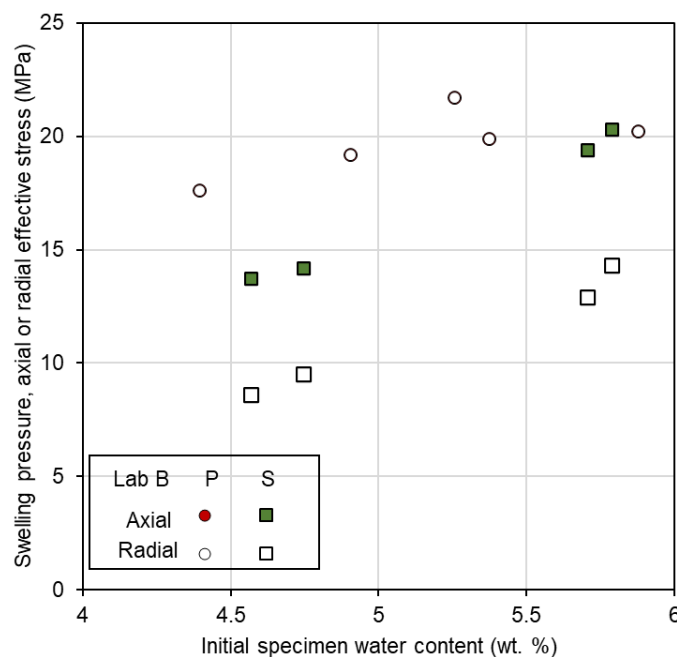


Fig. 6-3: Radial and axial swelling pressure versus initial specimen water content S-samples and P-samples (Opalinus Clay).

6.2.1.2 Swelling strain during saturation

In the alternative procedure tests from Lab C and test B12, swelling occurred to the samples once they were put in contact with high relative humidity in the desiccator. The swelling strain is calculated from the sample dimensions before and after the pre-conditioning in the desiccator. Water content variation is also estimated by the change in weight, divided by the dry weight, measured at the end of the test. The results are presented in Tab. 6-3.

Tab. 6-3: Water content change and strains during sample preconditioning in the dessicator

* Only one radial strain available for P-samples. This may be not representative of the radial strain in the direction both perpendicular and parallel to bedding, and an impact on the calculated volumetric strain is envisaged.

Long ID	Geo- metry	RH	Water content [-]		Strains [-]		
			Before RH equilibr.	After RH equilibr.	Radial	Axial	Volume tric
		[%]	[-]	[-]	[-]	[-]	[-]
C1_BOZ2_1_504_95S7CTCU	S	96	0.042	0.049	-0.0027	-0.0067	-0.0120
C2_BOZ2_1_504_95S13CTCU	S	92	0.046	0.051	-0.0027	-0.0067	-0.0120
C3_BOZ2_1_566_28S7CTCU	S	96	0.050	0.057	-0.0027	-0.0053	-0.0107
C4_BOZ2_1_566_28S13CTCU	S	92	0.045	0.050	-0.0013	-0.0040	-0.0067
C5_BOZ2_1_504_78S8CTCU	S	96	0.036	0.044	-0.0027	-0.0087	-0.0140
C6_BOZ2_1_504_78S13CTCU	S	92	0.039	0.044	-0.0013	-0.0067	-0.0093
C7_BOZ2_1_504_95S8CTCU	S	96	0.042	0.049	-0.0026	-0.0060	-0.0113
C8_BOZ2_1_566_28S7CTCU	S	92	0.047	0.054	0	-0.0033	-0.0033
C9_BOZ2_1_504_95S13CTCU	S	85	0.040	0.044	-0.0013	-0.0020	-0.0046
C10_BOZ2_1_566_28S7CTCU	S	85	0.048	0.052	0	-0.0033	-0.0033
C11_BOZ2_1_504_78S7CTCU	S	96	0.035	0.042	-0.0040	-0.0073	-0.0153
C12_BOZ2_1_504_78S7CTCU	S	85	0.035	0.042	0.0000	-0.0007	-0.0007
C13_BOZ2_1_566_28P7CTCU	P	85	0.043	0.053	-0.0093*	-0.0007	-0.0193*
C14_BOZ2_1_566_58P7CTCU	P	85	0.059	0.065	-0.0040*	-0.0014	-0.0094*
B12_BOZ2_1_519_28S7CTCU _RH	S	96	0.053	0.058	-0.0017	-0.0097	-0.0131

In several samples, the dessicator induced volumetric swelling strains are above 1%. In tests B12 from Lab B, the sample experienced an additional swelling in the triaxial cell (volumetric strain increment of -0.13%), while in contact with brine under a constant load.

An effect on the hydromechanical response of the geomaterial is observed, and discussed in Section 6.2.2.5.

6.2.1.3 B check tests

In each test, the specimen saturation was verified by performing Skempton's B checks. B values were computed over multiple steps. If the difference in B values among the steps was less than 10%, the average of the measurements was considered as the B coefficient and associated with the average effective confinement level at which B segments were performed. The values are reported in Fig. 6-4 for all results.

The compressibility of the apparatus can affect the accuracy of the measured B values. Wissa (1969) proposed a correction to the B value to consider the compressibility of the dead volume of water (i.e., the water in the drainage system) and the compressibility of the system (tubes and transducers). However, several researchers (e.g., Ghabezloo & Sulem 2010) show that the compressibility of modern types of steel tubes and transducers has a negligible impact on the B measurements compared to the dead water volume impact. Therefore, the results of the testing campaign have been analysed considering the dead water volume in each apparatus, and B values results ($B_{correct}$) were computed as (Wissa 1969, Favero et al. 2018):

$$B_{correct} = \frac{1}{\frac{1}{B_{obs}} - \frac{V_L}{V} - \frac{K}{K_f(1 - K/K_s)}} \quad (6-1)$$

where B_{obs} is the measured B value, V_L is the volume of fluid in the porewater lines, V is the volume of the specimen, K is the bulk modulus of the specimen, K_f the bulk modulus of the pore fluid and K_s the bulk modulus of the solid phase. Bulk and solid moduli $K = 6$ MPa and $K_s = 50$ MPa were considered for the corrections. The correction was applied for results of Lab B, while the Lab C apparatus considers a close to zero dead volume; therefore, no correction was applied. It has to be noted that the dead volume in the apparatus from Lab B is ~ 700 mm³. The results for the measured and corrected B values are reported in Fig. 6-4. An average value of 0.86 was calculated and marked as a dotted line in the graph.

In test B12, Skempton's B tests were conducted at approximately 6.5 MPa of effective confinement, yielding a measured value of 0.95. Applying the above-mentioned correction for water volume compressibility, the corrected B value results slightly above 1. This may be due to an overestimation of K in the low confinement range, which affects the correction.

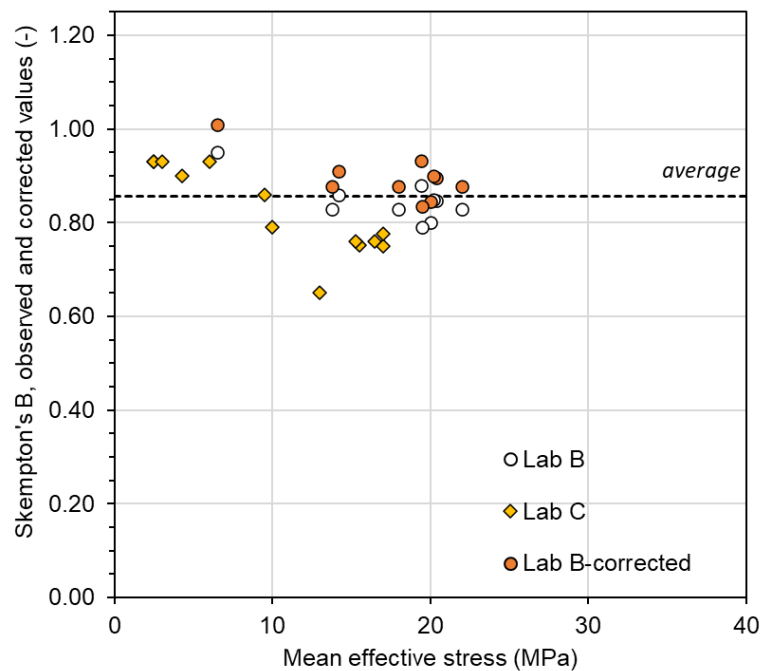


Fig. 6-4: Average Skempton's B values

B values versus the corresponding effective mean stress; data from BOZ2-1 (Opalinus Clay): Observed and corrected values accounting for dead water volume.

6.2.1.4 Consolidation phase

Drained consolidation phases were performed to achieve the target effective confining stress for shearing, and allow for determining the consolidation coefficient, according to Head (1998). The time to consolidate was obtained applying the square root of time method in the evaluation of the evolution of the volumetric strain. It is noted that the method refers to an instantaneous loading of the sample. However, in most test adopting a conventional method, the stress level at the end of saturation is higher than the target value for shearing, hence an unloading (with consequent swelling of the sample) was performed. Performing quasi-instantaneous unloading is challenging, given the stress levels involved, and often a ramp of several hours needs to be used. Therefore, the consolidation coefficient obtained from these results may be underestimated. It is further noted that the values were obtained by considering the time to consolidate excluding the time required to load. The obtained values for all tested specimens of Opalinus Clay are reported in Fig. 6-5 versus the mean effective stress at the end of the consolidation phase. In three cases, volumetric strain didn't reach a stable value in time, which makes the constraining of a consolidation coefficient value uncertain. These values are reported in the figure with a light-colored marker with dotted edge line.

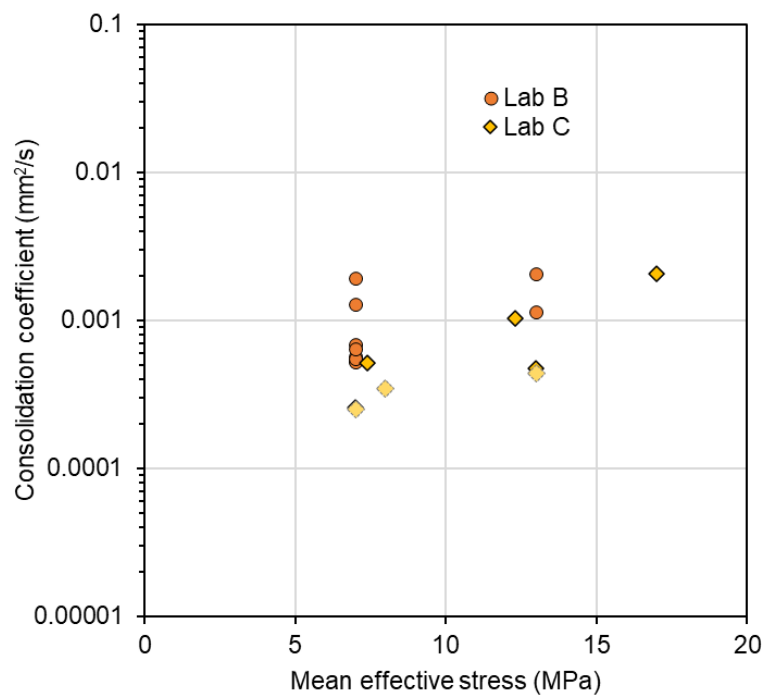


Fig. 6-5: Consolidation coefficient for Opalinus Clay specimens (all geometries)

Light-colored markers refer to values obtained in consolidation phases in which strains did not achieve a stable level in time, and the consolidation coefficient is affected.

6.2.2 Shearing phase

This section provides the results of the shearing phase of tests. The stress paths are reported in the $q - p'$ plane, where q is the deviatoric stress (Eq. 4-2) and p' is the mean effective stress, obtained by subtracting the porewater pressure u_w from the total stress (Eq. 4-1).

6.2.2.1 Stress paths of Opalinus Clay subunits

This section focuses on the stress paths obtained on Opalinus Clay specimens during the shearing phase of the tests. The behaviour of the tested specimens is characterised by a pronounced non-linearity before the peak stress and softening response after the peak. A similar evolution of the deviatoric stress (q) and porewater pressure (u_w) with the axial effective strain is observed among the tests (see Appendix B). The effective stress paths obtained on Opalinus Clay specimens are here grouped by the lithological sub-units (Fig. 6-6), as presented in Section 4.4.1. Results are further subdivided by the sample geometry.

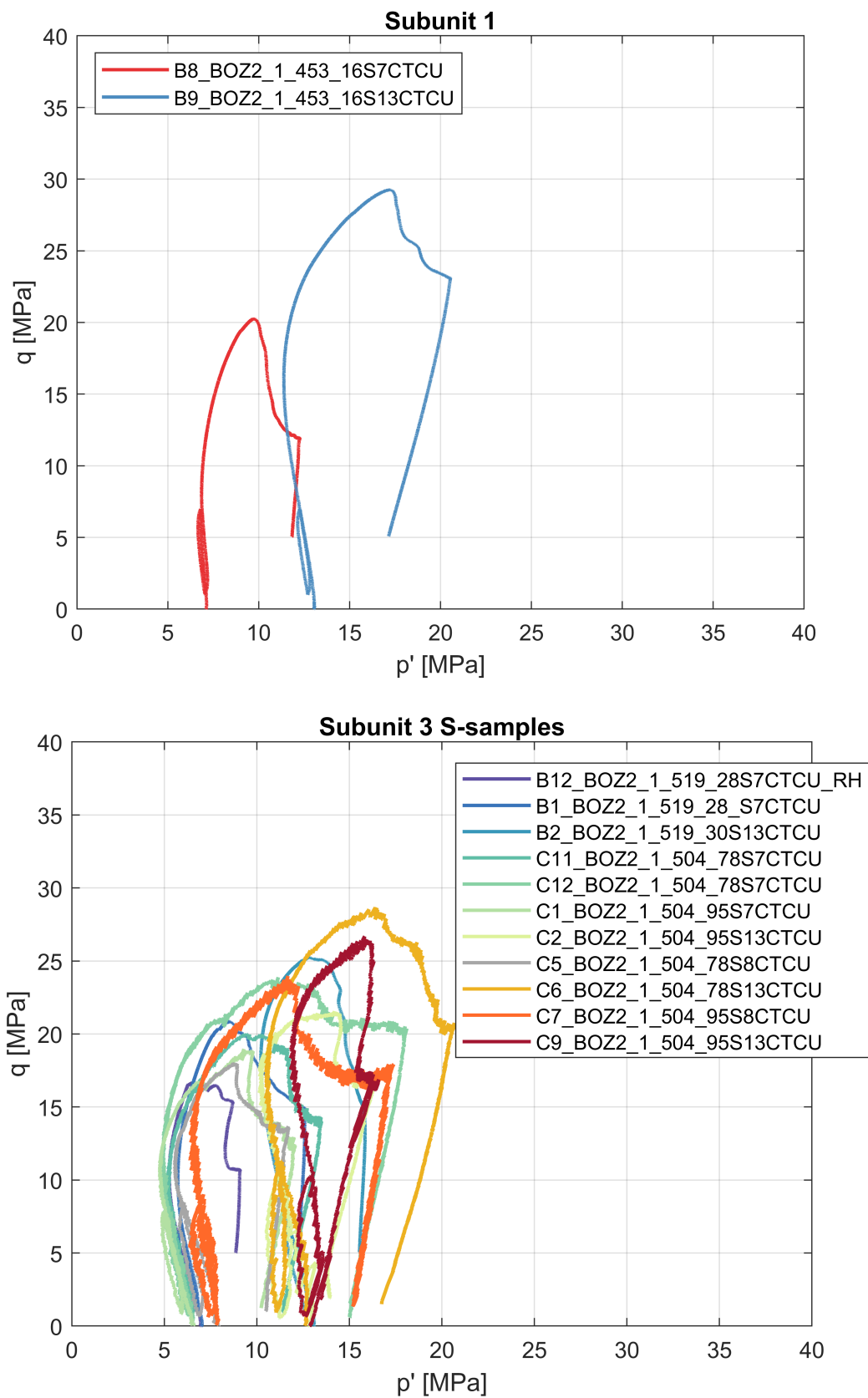


Fig. 6-6: Effective stress paths of tested specimens grouped by the lithological (sub-)unit

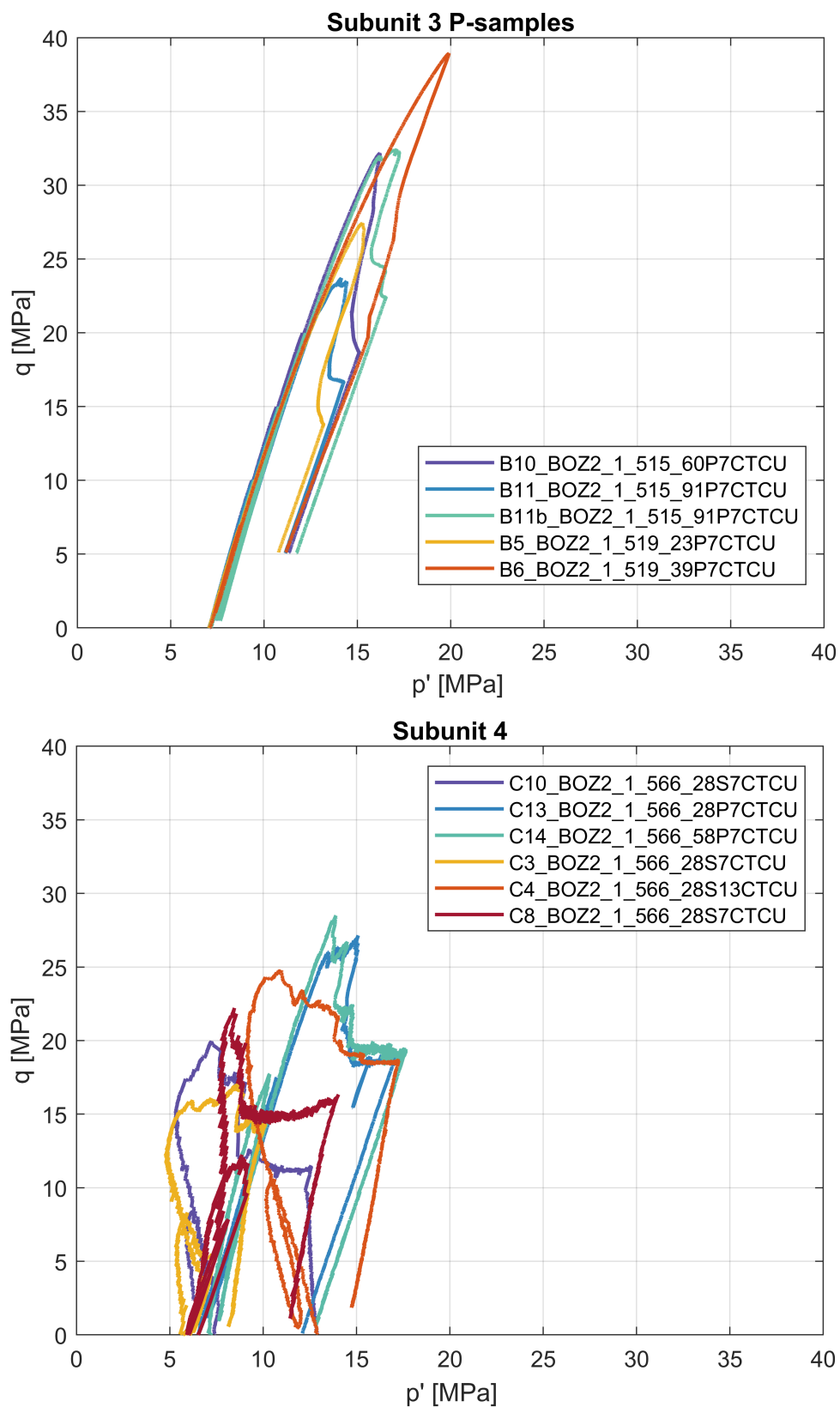


Fig. 6-6: (continued)

Due to their unusual stress path history and evolution, some tests exhibited a lower peak shear strength compared to the majority of the results. These tests are analysed in more detail in Section 6.2.2.5, as they help to understand the importance of the sample history in the analysis of the final results.

6.2.2.2 Elastic phase

The analysis of the elastic parameters for Opalinus Clay samples is presented in this section. Unloading/reloading cycles were performed to estimate the elastic response of the material during an unloading phase. As requested in the testing procedure, the cycles were carried out during the shearing of the specimens before the achievement of the peak stress.

During unloading and reloading, shales present a hysteretic and non-linear behaviour. Depending on the strain amplitude of the unloading/reloading loop, the secant moduli may vary considerably. The strains are calculated as the ratio of the variation in height (or diameter) to the initial height (or diameter). To eliminate the dependency of the moduli on the amplitude of the unloading loop, the elastic modulus for all analysed tests was computed as the secant modulus during unloading for a pre-fixed strain range, 0.02 – 0.04% from the beginning of the unloading phase (Fig. 6-7). The strain calculation refers to the initial specimen height. The strain amplitude was selected as common to all the analysed test results.

Small-strain moduli were also evaluated from the stress cycles (Fig. 6-7) according to the procedure presented in Giger et al. (2018). An example of elastic moduli evaluation is reported in Fig. 6-7, with reference to test BUL1_1_950_62S9CTCU_B (BUL1-1 testing campaign; Nagra 2021a). The top graph in Fig. 6-7 shows the evolution of the secant moduli with the axial strain range used for their computation, for the unloading phase. A clear non-linear decrease of the modulus is observed with the axial strain, which reflects the non-linearity of the material's response. This feature highlights the importance of the axial strain range adopted to perform unloading/reloading cycles. Different ranges lead to different moduli, making a comparison among the tests difficult and misleading. Generally, larger strain ranges lead to lower moduli (Minardi et al. 2019).

A summary plot comparing small strain moduli and secant moduli is provided in Fig. 6-8. It is highlighted that small strain moduli are always higher than the secant moduli computed over the common strain range. Secant moduli from P- and S-samples are provided in Fig. 6-9, sorted by specimen final water content. In the case of P-tests, higher values of the undrained elastic moduli with respect to S-tests are observed.

In terms of radial response, the relationship between axial and radial deformations during the unloading phase of the cycles performed before the achievement of the peak stress was used ($-\Delta\epsilon_r/\Delta\epsilon_a$) for the assessment of the undrained equivalent of the drained Poisson's ratio (ν). In the undrained conditions, deviations from the theoretical value of 0.5, typically obtained from the linear isotropic elasticity, are due to the anisotropic features of the material and possible poro-elastic effects. The computed parameters for the undrained unloading loops are reported in Fig. 6-10 (also, Appendix E), divided by specimen geometry (S and P) and along with the corresponding elastic moduli.

For P-samples, the radial sensors detected the expected anisotropic response, with higher deformation in the direction perpendicular, compared to the direction parallel to the bedding plane. As a consequence, the Poisson's ratios computed using the strain perpendicular to bedding are higher than those parallel to bedding (values in Appendix E). This agrees with previous findings.

Ultrasonic velocities of P (V_p) and S (V_s) waves were also measured by Lab B and C. Both laboratories measured the velocity of P and S waves in the axial direction (V_p and V_s). In 5 tests, Lab B measured P wave velocity also in the direction orthogonal to the cylinder axis (V_{ph}).

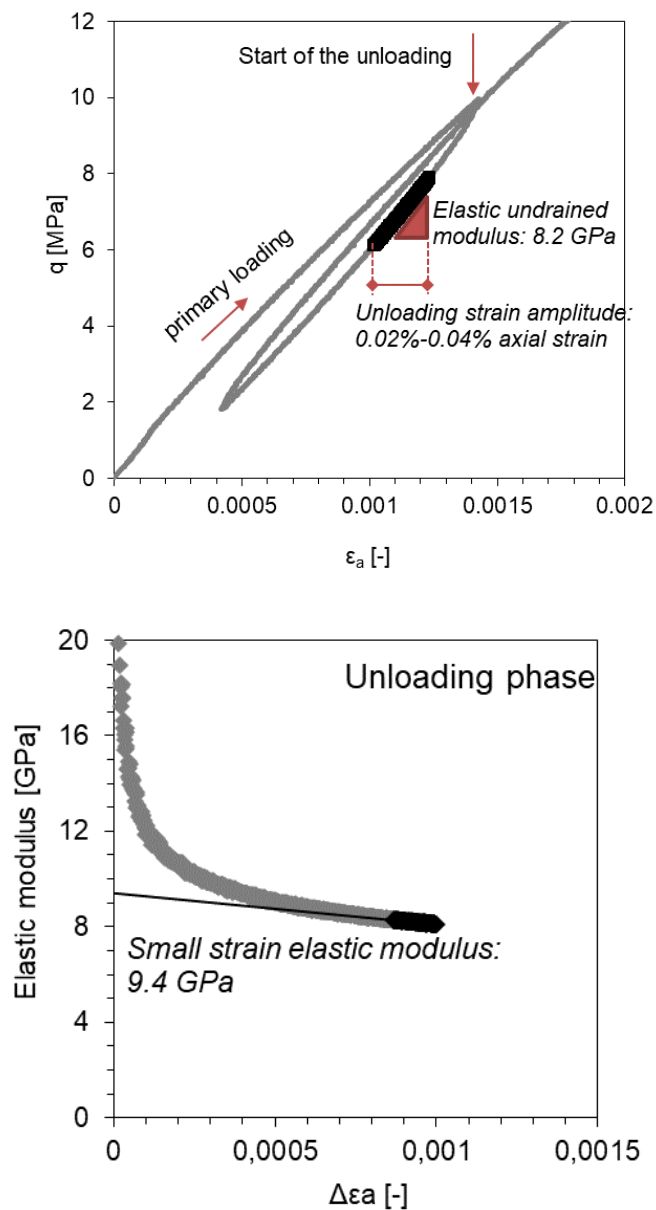


Fig. 6-7: Unloading/reloading cycle and small strain elastic modulus in triaxial tests

Determination of the elastic undrained moduli (E_u) during the unloading phase, for a pre-determined strain amplitude (top); small strain elastic modulus obtained on the unloading phase (bottom) (test BUL1_1_950_62S9CTCU_B, Nagra 2021a).

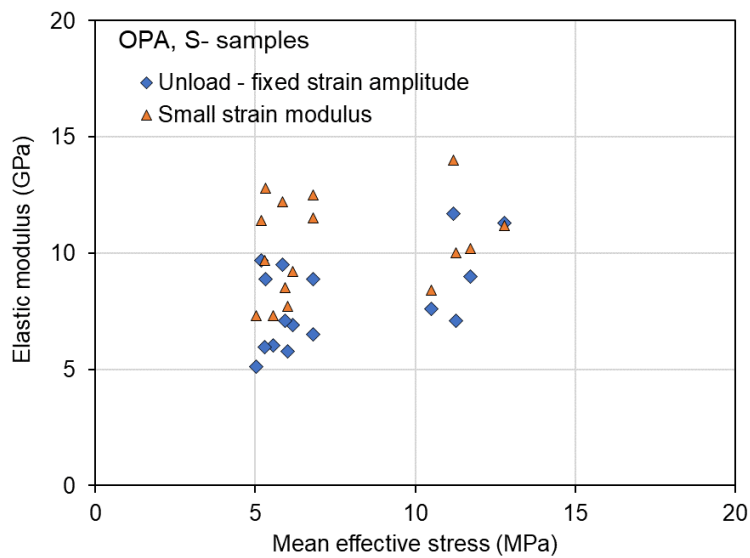


Fig. 6-8: Elastic undrained moduli calculated over an unloading (UL) path: modulus of a fixed strain interval and small strain extrapolation (S-samples)

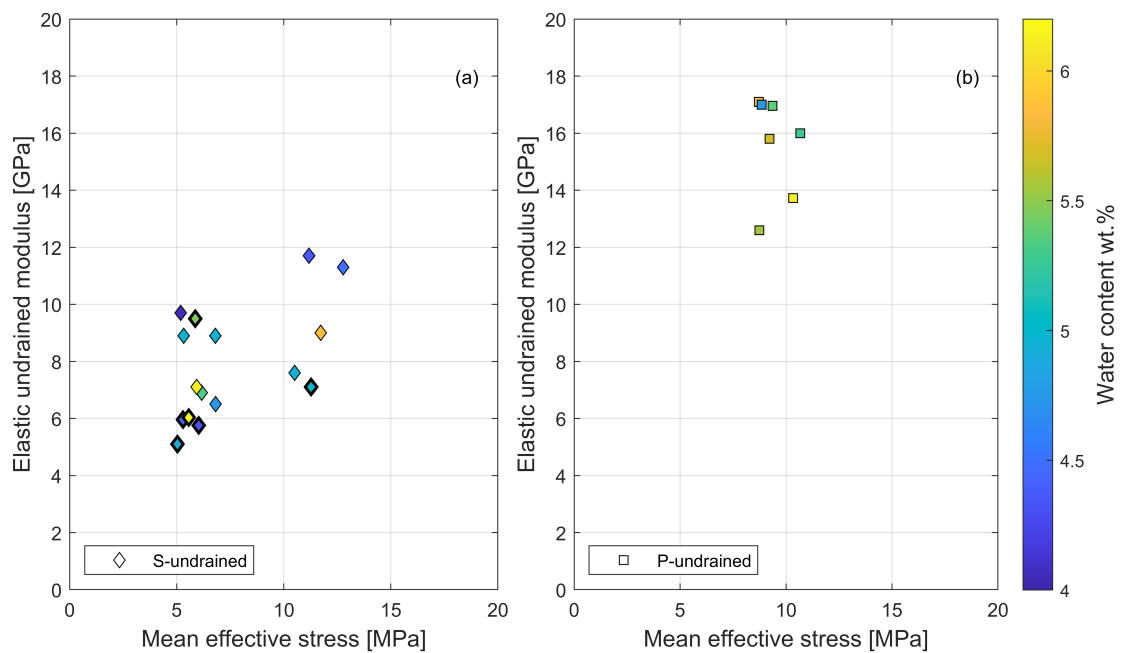


Fig. 6-9: Elastic undrained moduli, sorted by specimen final water content

Moduli are calculated over a fixed strain interval during an unloading (UL) path: P- and S-geometries, sorted by water content at the end of the test (final). Thicker marker lines indicate samples for which lower strength was achieved (damaged). The high stiffness value at 9.5 MPa is sample C3_BOZ2_1_566_28S7CTCU, see Section 6.2.2.5 for further details.

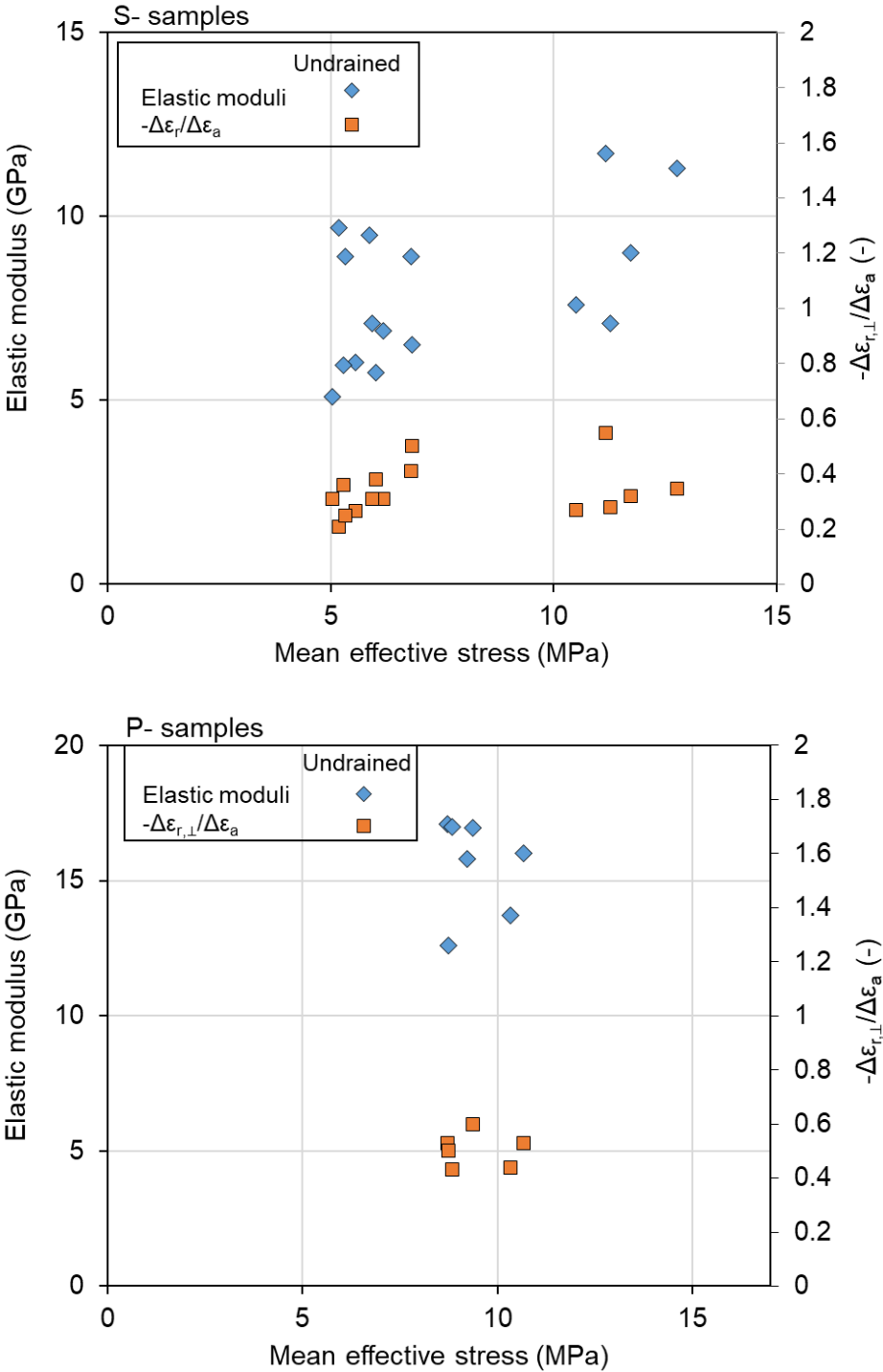


Fig. 6-10: Elastic undrained properties

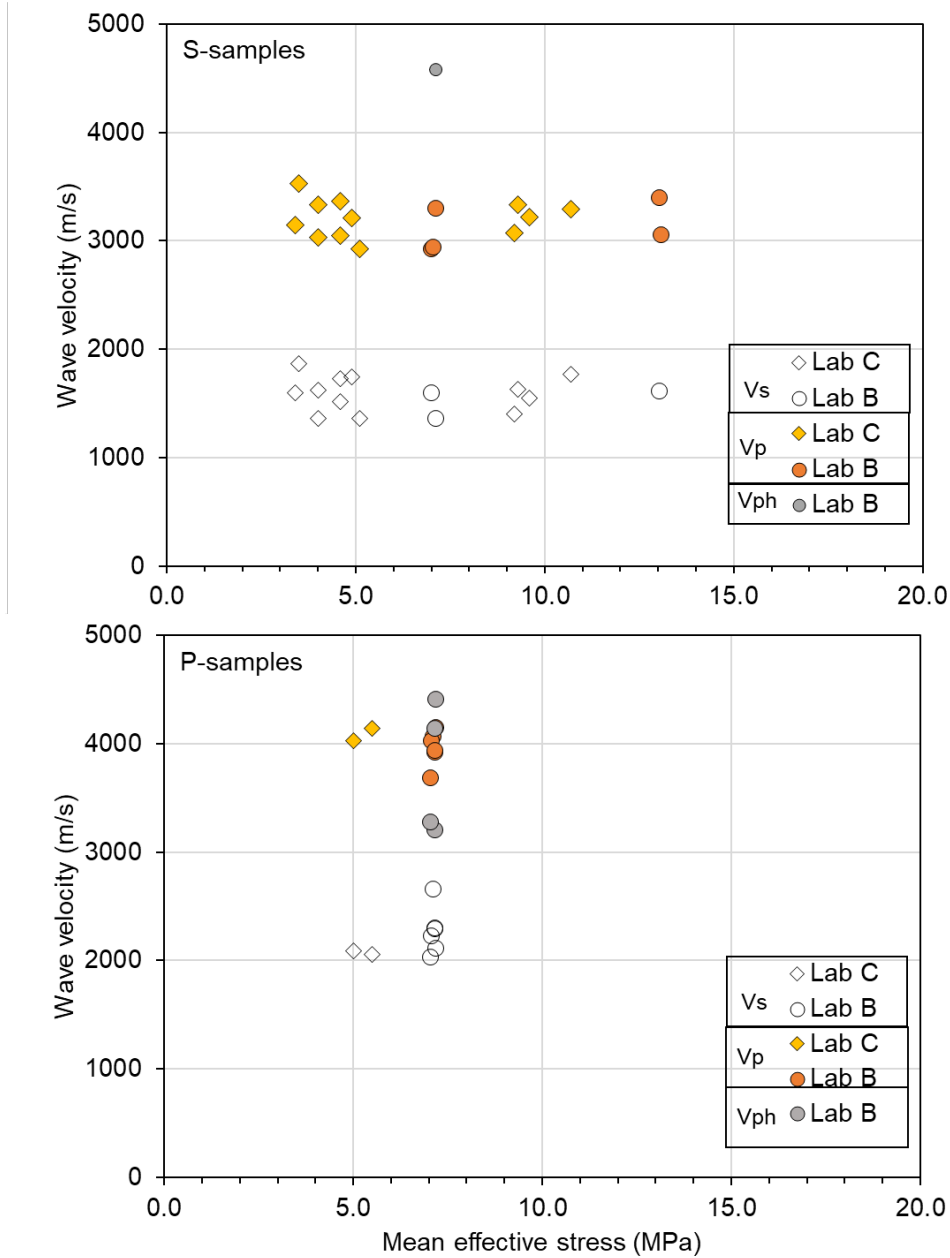


Fig. 6-11: Wave velocities at the beginning of the shearing phase

Results are divided by specimen geometry (data in Appendix E).

6.2.2.3 Pore pressure evolution

In Fig. 6-12, the stress levels ($p' - q$), at which the maximum value of the AB parameter and the maximum pore pressure u_w are reached, are plotted along with the peak shear strength for all test results (data in Appendix B). q is the deviatoric stress, p' is the mean effective stress, Δu_w is the variation of pore fluid pressure from the beginning of the shearing, AB is the ratio between Δu_w and q . The results are divided by specimen geometry.

On each graph, the tests that showed a not in conformity response (i.e. peak strength considerably lower than the majority of the tests or inconsistent stress path evolution) are highlighted. Those tests are indicated with a short code, being the initial part of the Specimen ID (Section 6.2), and are reported in Section 6.2.2.5. A detailed discussion of these results is out of the scope of the current report, and will be addressed in dedicated contribution.

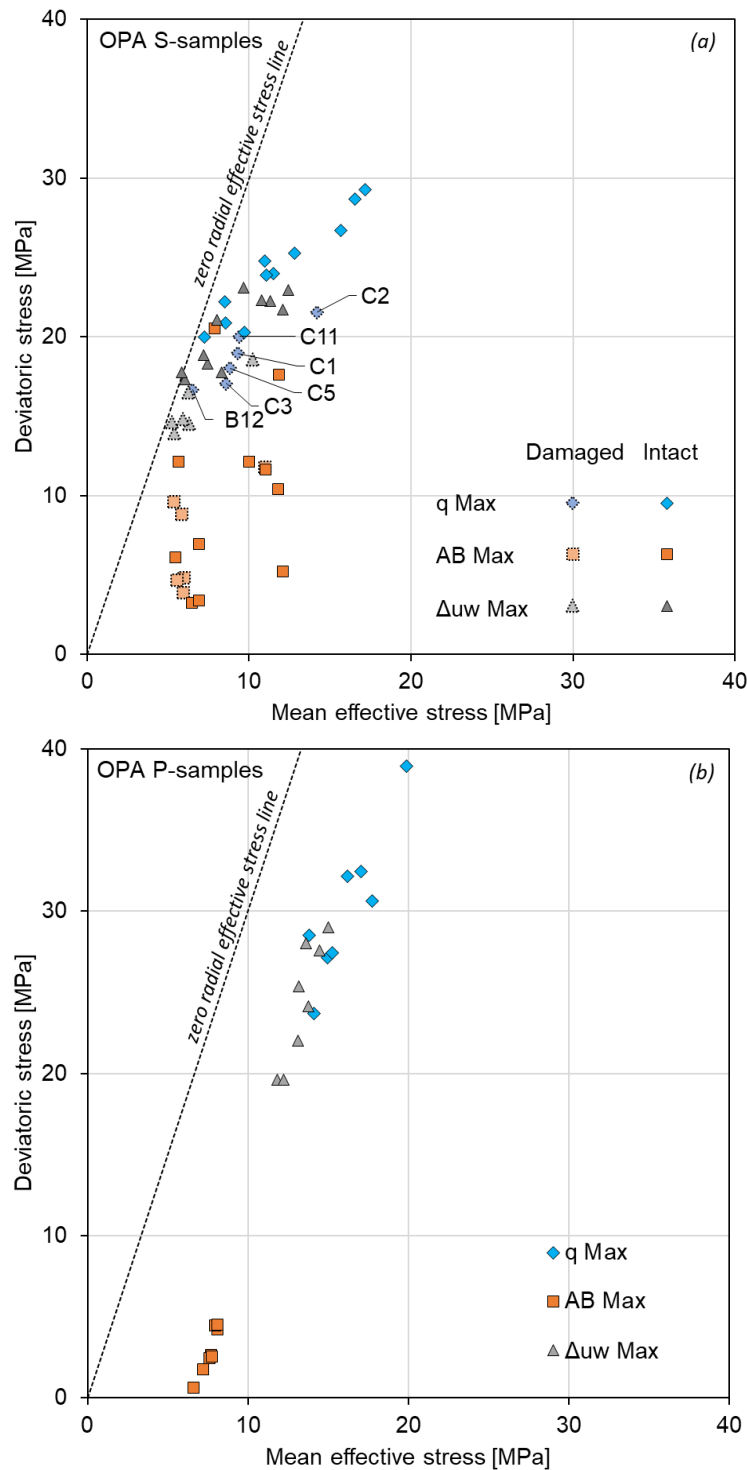


Fig. 6-12: Stress level at which the maximum deviatoric stress, the maximum value of pore pressure and the maximum value of the AB parameter are achieved
Opalinus Clay results, all geometries (a) S-samples, (b) P-samples.

6.2.2.4 Shear strength

For all tested specimens, during shearing, a peak in deviatoric stress was achieved, before softening occurred, followed by near-constant deviatoric stress. The peak value is reported below, as the *peak shear strength*, while the constant deviatoric stress achieved during continuing shearing (axial strain up to 2 – 3%) is hereafter referred to as *post-peak shear strength*.

In Fig. 6-13, peak (a) and post-peak shear strength (b) are reported in the $p' - q$ plane. Only Opalinus Clay results are reported and grouped by specimen geometry. The dotted lines highlight the pair of $p' - q$ values, at which radial effective stress equals zero. This line would correspond to the same boundary conditions as a UCS test if pore fluid pressure was zero. The stress states on the left side of this line cannot be achieved (negative radial effective stress) in a triaxial apparatus.

In Fig. 6-14 the peak shear strength results are analysed, sorted by the water content (Fig. 6-14a) of the specimens (obtained at the end of the test) and by the clay mineral content (Fig. 6-14b), where available. The plot includes the results of S-samples of Opalinus Clay. The results are reported also in Fig. 6-15 in terms of radial versus axial effective stress.

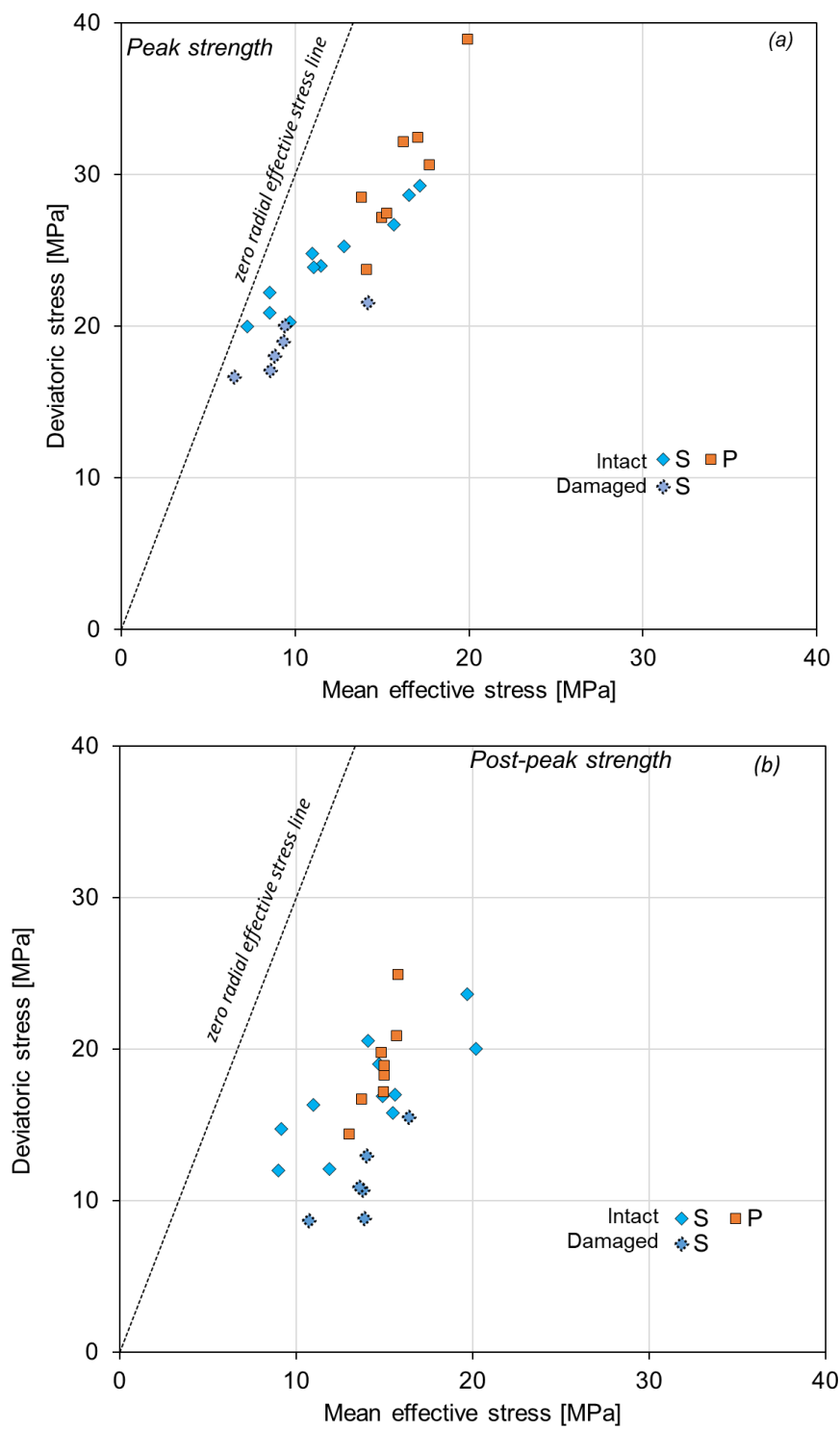


Fig. 6-13: Peak (a) and post-peak (b) shear strength of Opalinus Clay BOZ2-1 specimens
Results divided by geometry.

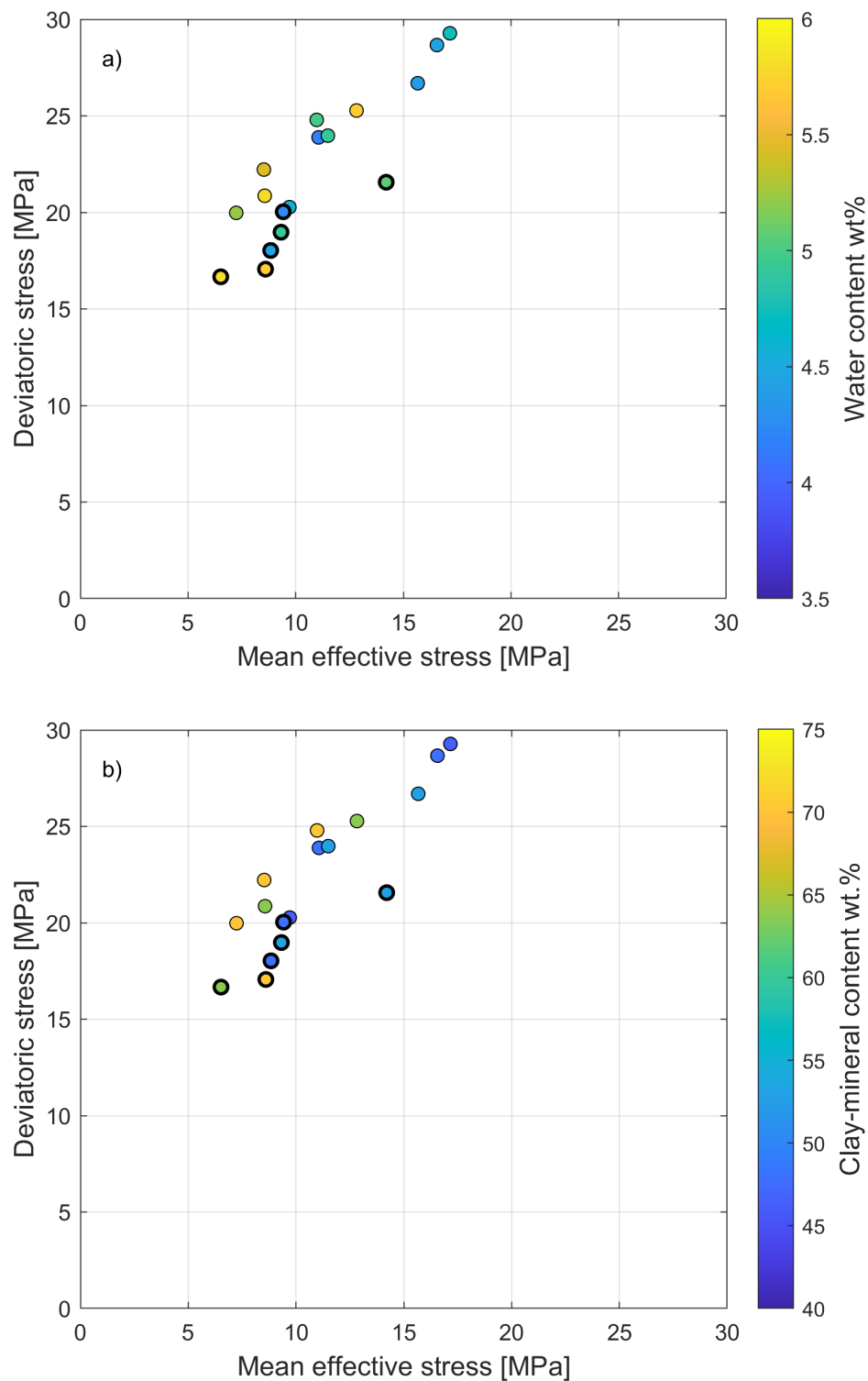


Fig. 6-14: Peak shear strength of Opalinus Clay specimens

Results in mean effective versus deviatoric stress, sorted by (a) water content and (b) clay mineral content, when available. Only S-samples are reported. Samples that showed low strength are highlighted with a thick marker line.

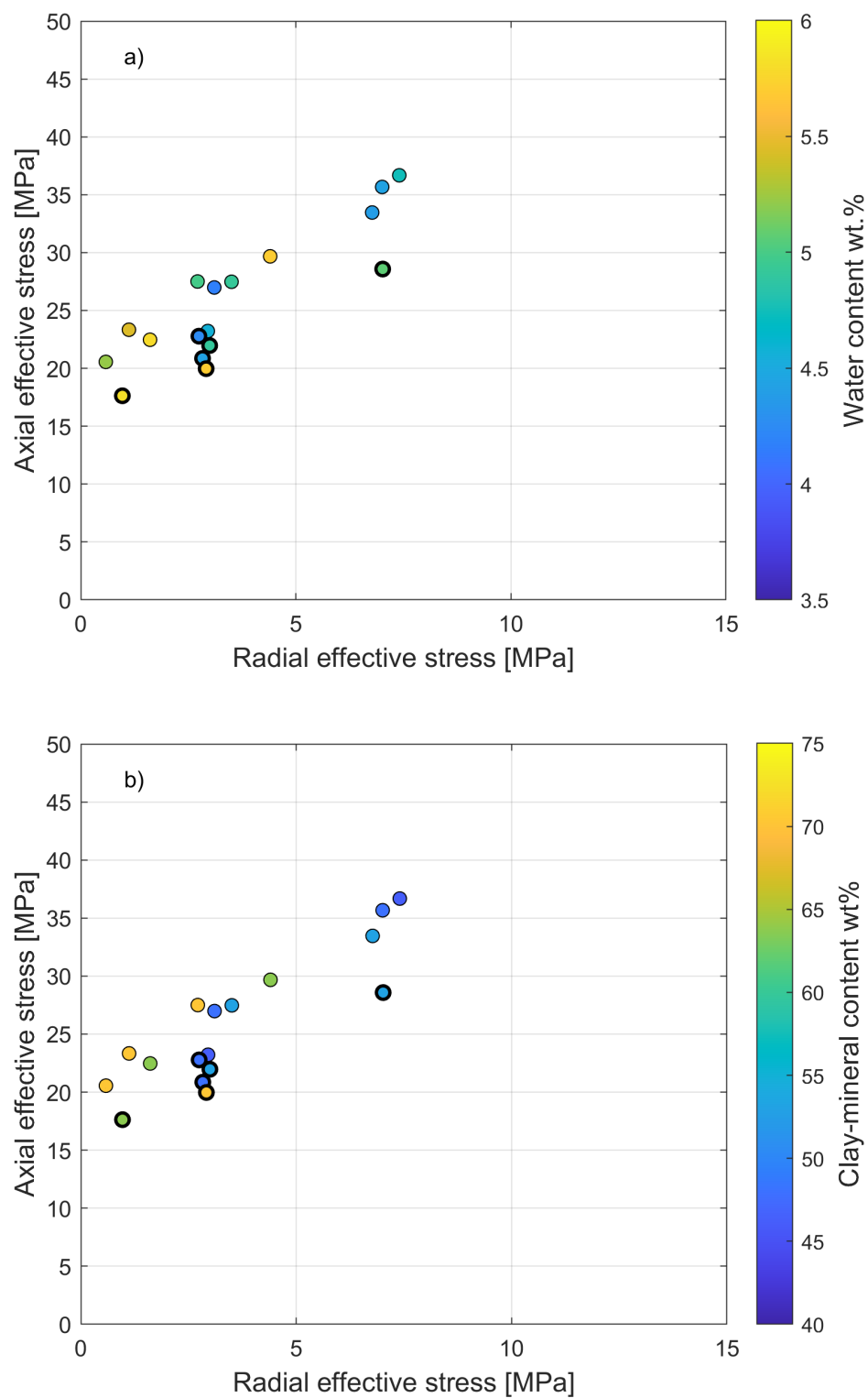


Fig. 6-15: Peak shear strength of Opalinus Clay specimens

Results in radial versus axial effective stress, sorted by (a) water content and (b) clay mineral content, when available. Only S-samples are reported. Samples that showed low strength are highlighted with a thick marker line.

6.2.2.5 Not in conformity low strength samples

In the following, the short code including the laboratory letter and the sequential number is adopted to refer to the test IDs.

Tests C1, C5, and C11 showed lower strength compared with tests C7 and C12, while they are from the same sections (Fig. 6-16) and considered comparable. It is noted that the three samples which showed lower strength, also reached maximum pore pressure earlier in their respective stress paths.

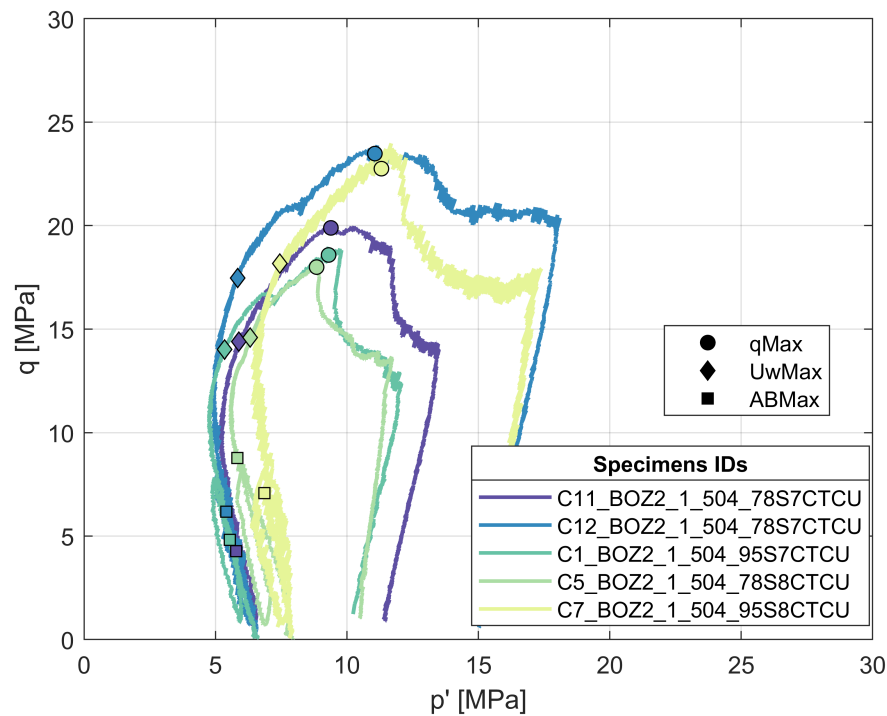


Fig. 6-16: Stress paths of tests C1_BOZ2_1_504_95S7CTCU, C5_BOZ2_1_504_78S8CTCU and C11_BOZ2_1_504_78S7CTCU, compared with stress path of 2 tests from the same section

Test C2 reached peak strength earlier than tests C6 and C9 from the same section (Fig. 6-17). Also in this case, maximum pore pressure was achieved earlier during the stress path. After reaching the maximum, the pore pressure in test C2 dropped at faster rate, hence the stress path turned towards higher p' values.

Test C3 reached peak strength later than test C10 from the same section (Fig. 6-18). The stress path showed multiple jumps and after peak, only a limited strength reduction was observed.

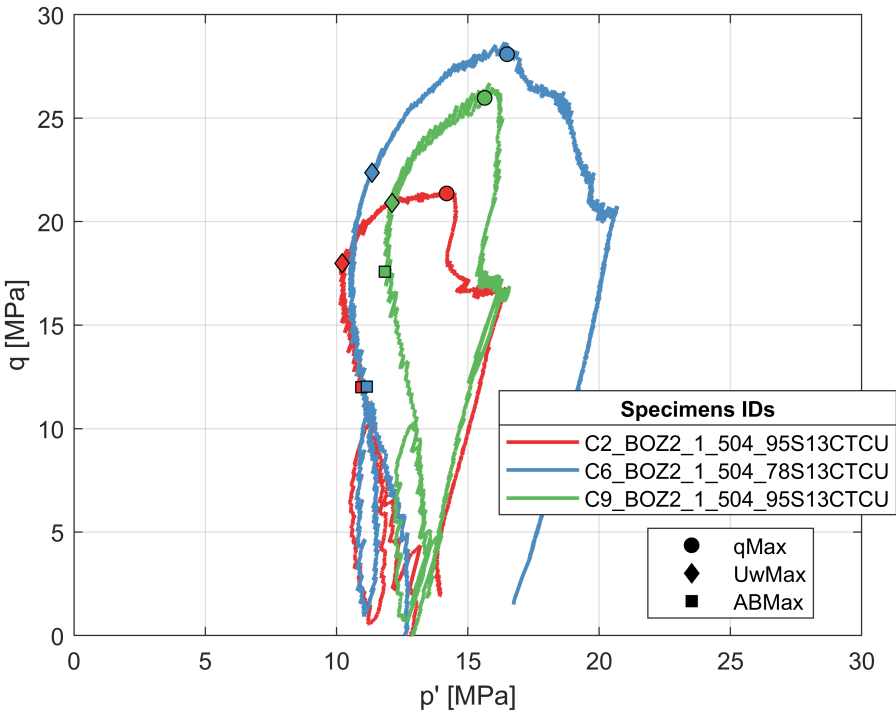


Fig. 6-17: Stress path C2_BOZ2_1_504_95S13CTCU, compared with the stress path of 2 tests from the same section

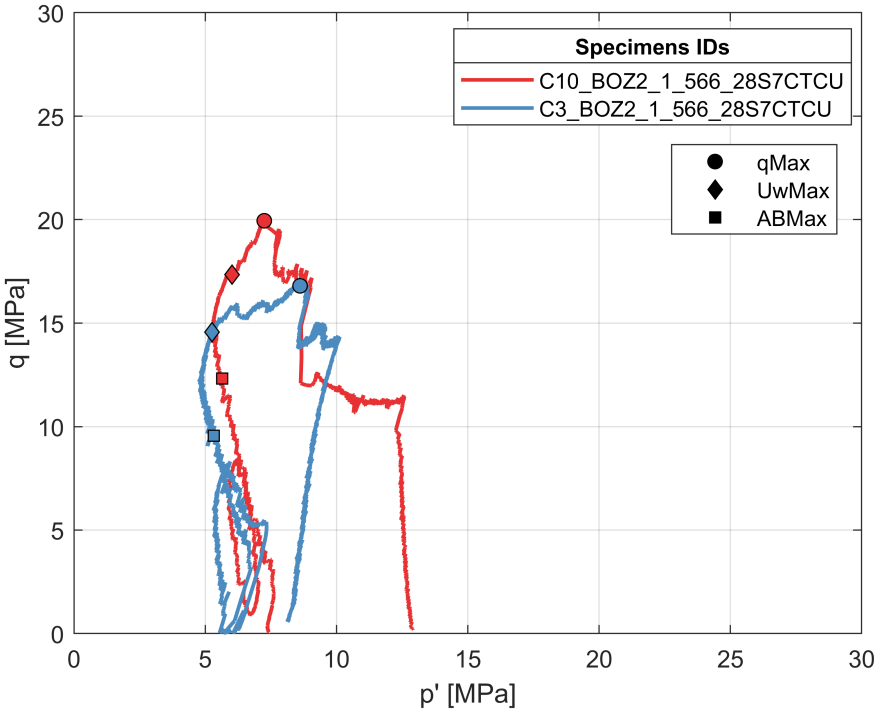


Fig. 6-18: Stress paths of sample C3_BOZ2_1_566_28S7CTCU (low strength), compared with test C10_BOZ2_1_566_28S7CTCU

All the above mentioned samples, showing low strength compared to similar samples from the same sections, had also experienced volumetric swelling strain during the pre-conditioning above 1%.

Sample B12_BOZ2_1_519_28S7CTCU_RH was equilibrated in the desiccator at a relative humidity of 96% for over 6 weeks, during which the sample experienced a volumetric swelling strain of about -1.3%. X-ray computer tomography scans showed that microfissures had developed in the sample during the equilibration in the desiccator. The stress path during shearing is reported in Fig. 6-19. Sample B12 reached peak strength abruptly right after the maximum pore pressure, and failed at a lower stress level compared to the twin sample B1, obtained from the same section, that followed the conventional testing procedure.

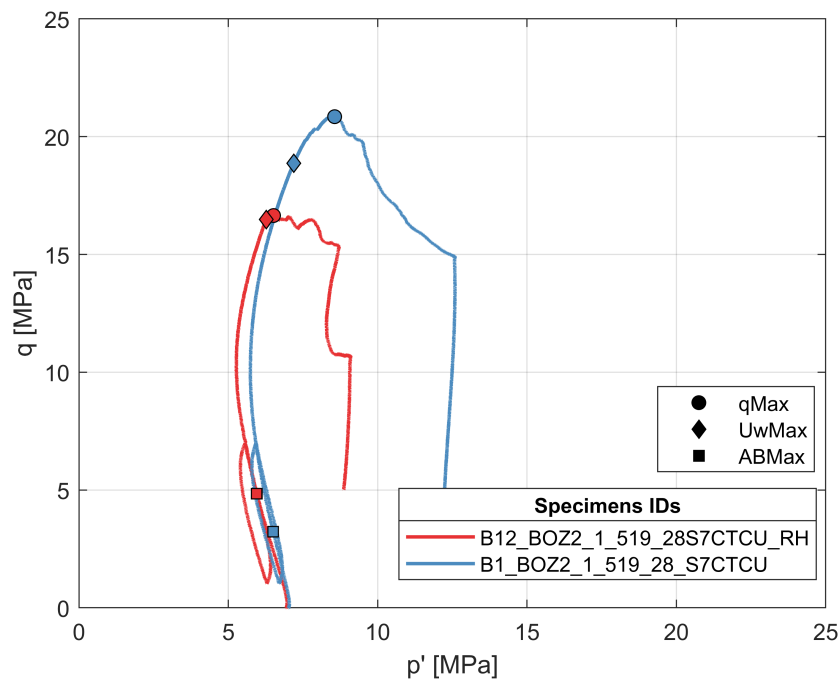


Fig. 6-19: Stress path of sample B12_BOZ2_1_519_28S7CTCU_RH (low strength), compared with test B1_BOZ2_1_519_28_S7CTCU

6.2.2.6 Analysis of the outlier results and of the anomalies

In this section, tests that showed a response significantly different not in compliance with the majority of the results (outliers) are analysed in more detail. Diagnostic plots are also available in Appendix C.

C8_BOZ2_1_566_28S7CTCU and C3_BOZ2_1_566_28S7CTCU

During the early phase of the shearing in test C8_BOZ2_1_566_28S7CTCU, a jump occurred in the axial stress (Fig. 6-20). The evolution of the pore pressure in this phase cannot be considered as representative of the pore pressure of the entire sample, therefore the initial part of the stress path cannot be considered reliable. After the initial jump, the response of the sample appears coherent with the other test results. A similarly stiff response was found in test C3_BOZ2_1_566_28S7CTCU. It is considered that at peak, the pore pressure should have reached equilibrium and hence the value should not have been affected.

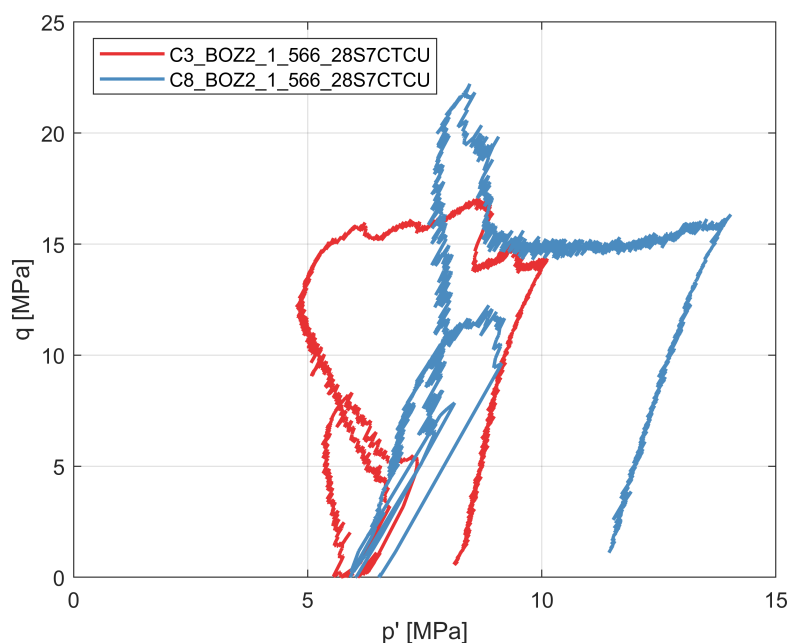


Fig. 6-20: Stress path of tests experiencing a high deviatoric stress increase in early test phase
Tests C8_BOZ2_1_566_28S7CTCU, C3_BOZ2_1_566_28S7CTCU.

B11_BOZ2_1_515_91P7CTCU

In test B11_BOZ2_1_515_91P7CTCU, a faulty measurement of the radial strains occurred. The strain parallel to the bedding appears to be particularly affected (Fig. 6-21). The test was repeated after fixing the problem, in test B11b. No Poisson's ratios are reported for test B11.

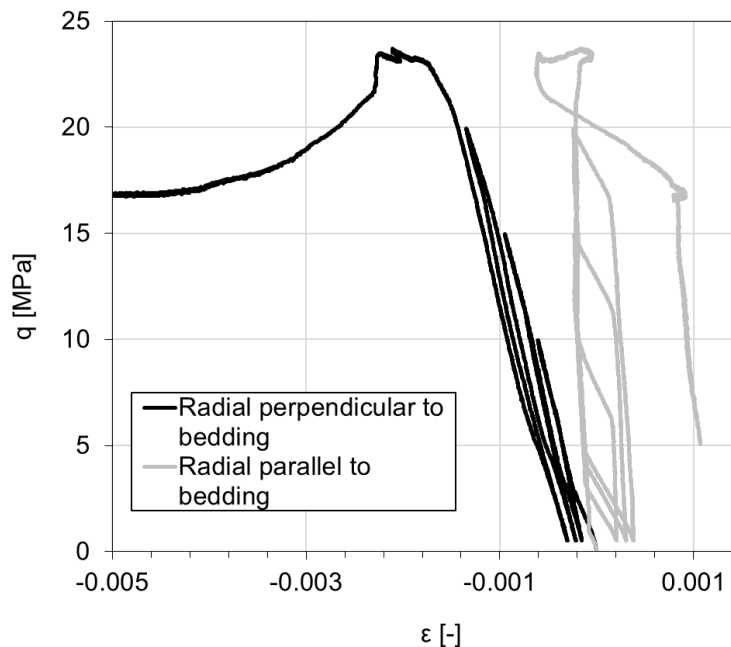


Fig. 6-21: Radial strain measurements (perpendicular and parallel to bedding) of tests B11_BOZ2_1_515_91P7CTCU

6.3 Oedometric tests, one-dimensional swelling and complementary permeability tests

This section includes the results obtained on:

- High-pressure oedometric tests (OED), including two constant-head permeability tests
- Constant-head permeability tests (PERM) obtained in triaxial and oedometric conditions (outside of an oedometric test)

6.3.1 Overview of the performed tests and initial specimen conditions

An overview of the performed tests is provided in Tab. 6-4.

Tab. 6-4: Tests performed in oedometric conditions and complementary permeability tests

For specimen geometry see Fig. 4-1.

ID	OED	Perm	Depth [m]	Laboratory	Specimen geometry	Formation
D3_OED_BOZ2_1	×		464.35	D	S	Opalinus Clay
D5_OED_BOZ2_1	×	×	464.38	D	P	Opalinus Clay
D1_OED_BOZ2_1	×		529.58	D	S	Opalinus Clay
D6_OED_BOZ2_1	×		529.54	D	S	Opalinus Clay
D4_OED_BOZ2_1	×		529.83	D	S	Opalinus Clay
D2_OED_BOZ2_1	×		529.83	D	S	Opalinus Clay
D7_OED_BOZ2_1	×	×	529.72	D	P	Opalinus Clay
A1_PERM_BOZ2_1		×	635.82	A	P	Klettgau-Fm.
D1_PERM_BOZ2_1		×	646.01	D	P	Klettgau-Fm.

The tests in oedometric conditions were labelled by indicating the letter of the laboratory that performed the test (e.g. Lab A), a sequential number (01) and the type of test (OED = oedometric, PERM = constant-head permeability).

6.3.2 Oedometric test results

The settlement over time curve for each loading increment is analysed adopting an extension to the consolidation theory tailored on shales response (Ferrari et al. 2016). The solution combines a modified form of the classical Biot theory (Biot 1941), to account for the behaviour of shales in oedometric conditions, and an extended one-dimensional consolidation theory, to consider the poroelastic behaviour of shales and time-dependent loading conditions. For each loading step, the method allows for the identification of the primary consolidation settlement, related to the water overpressure dissipation, the secondary compression coefficient, the hydraulic conductivity.

As an example, the results of one oedometric test are reported in Fig. 6-22, in terms of oedometric curves. The graph presents the void ratio (e) obtained at the end of the primary consolidation, versus the vertical effective stress (σ'_v). The initial void ratio (e_0), the swelling pressure attained at the end of the resaturation phase (S_p), the yield stress ($\sigma'_{v,y}$) obtained through the Casagrande's construction, the compressibility (C_c) and the unloading (C_s) indexes are marked in the figure. The results from the performed tests are summarised in Tab. 6-5. Corresponding plots are reported in Appendix F. Tab. 6-5 also includes the effective stress level at which the constant-head permeability test was performed, where applicable.

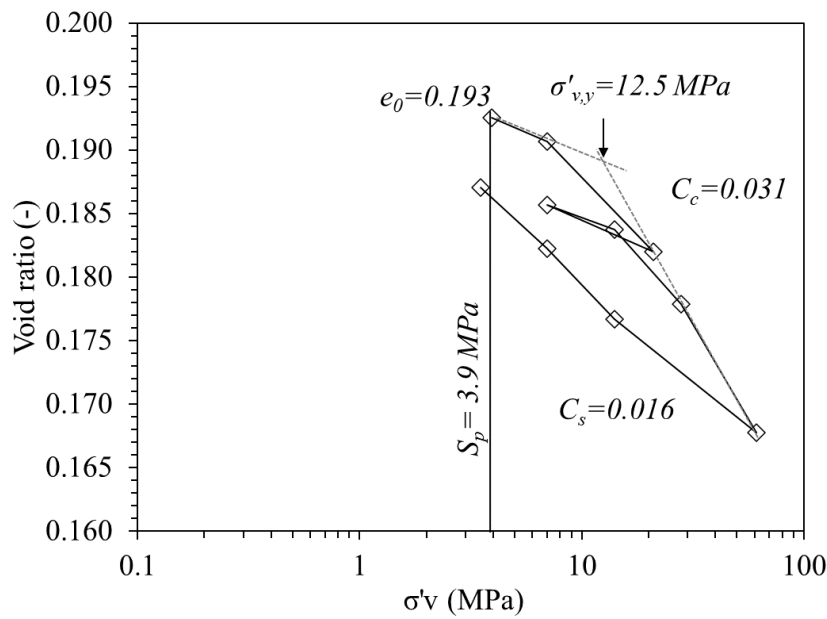


Fig. 6-22: Oedometric curve in void ratio versus vertical effective stress plane
Results from D1_OED_BOZ2_1.

Tab. 6-5: Oedometric test results
For specimen geometry see Fig. 4-1.

Specimen ID	Specimen geometry	Specimen depth	e_0	C_c	S_p	$\sigma'_{v,y}$	C_s	PERM test at σ'_v (or p')
		[m]	[-]	[-]	[MPa]	[MPa]	[-]	[MPa]
D3_OED_BOZ2_1	S	464.35	0.116	0.017	1.86	11.7	0.010	
D5_OED_BOZ2_1	P	464.38	0.126	0.011	1.18	9.9	0.007	10
D1_OED_BOZ2_1	S	529.58	0.193	0.031	3.90	12.5	0.016	
D6_OED_BOZ2_1	S	529.54	0.123	0.017	2.14	9.0	0.008	
D4_OED_BOZ2_1	S	529.83	0.182	0.027	2.57	10.5	0.013	
D2_OED_BOZ2_1	S	529.83	0.179	0.026	2.14	5.4	0.012	
D7_OED_BOZ2_1	P	529.72	0.117	0.013	1.16	10.0	0.007	10

The swelling pressure ranged from about 1.1 MPa to 3.9 MPa. It is noted that those values are generally lower than those obtained in triaxial conditions. This is attributed to a more precise strain control available in the triaxial setups.

6.3.3 Hydraulic conductivity: direct and indirect measurements

From the consolidation theory application, hydraulic conductivity at each loading step can be derived. In Fig. 6-23, the hydraulic conductivity of P- and S-samples obtained from consolidation theory are reported. The ranges of values obtained upon primary loading are represented as the

average plus bars: the plot considers the values obtained for a range of vertical effective stress comparable to what is expected in situ (5 – 20 MPa). The results are combined with constant-head permeability measurements and labelled with the values of vertical effective stress or mean effective stress at which the test was performed. The figure focuses on the Opalinus Clay section. Data of hydraulic conductivity computed from the consolidation and those from constant-head tests are reported in Tab. 6-6, including the results of the PERM tests.

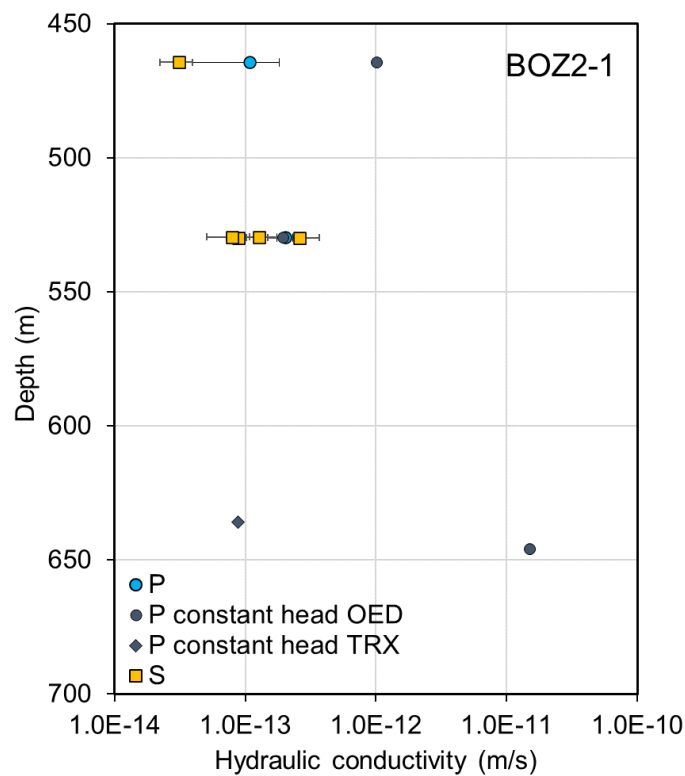


Fig. 6-23: Hydraulic conductivity versus depth

Results obtained from the analysis consolidation test, for the range of effective vertical stress 5 – 20 MPa, and constant-head tests in oedometric (vertical effective stress 10 MPa) and triaxial conditions (mean effective stress 10 MPa).

Tab. 6-6: Hydraulic conductivity test results: from consolidation and constant-head tests

Specimen ID	Specimen geometry	Depth	Consolidation stages		Constant-head tests	
			Average k (4 – 20 MPa)	Standard deviation	k	σ'_v or p'
		[m]	[m/s]	[m/s]	[m/s]	[MPa]
D3_OED_BOZ2_1	S	464.35	3.1E-14	8.7E-15		
D5_OED_BOZ2_1	P	464.38	1.1E-13	7.4E-14	1.0E-12	$\sigma'_v = 10$
D1_OED_BOZ2_1	S	529.58	1.3E-13	5.6E-14		
D6_OED_BOZ2_1	S	529.54	8.0E-14	2.9E-14		
D4_OED_BOZ2_1	S	529.83	8.9E-14	1.3E-14		
D2_OED_BOZ2_1	S	529.83	2.6E-13	1.1E-13		
D7_OED_BOZ2_1	P	529.72	2.0E-13	2.8E-14	2.0E-13	$\sigma'_v = 10$
A1_PERM_BOZ2_1	P	635.82	-	-	8.9E-14	$p' = 10$
D1_PERM_BOZ2_1	P	646.01	-	-	1.5E-11	$\sigma'_v = 10$

7 Representativeness of test results

A critical question revolving around any rock-mechanical or geomechanical laboratory programme is how representative the chosen specimens are for a given formation. This depends on several factors, notably material heterogeneity.

One possible way to address this is to compare wave velocities derived from the sonic scanner *in situ* (Fig. 7-1, blue line) and ultrasonic velocities constrained in triaxial tests on cores in the laboratory (*cf.* Tab. 5-3 and E-1, orange squares in Fig. 7-1). Such correlations can be used for both i) checking the plausibility of test results and ii) estimating the variability of material properties in (sub-)formations. Therefore, the tests conducted in the rock-mechanical testing programme with formations other than Opalinus Clay (and confining units) are used as guidance to estimate rock-mechanical formation properties.

In contrast, the ambition of the geomechanical testing programme (of Opalinus Clay in particular) is to cover the relevant spectrum of material properties by actual laboratory testing. Whether this was achieved is primarily assessed by comparing the basic properties and mineralogy of tested specimens with the larger database (*cf.* Dossier VIII). In this larger database, water content and mineralogy were constrained every 2 to 3 m along the 122 m thick interval of Opalinus Clay, and each measurement reflects a mean value over a 25 cm core interval.

The water content of geomechanically tested specimens was measured on trimming material from the specimen preparation and on the specimens themselves (before and after testing). For a same specimen, these values were averaged, and the error bars constructed to include the variability in the measurements. Those results are reported versus the specimens sourcing depth in Fig. 7-2. Based on the water content, the comparison with the larger database reveals that the spectrum of water contents is covered by the geomechanical tests.

The bulk mineralogy was also assessed for the tested specimens. However, it is noted that for a given depth interval, multiple «twin specimens» were sourced to constrain stress-dependent properties of the same material. As the material's variability in the horizontal direction in the Opalinus Clay is generally considered very small compared to the variability in the vertical direction, only one specimen was generally used for a given depth interval as a reference mineralogy for other specimens. This assumption was verified with repeated analyses of two plugs from an identical depth interval. Therefore, the bulk mineralogy obtained on one specimen was attributed to the other specimens from the same vertical interval of the core. The clay-mineral content (wt.-%) is reported in Fig. 7-3 against depth, together with the large database obtained from University of Bern (*cf.* Dossier VIII).

The comparisons of Figs. 7-2 and 7-3 demonstrate that tested specimens in the geomechanical testing programme capture the material variability and can thus be considered representative of the entire formation.

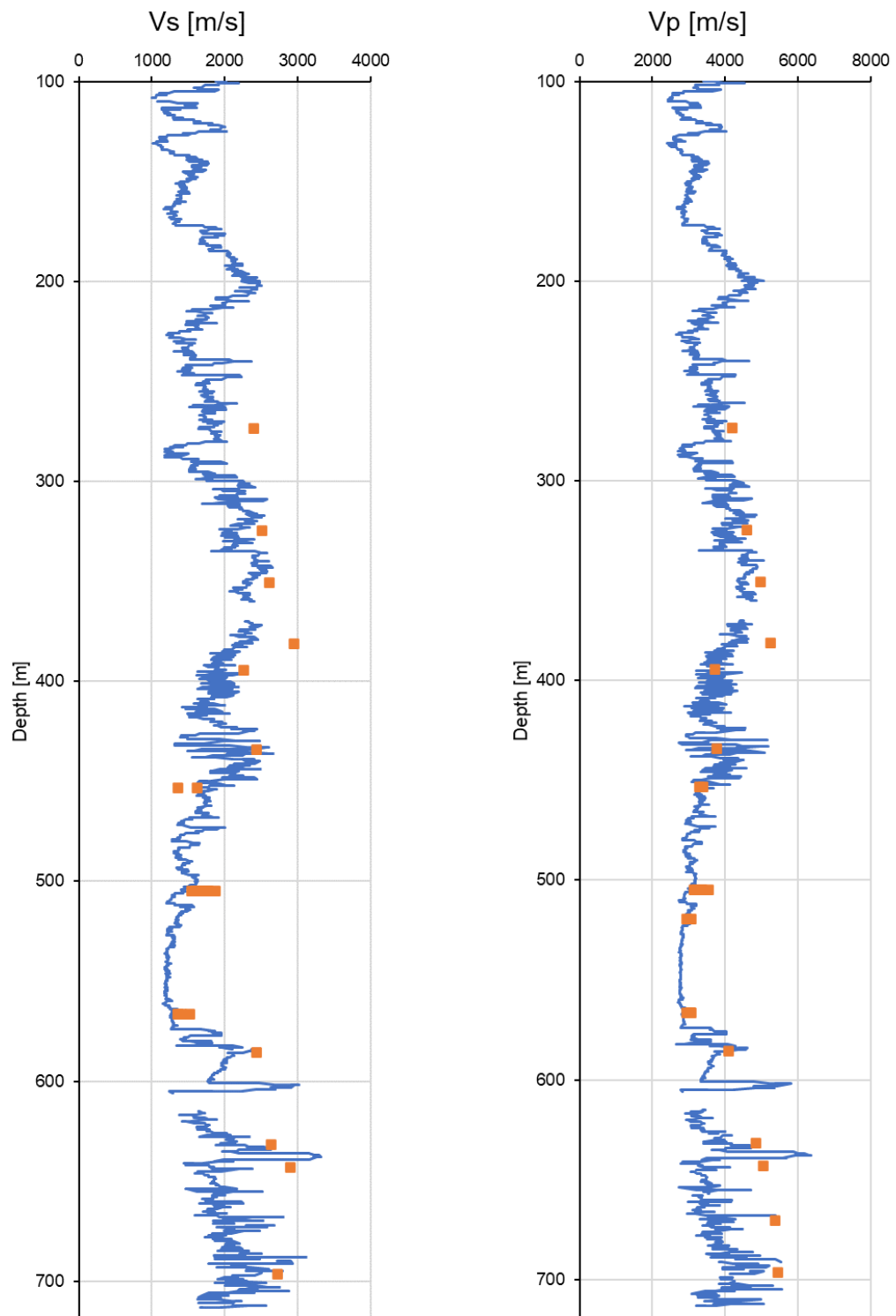


Fig. 7-1: Compressional (a) and shear-wave velocities (b) from borehole and lab testing
Blue line: continuous measurements from borehole sonic scanner (kHz frequency). Orange squares: lab-measurements (MHz frequency).

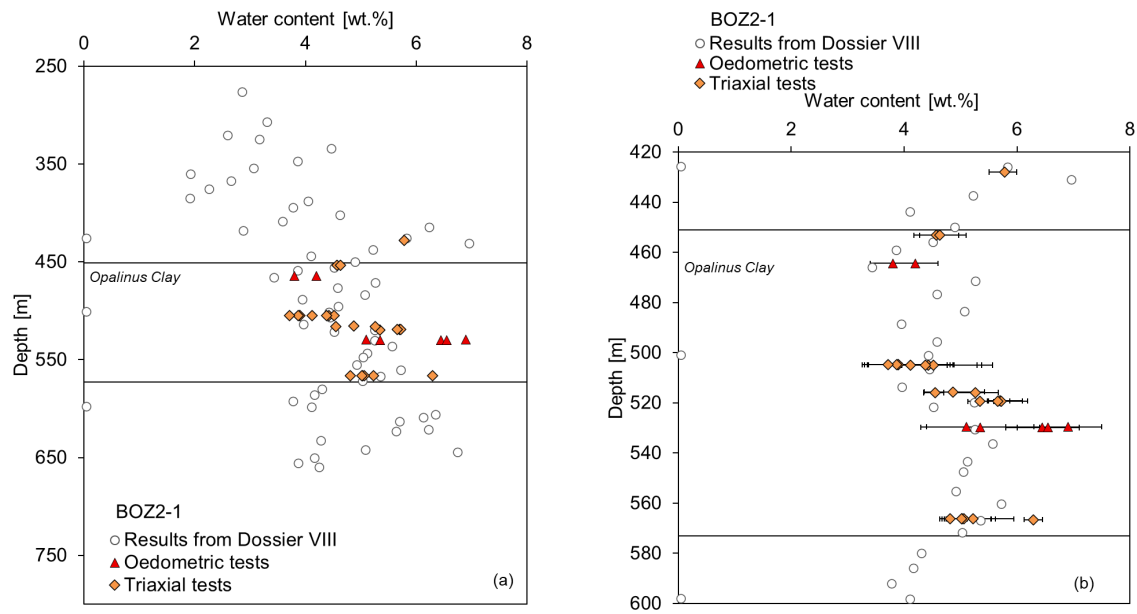


Fig. 7-2: Water content vs. depth from the large database and from tested specimens
Results include those from Dossier VIII for the BOZ2-1 borehole (a) and zoom into the Opalinus Clay and confining units' section (b).

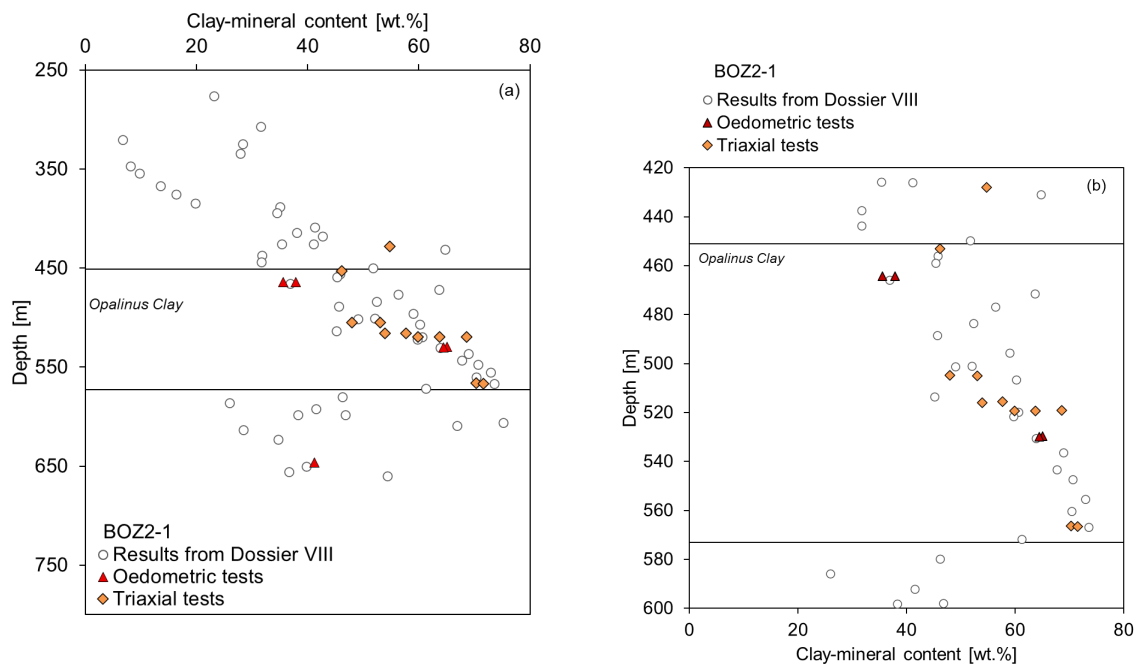


Fig. 7-3: Clay-mineral content vs. depth from the large database and from tested specimens
Results include those from Dossier VIII for the BOZ2-1 borehole (a) and zoom into the Opalinus Clay and confining units' section (b).

8 References

- ASTM (2014): D7012-14e1: Standard test method for compressive strength and elastic moduli of intact rock core specimens under varying states of stress and temperatures. ASTM International, West Conshohocken, PA.
- ASTM (2016): D3967-16: Standard test method for splitting tensile strength of intact rock core specimens. ASTM International, West Conshohocken, PA.
- ASTM (2017a): D4318-17e1: Standard test methods for liquid limit, plastic limit, and plasticity index of soils. ASTM International, West Conshohocken, PA.
- ASTM (2017b): D6913/D6913M-17: Standard test methods for particle-size distribution (gradation) of soils using sieve analysis. ASTM International, West Conshohocken, PA.
- ASTM (2017c): D7928-17: Standard test method for particle-size distribution (gradation) of fine-grained soils using the sedimentation (hydrometer) analysis. ASTM International, West Conshohocken, PA.
- ASTM (2019): D4543-19: Preparing rock core as cylindrical specimens and verifying conformance to dimensional and shape tolerances. ASTM International, West Conshohocken, PA.
- Aydin, A. (2014): Upgraded ISRM suggested method for determining sound velocity by Ultrasonic Pulse Transmission Technique. *Rock Mechanics and Rock Engineering* 47, 255-259.
- Biot, M.A. (1941): General theory of three-dimensional consolidation. *Journal of Applied Physics* 12/2, 155-164.
- Crisci, E., Ferrari, A., Giger, S.B. & Laloui, L. (2019): Hydro-mechanical behaviour of shallow Opalinus Clay shale. *Eng. Geol.* 251, 214-227. <https://doi.org/10.1016/j.enggeo.2019.01.016>
- Ewy, R.T. (2014): Shale swelling/shrinkage and water content change due to imposed suction and due to direct brine contact. *Acta Geotech.* 9, 869-886. <https://doi.org/10.1007/s11440-013-0297-5>
- Ewy, R.T. (2015): Shale/claystone response to air and liquid exposure, and implications for handling, sampling and testing. *International Journal of Rock Mechanics and Mining Sciences* 80, 388-401. <https://doi.org/10.1016/j.ijrmms.2015.10.009>
- Favero, V. (2017): Multiphysical behaviour of shales from Northern Switzerland. <https://doi.org/10.5075/epfl-thesis-7539>, urn:nbn:ch:bel-epfl-thesis7539-7
- Ferrari, A., Favero, V. & Laloui, L. (2016): One-dimensional compression and consolidation of shales. *Int. J. Rock Mech. Min. Sci.* 88, 286-300. <https://doi.org/10.1016/j.ijrmms.2016.07.030>
- Favero, V., Ferrari, A. & Laloui, L. (2018): Anisotropic behaviour of Opalinus Clay through consolidated and drained triaxial testing in saturated conditions. *Rock Mechanics and Rock Engineering* 51, 1305-1319.

- Ghabezloo, S. & Sulem, J. (2010): Effect of the volume of the drainage system on the measurement of undrained thermo-poro-elastic parameters. *International Journal of Rock Mechanics and Mining Sciences* 47, 60-68. <https://doi.org/10.1016/j.ijrmms.2009.03.001>
- Giger, S.B., Ewy, R.T., Favero, V., Stankovic, R. & Keller, L.M. (2018): Consolidated-undrained triaxial testing of Opalinus Clay: Results and method validation. *Geomechanics for Energy and the Environment* 14, 16-28.
- Head, K.H. (1998): *Manual of soil laboratory testing. Volume 3: Effective stress tests.* Second Edition John Wiley and Sons.
- Isler, A., Pasquier, F. & Huber, M. (1984): *Geologische Karte der zentralen Nordschweiz 1:100'000.* Herausgegeben von der Nagra und der Schweiz. Geol. Komm.
- Keller, L.M. & Giger, S.B. (2019): Petrophysical properties of Opalinus Clay drill cores determined from Med-XCT images. *Geotech. Geol. Eng.* 37/4, 3507-3522. <https://doi.org/10.1007/s10706-019-00815-2>
- Minardi, A., Ferrari, A. & Laloui, L. (2019): Benchmark study on triaxial testing of Opalinus Clay: Analysis and comparative evaluation of tests results. *Nagra Arbeitsbericht NAB 19-18.*
- Minardi, A., Giger, S.B., Ewy, R.T., Stankovic, R., Stenebråten, J., Soldal, M., Rosone, M., Ferrari, A. & Laloui, L. (2020): Benchmark study of undrained triaxial testing of Opalinus Clay shale: Results and implications for robust testing. *Geomechanics for Energy and the Environment* 25, 100210.
- Nagra (2014): SGT Etappe 2: Vorschlag weiter zu untersuchender geologischer Standortgebiete mit zugehörigen Standortarealen für die Oberflächenanlage. *Geologische Grundlagen. Dossier II: Sedimentologische und tektonische Verhältnisse. Nagra Technischer Bericht NTB 14-02.*
- Nagra (2021a): TBO Bülach-1-1: Data Report. Dossier IX: Rock-mechanical and Geomechanical Laboratory Testing. *Nagra Arbeitsbericht NAB 20-08.*
- Nagra (2021b): TBO Trüllikon-1-1: Data Report. Dossier IX: Rock-mechanical and Geomechanical Laboratory Testing. *Nagra Arbeitsbericht NAB 20-09.*
- Pietsch, J. & Jordan, P. (2014): *Digitales Höhenmodell Basis Quartär der Nordschweiz – Version 2013 (SGT E2) und ausgewählte Auswertungen.* Nagra Arbeitsbericht NAB 14-02.
- Rufer, D. (2019): *Field manual: Drill core sampling for analytical purposes.* Nagra Arbeitsbericht NAB 19-13.
- Tuttolomondo, A. (2021): *Effective stress for unsaturated active clays and in-situ effective stress estimation methodology.* EPFL PhD Thesis n° 8291.
- Wissa, A.E.Z. (1969): Pore pressure measurement in saturated stiff soils. *Journal of the Soil Mechanics and Foundations Division* 95, 1063-1074.
- Wersin, P., Mazurek, M., Waber, H.N., Mäder, U.K., Gimmi, T., Rufer, D. & de Haller, A. (2013): Rock and porewater characterisation on drillcores from the Schlattingen borehole Nagra Arbeitsbericht NAB 12-54.
- Witteveen, P., Ferrari, A. & Laloui, L. (2013): An experimental and constitutive investigation on the chemo-mechanical behaviour of a clay. *Geotechnique* 63/3, 244-255.

Appendix A Photo documentation of the rock mechanical testing programme

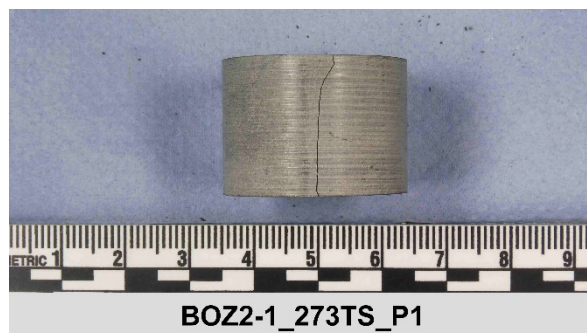
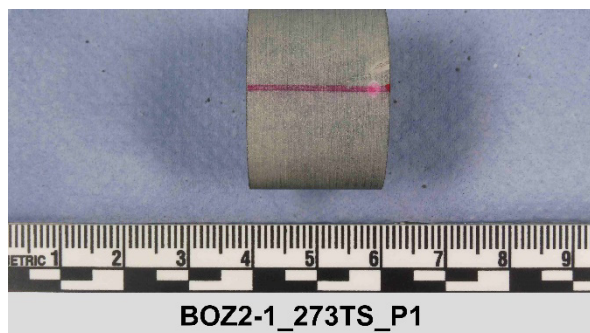
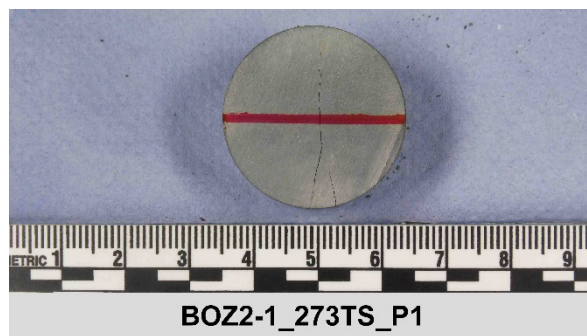
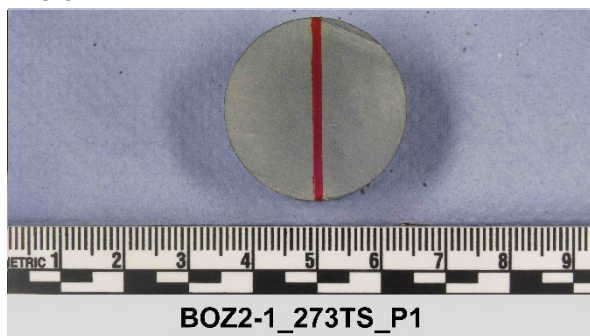
TS (average depth of sample)

BOZ2-1

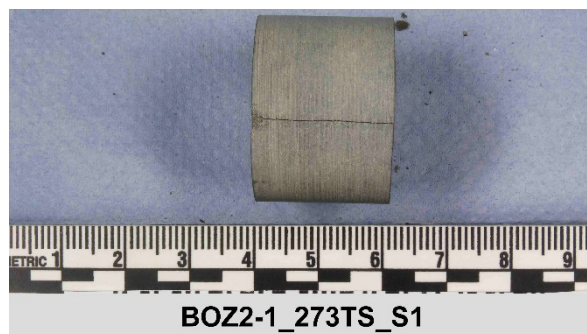
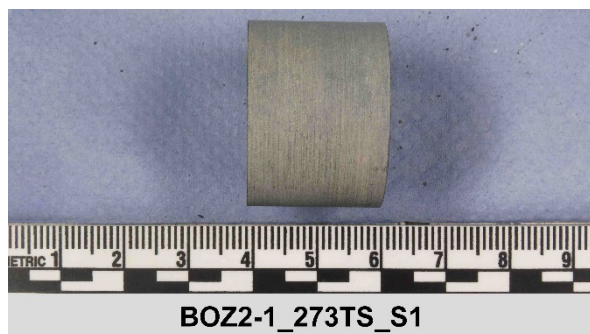
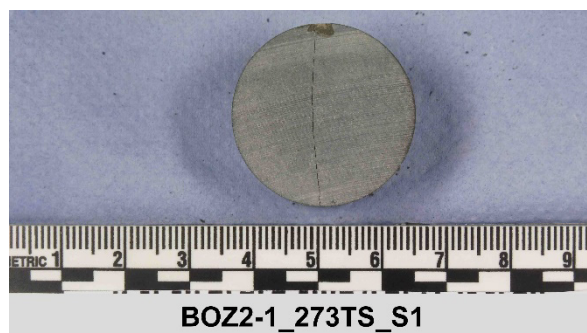
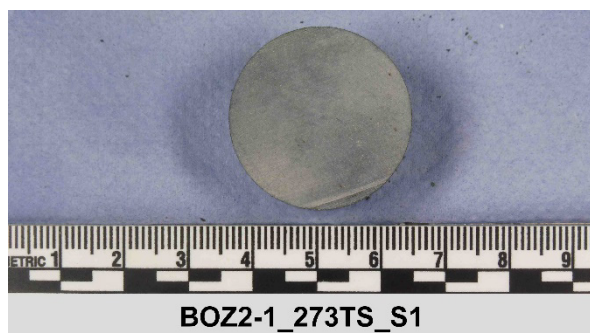
before testing

after testing

273.67 m

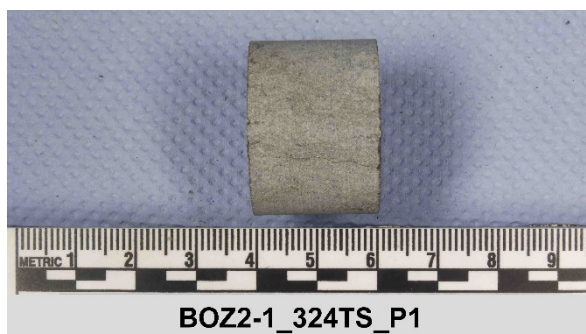
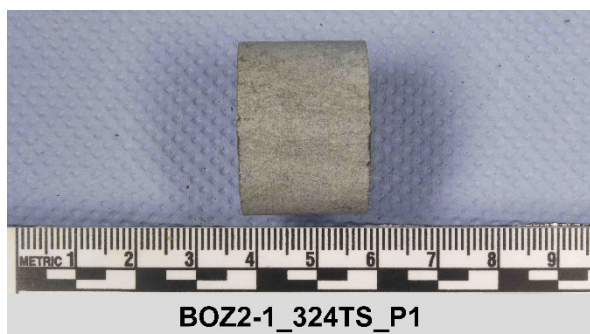
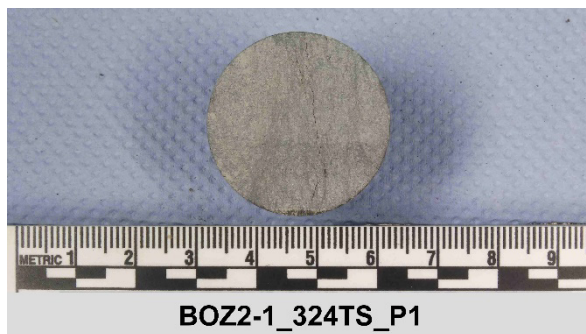
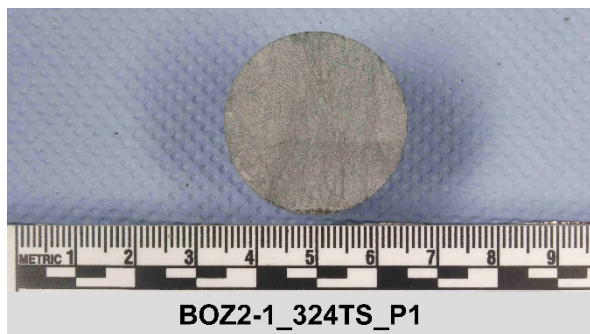


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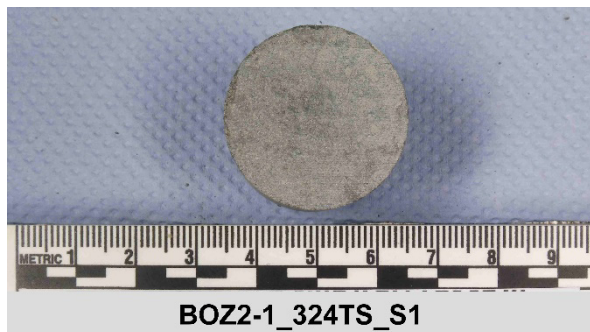


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324.43 m



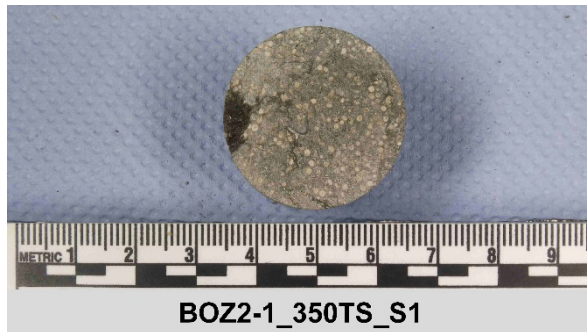
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after testing

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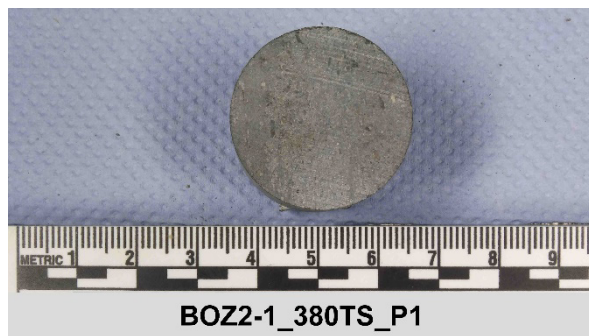
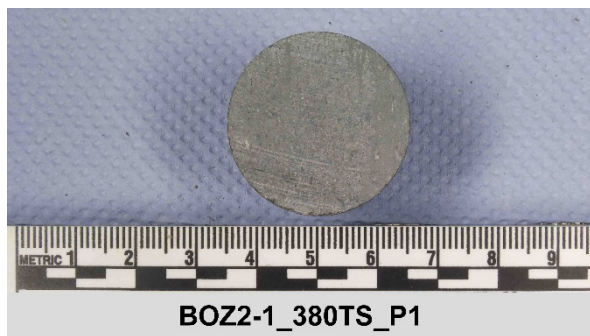


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before testing**after testing**

381.19 m



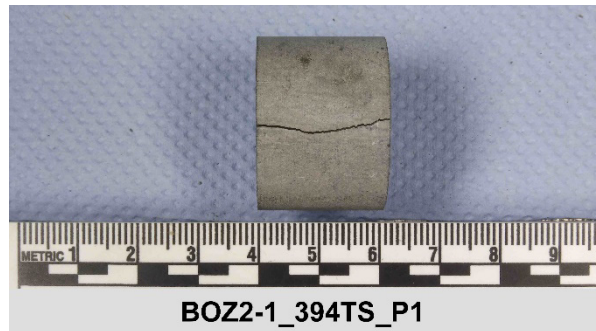
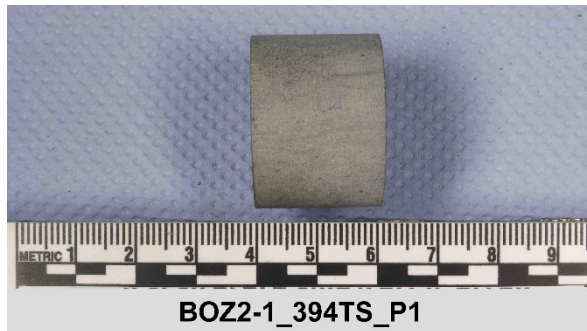
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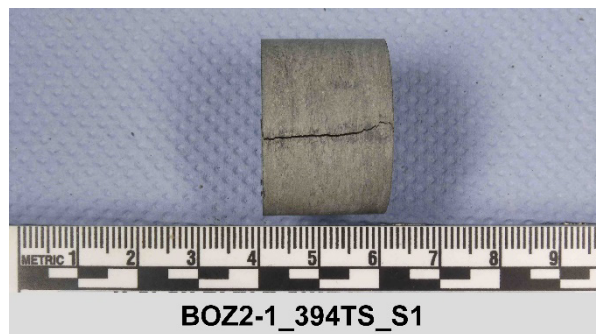
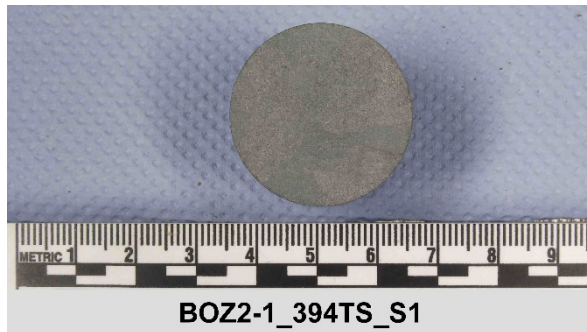
before testing

after testing

394.59 m

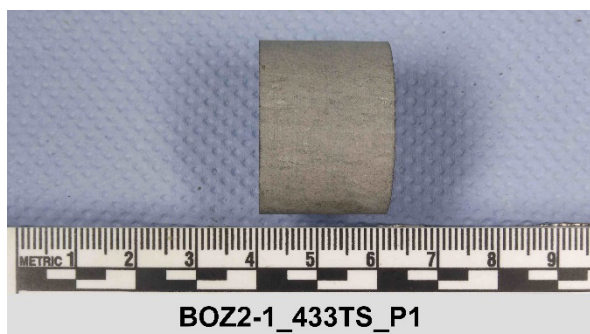
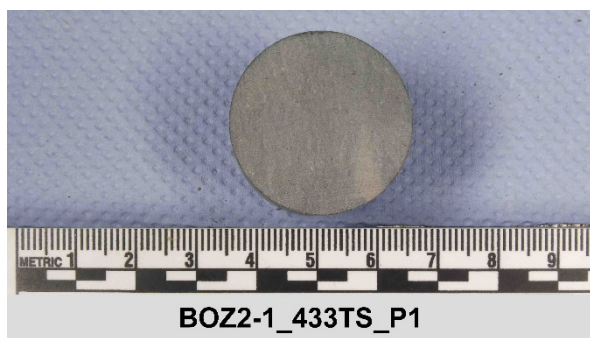


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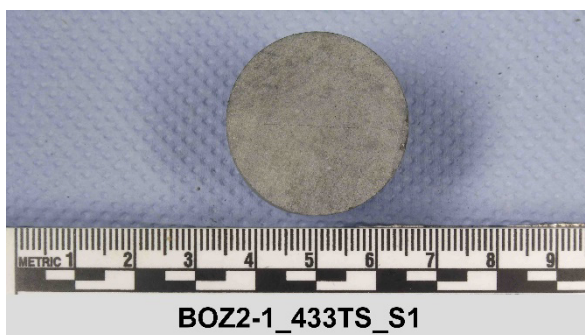
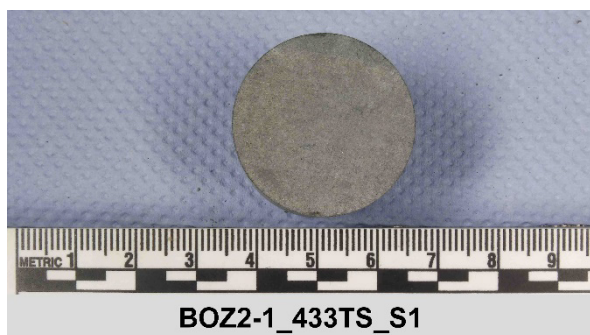


before testing**after testing**

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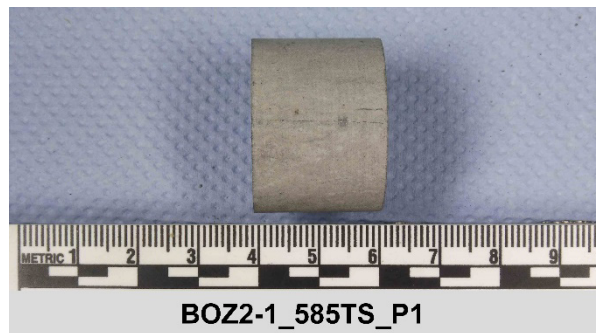
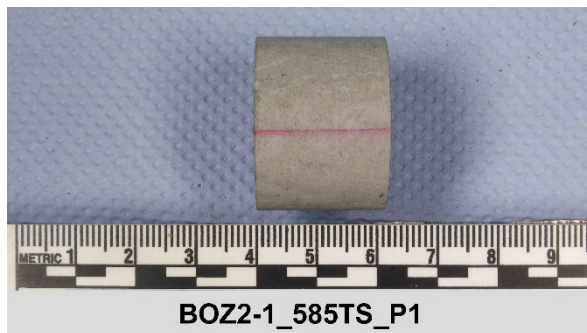
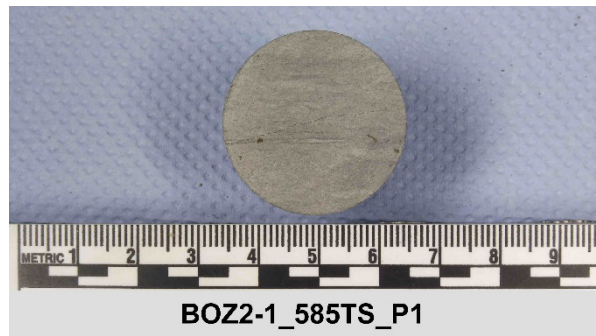
433.86 m



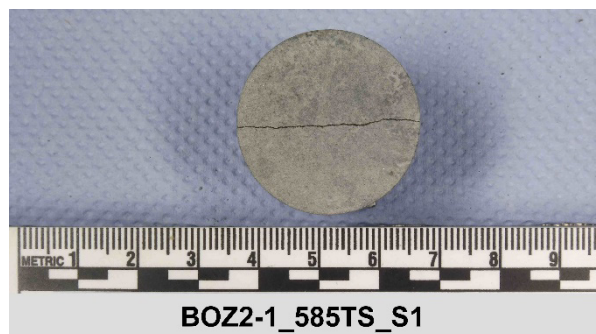
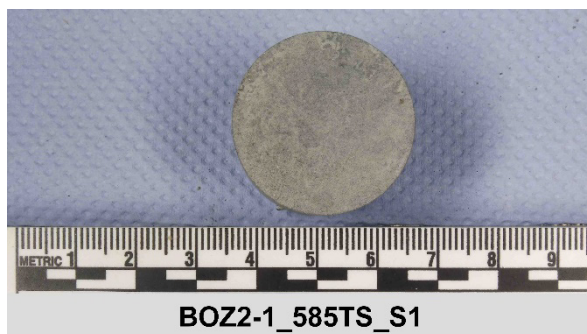
before testing

after testing

585.62 m

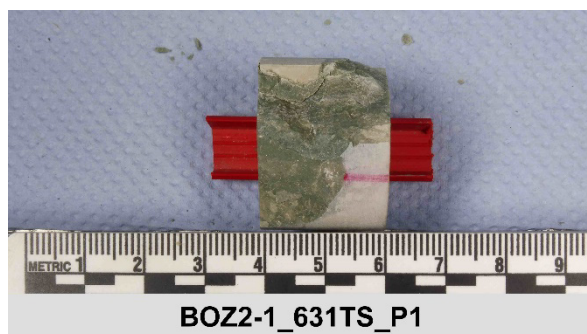
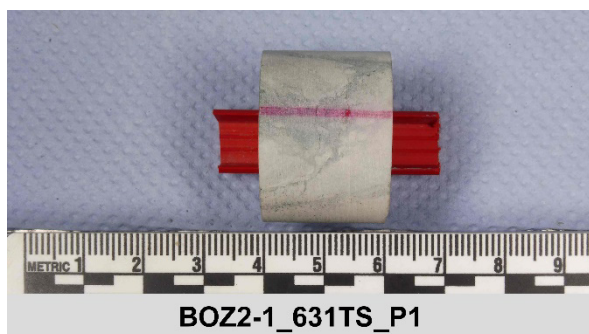
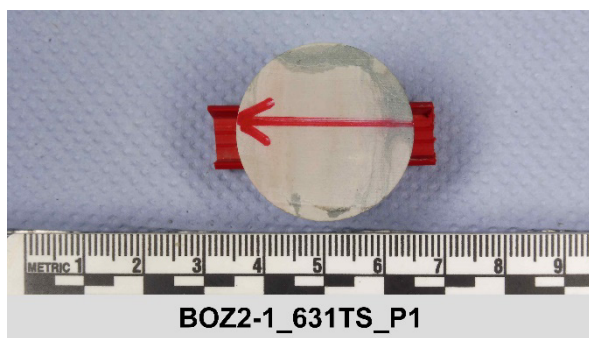


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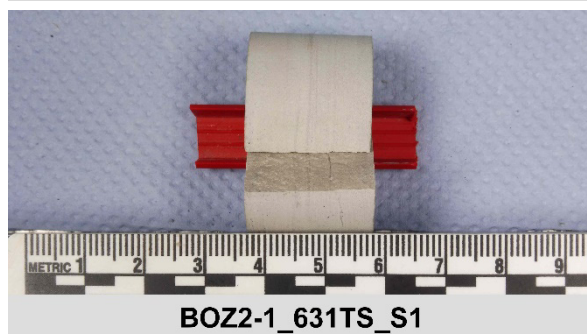
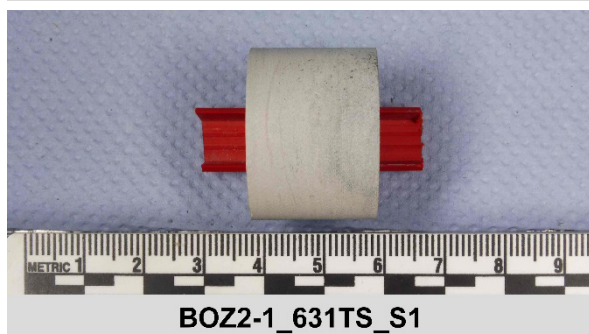
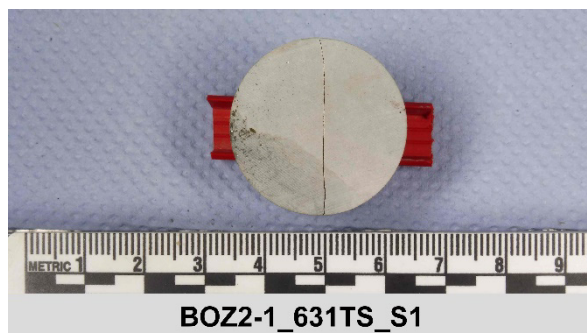


before testing**after testing**

631.55 m



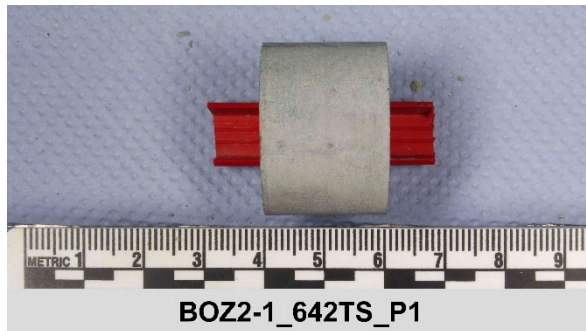
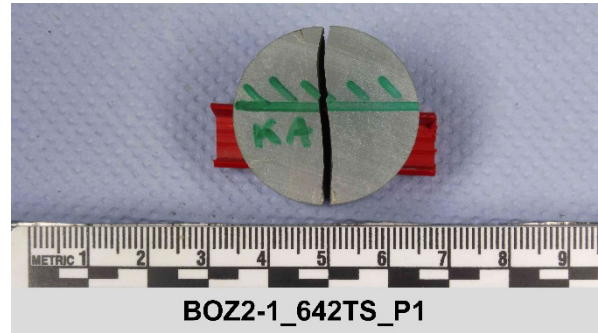
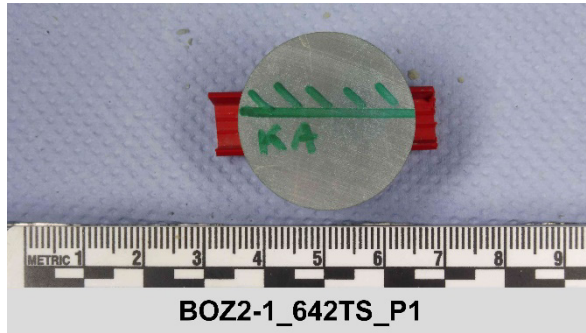
631.46 m



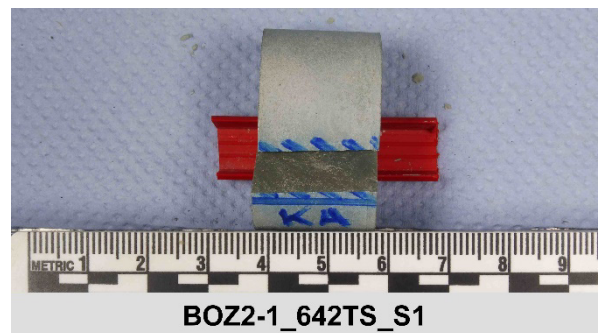
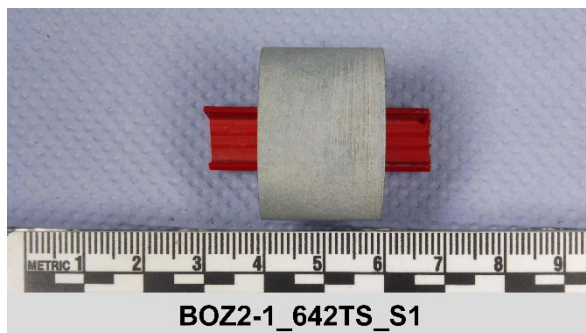
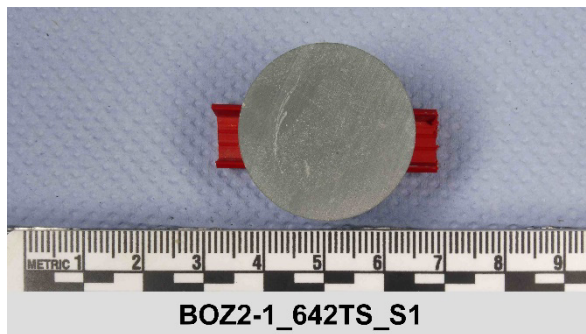
before testing

after testing

642.84 m



642.80 m



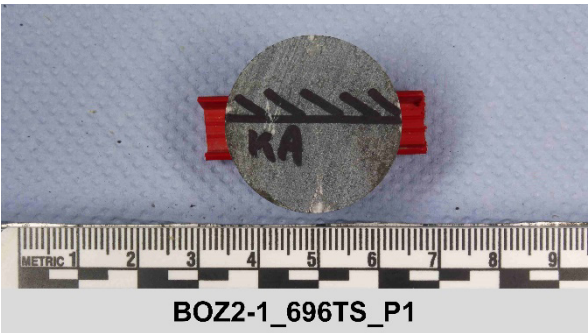
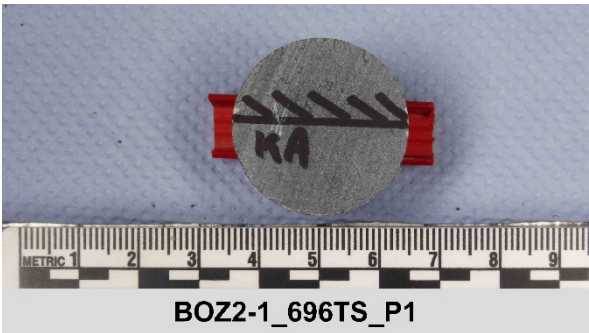
before testing

after testing

670.76 m



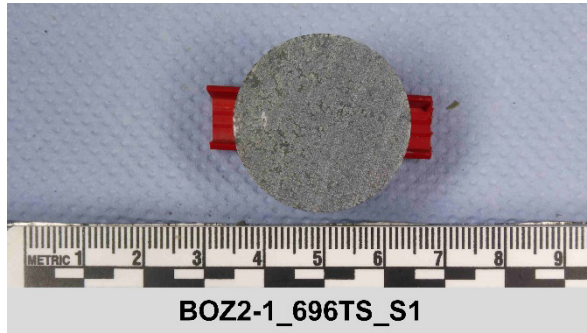
696.65 m



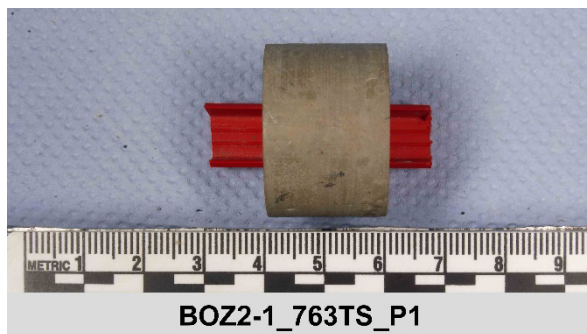
before testing

after testing

696.61 m



763.98 m

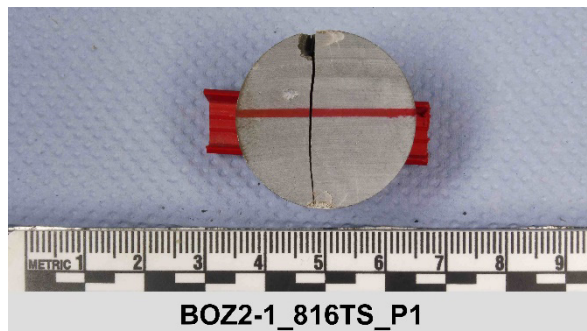
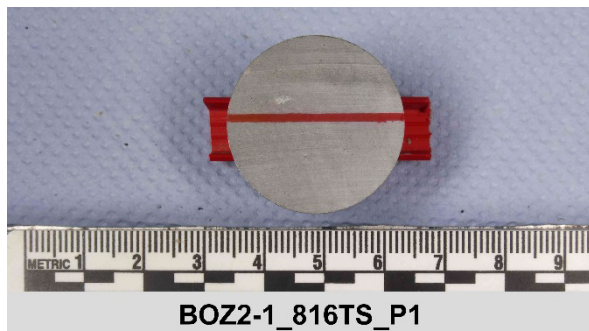


before testing**after testing**

763.94 m



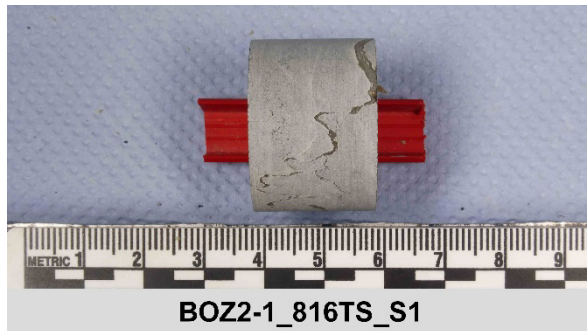
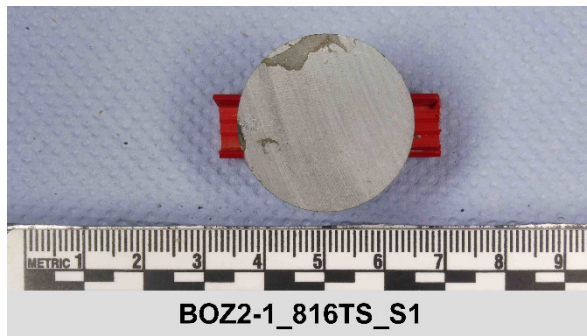
816.67 m



before testing

after testing

816.64 m



826.04 m



before testing**after testing**

826.01 m



UCS (depth of sample top)

BOZ2-1

before testing

after testing

273.41 m



273.71 m



324.45 m



324.49 m

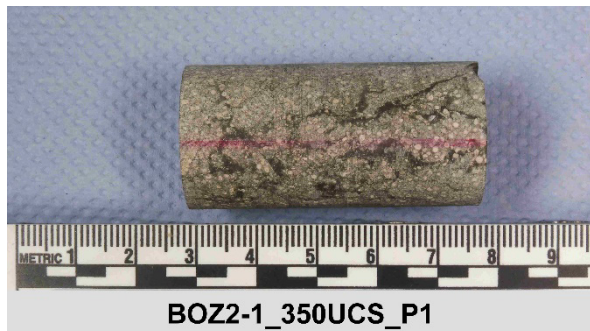


before testing**after testing**

324.07 m



350.76 m



350.70 m



381.22 m



before testing

after testing

381.25 m



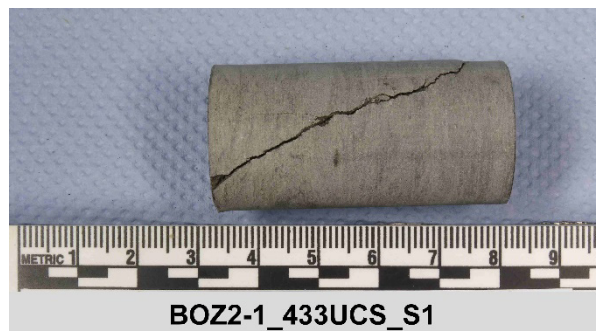
380.96 m



394.49 m



433.94 m



before testing

after testing

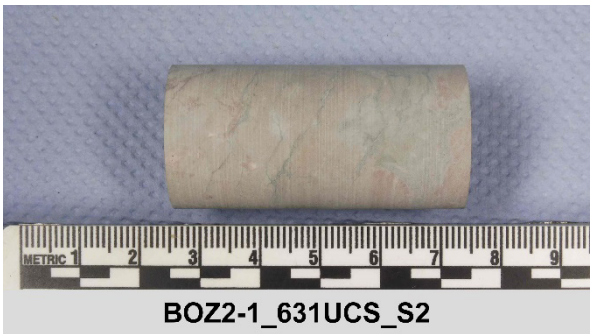
585.65 m



631.58 m



631.20 m



631.30 m



before testing

after testing

642.86 m



670.68 m



696.53 m



696.79 m



before testing

after testing

764.01 m



764.06 m



816.72 m



816.53 m



before testing

826.07 m



after testing



TRX (depth of sample top)**BOZ2-1****before testing****after testing**

273.71 m



324.19 m



350.70 m



381.25 m



before testing

after testing

394.49 m



433.94 m



585.65 m



631.58 m



before testing

after testing

642.86 m



670.52 m



696.53 m



764.01 m



before testing

after testing

816.72 m

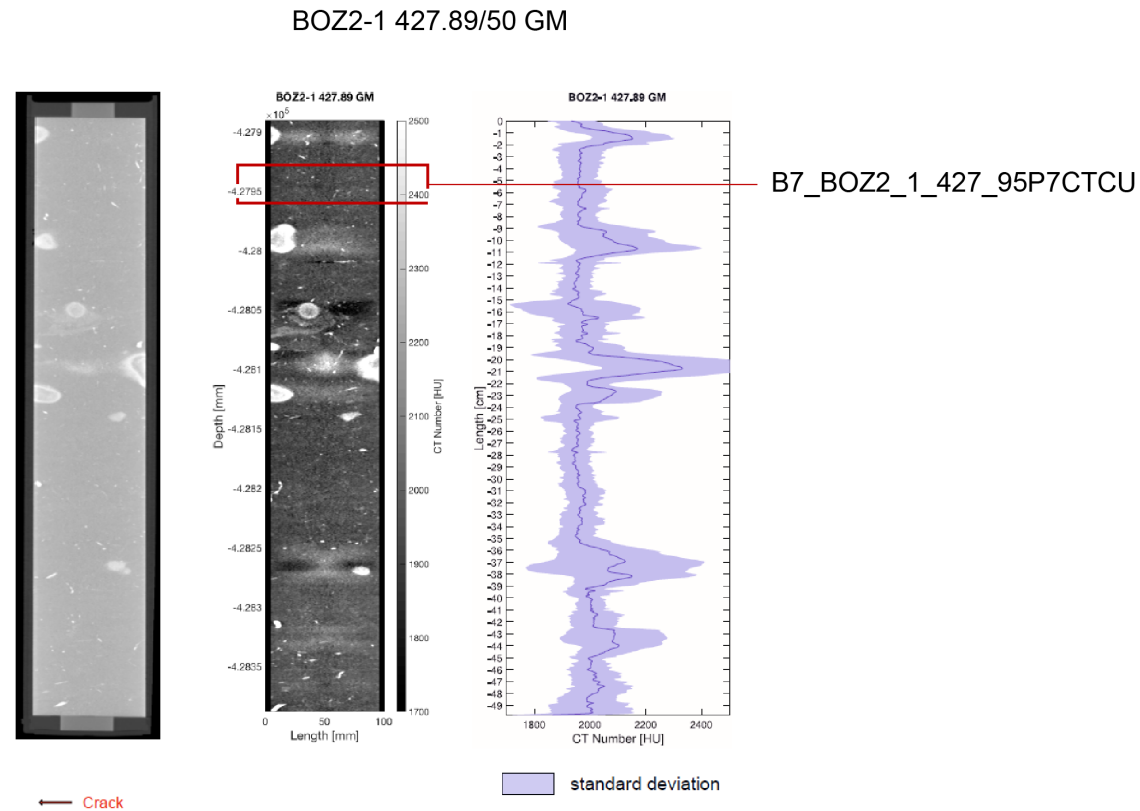


826.07 m

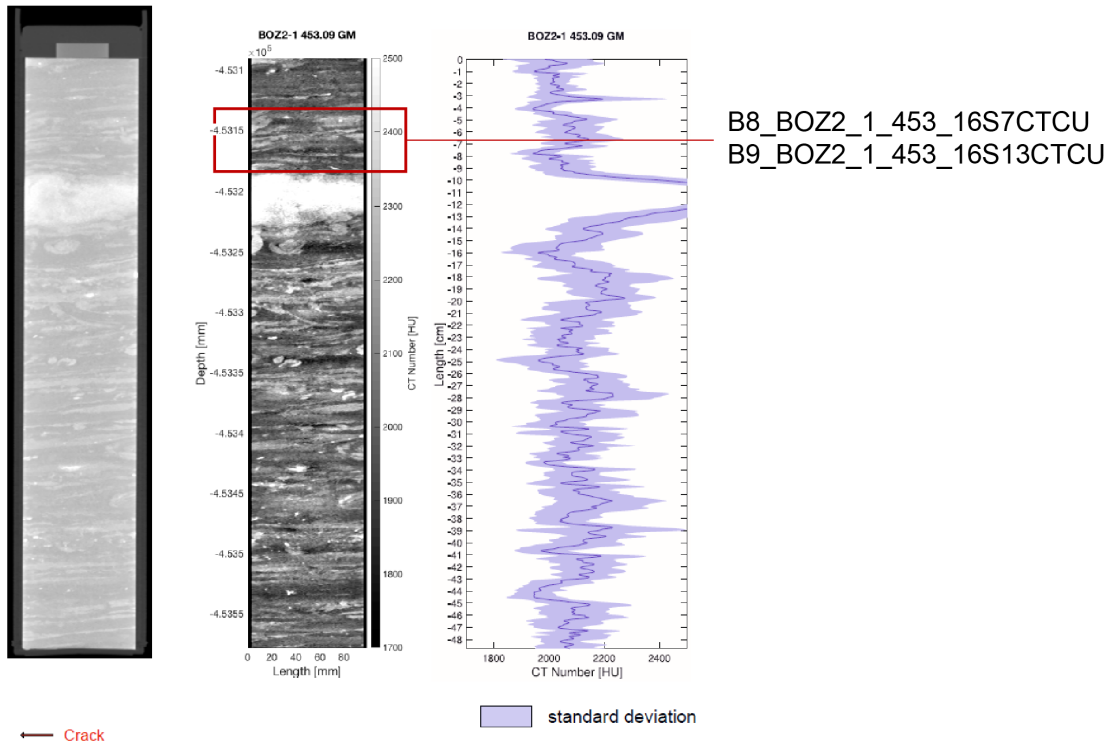


Appendix B XCT cross-sections with selection of test specimens

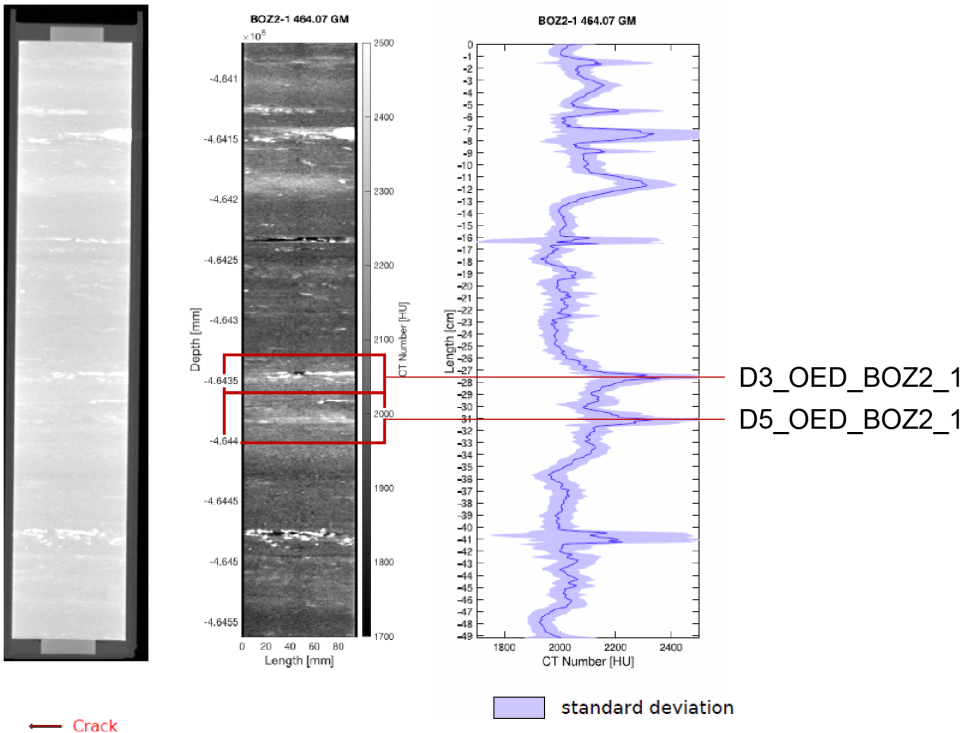
The computed tomography scans of the tested cores are here reported, and the sections used in the testing programme are indicated.

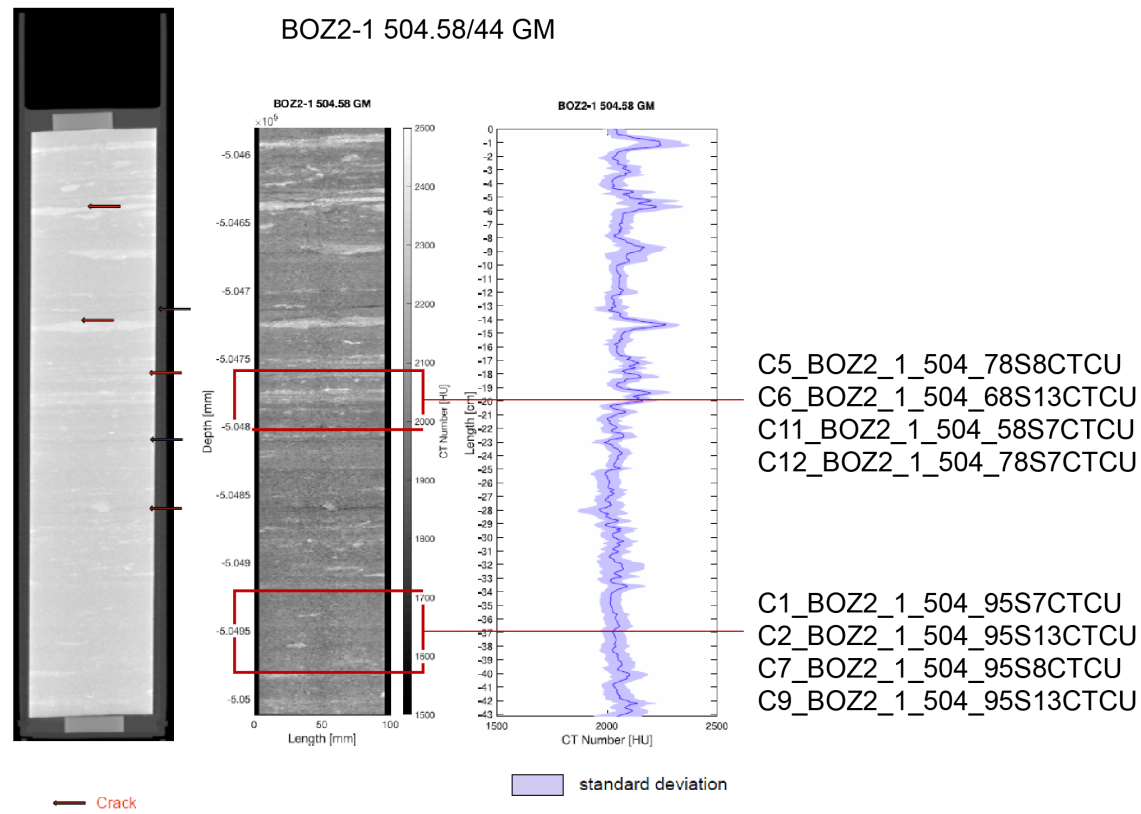


BOZ2-1 453.09/50 GM

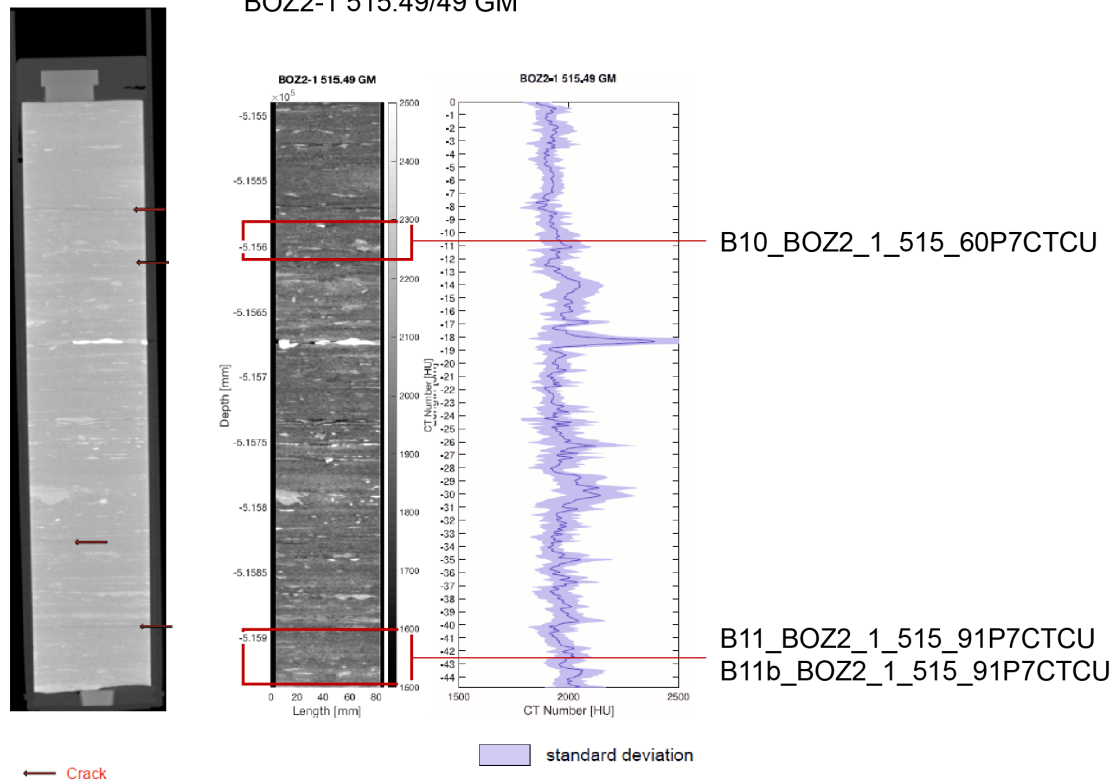


BOZ2-1 464.07/50 GM

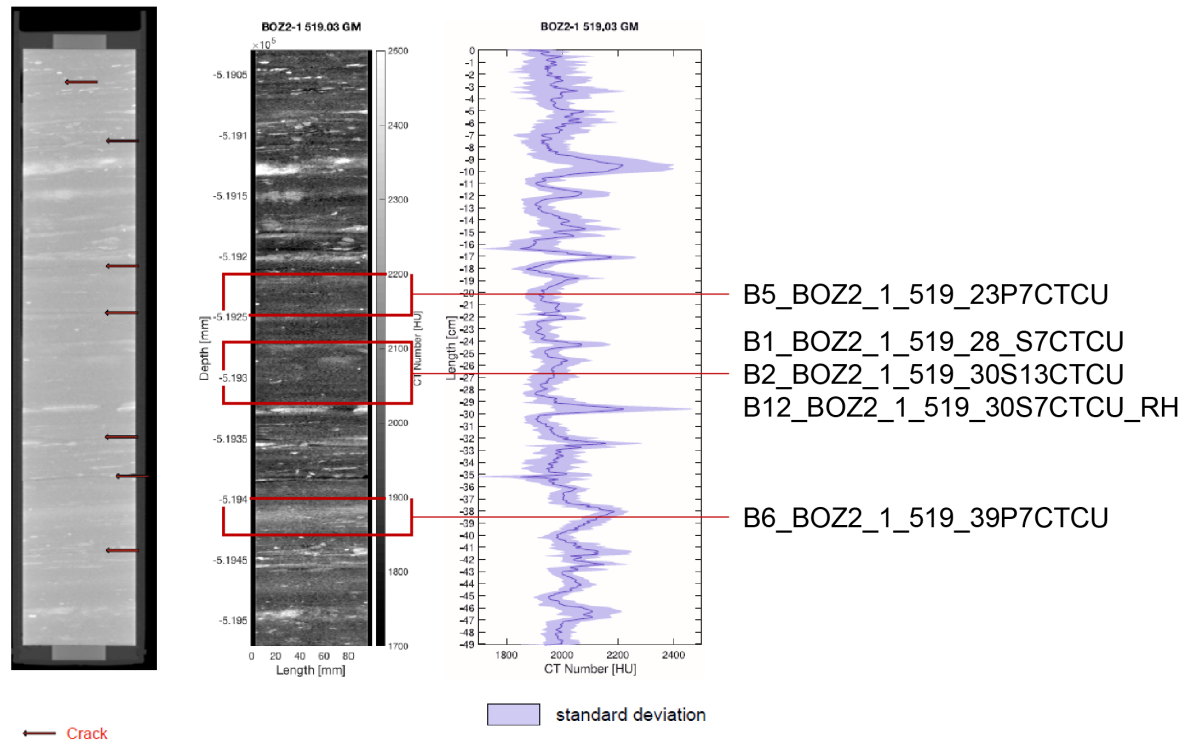


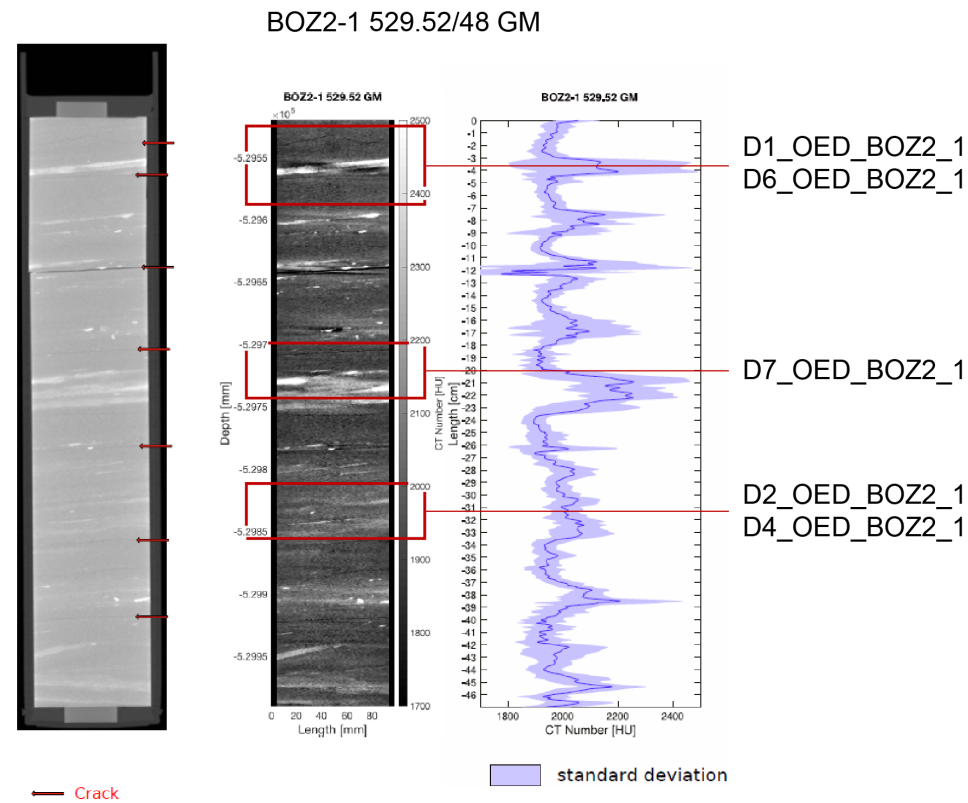


BOZ2-1 515.49/49 GM

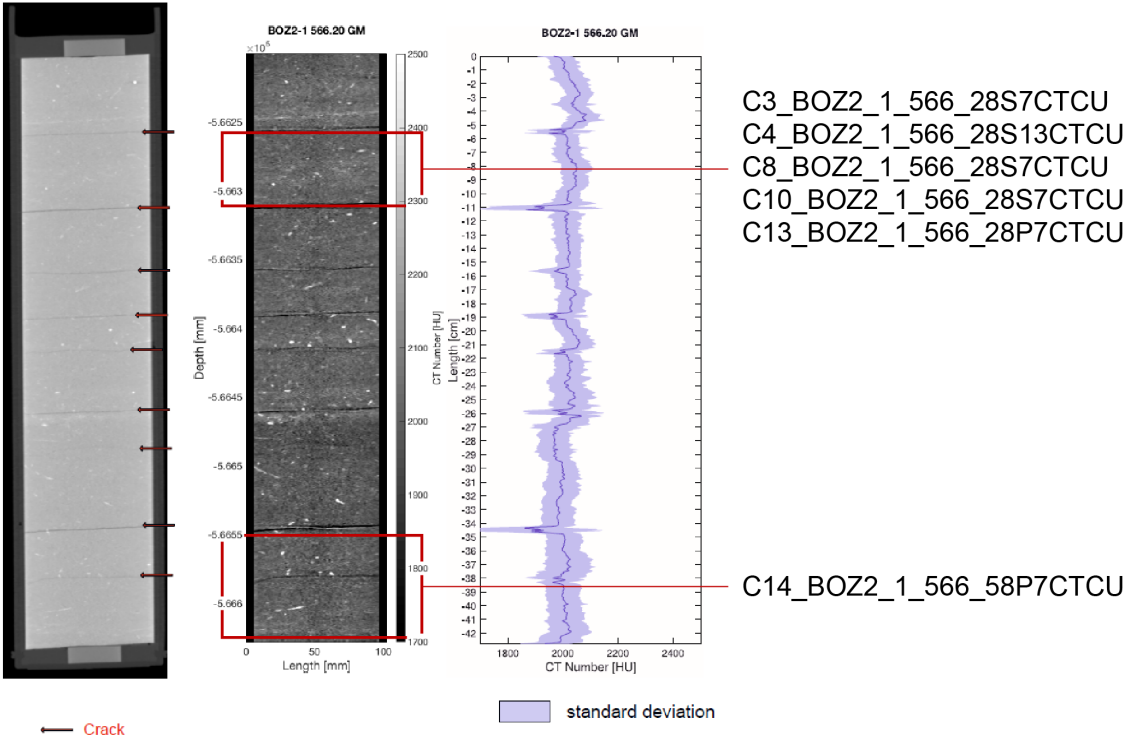


BOZ2-1 519.03/50 GM

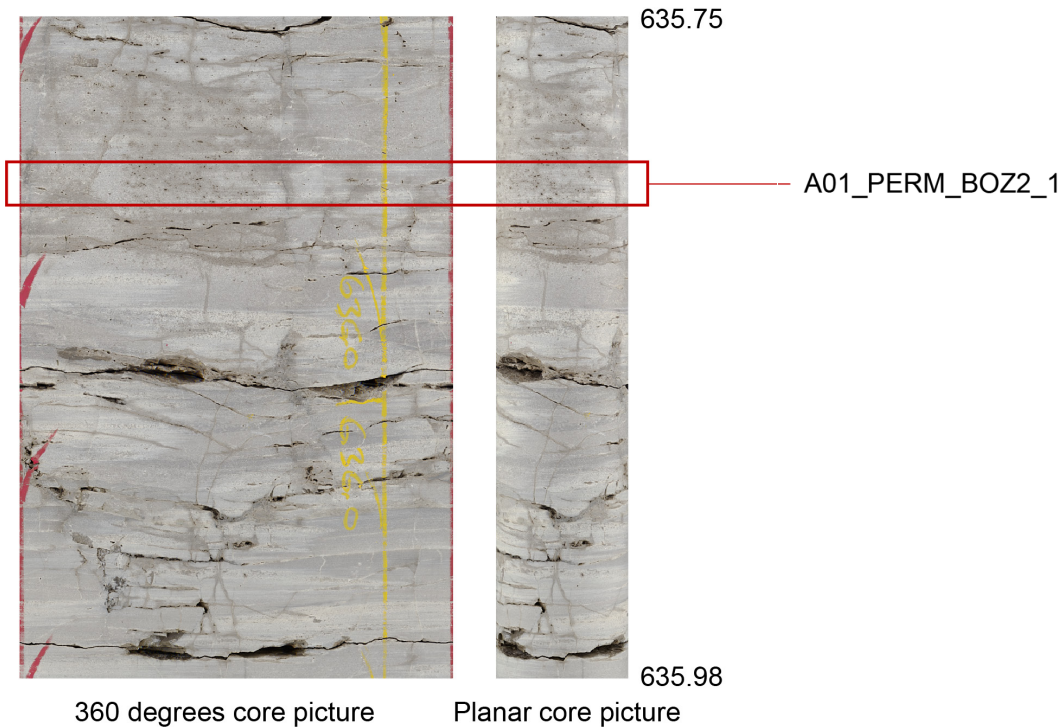




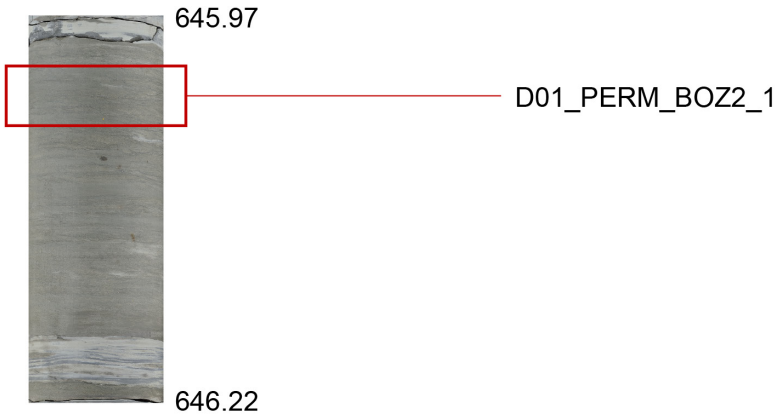
BOZ2-1 566.20/43 GM



BOZ2-1 635.75/23 GM



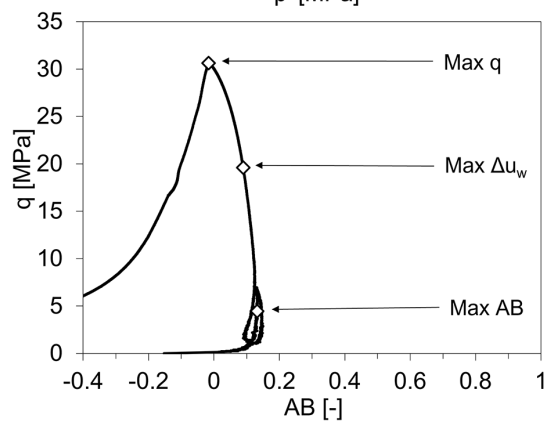
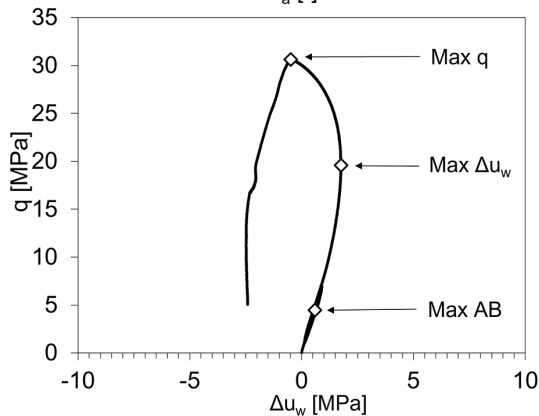
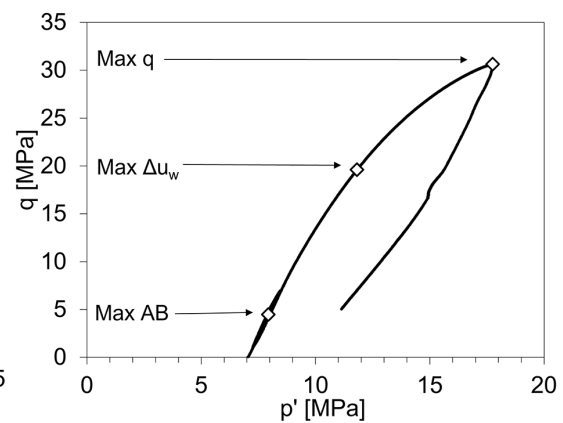
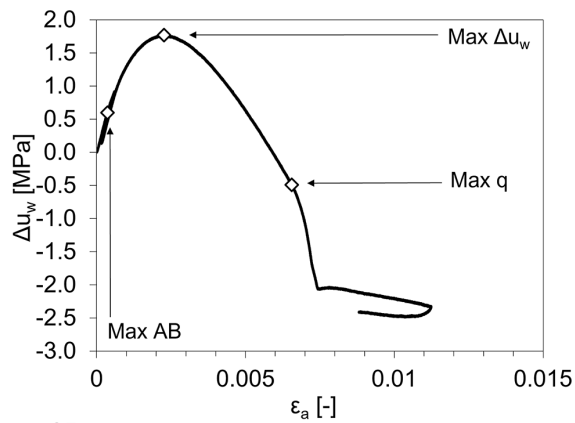
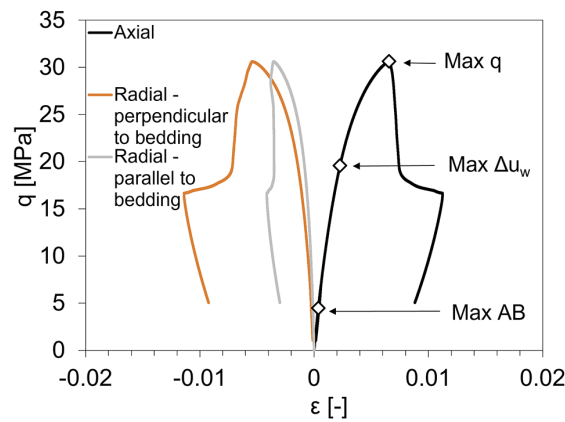
BOZ2-1 645.97/25 GM



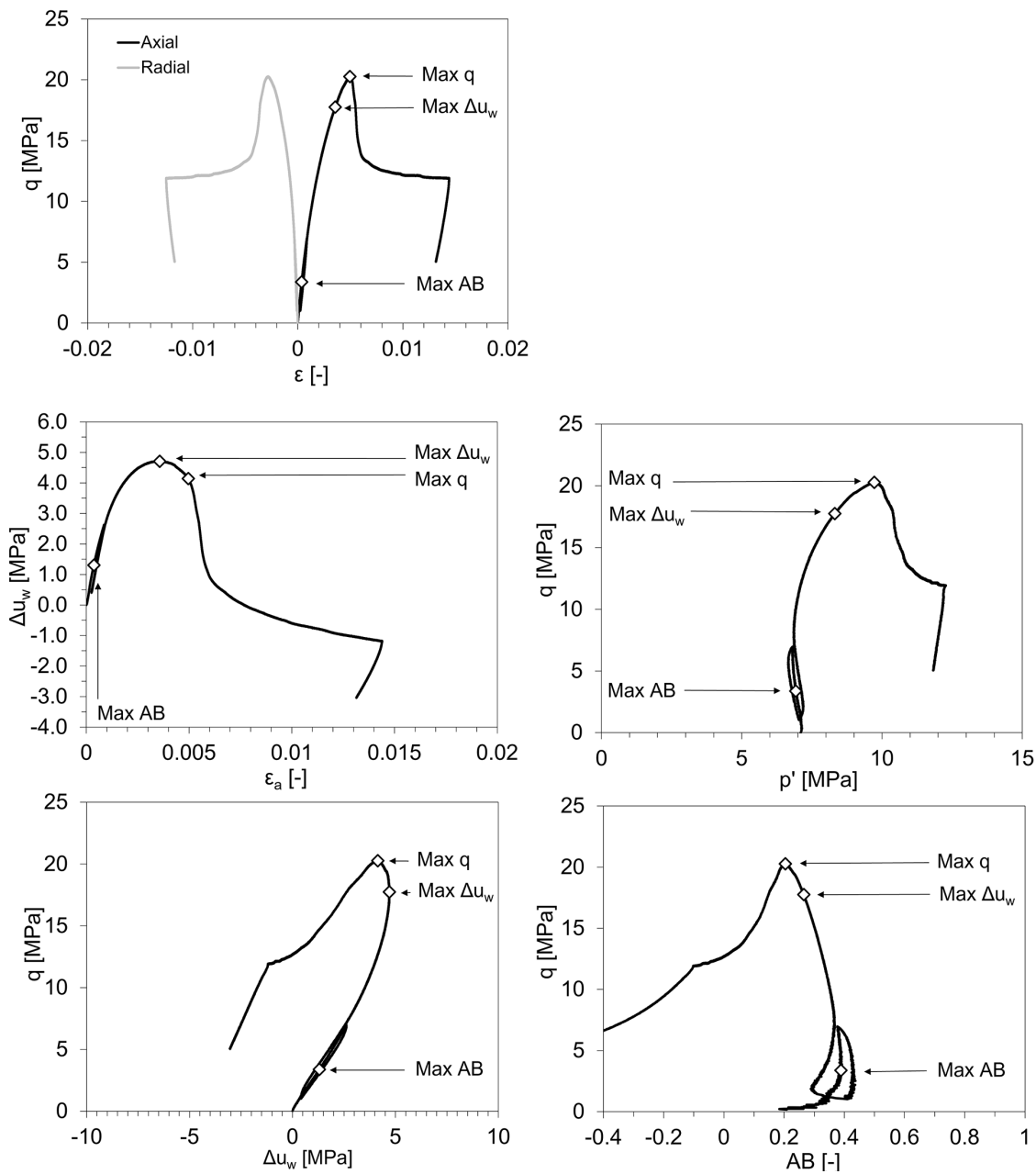
Appendix C Diagnostic plots of triaxial tests (geomechanical testing programme)

For each triaxial test, the diagnostic plots are here reported (order of tests according to Tab. E-2). The plots include: the evolution of axial and radial strains with deviatoric stress q , the pore pressure change Δu_w during shearing versus the axial strain ε_a , the stress path in the p' - q plane, the pore pressure variation Δu_w and the AB parameter evolution with q . In all the plots, the conditions at which the maximum deviatoric stress (Max q), the maximum pore pressure change (Max Δu_w) and the maximum AB (Max AB) (excluding evolution during unload/reload loops) are marked, as mentioned in Section 6.2.2.4. Testing conditions are reported in Tab. 6-2.

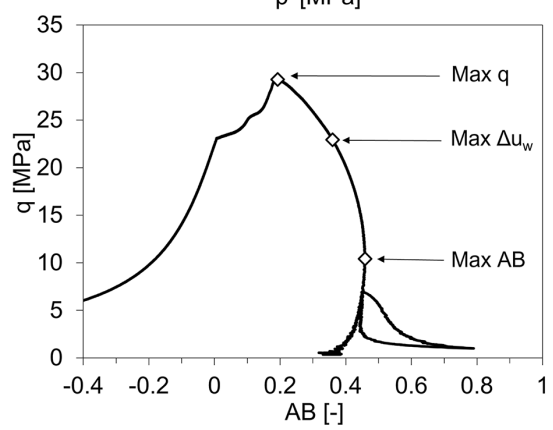
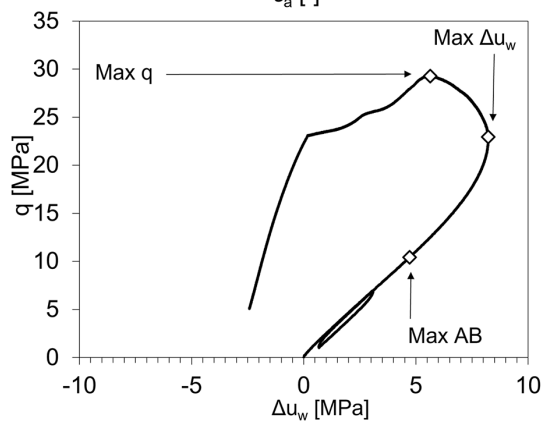
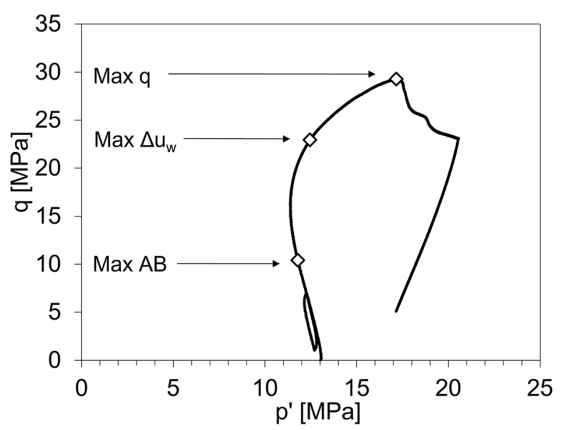
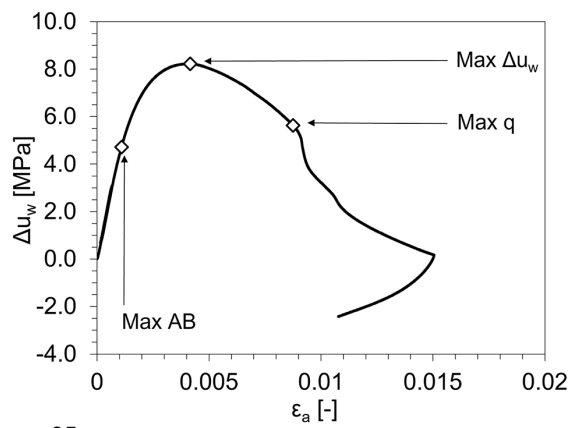
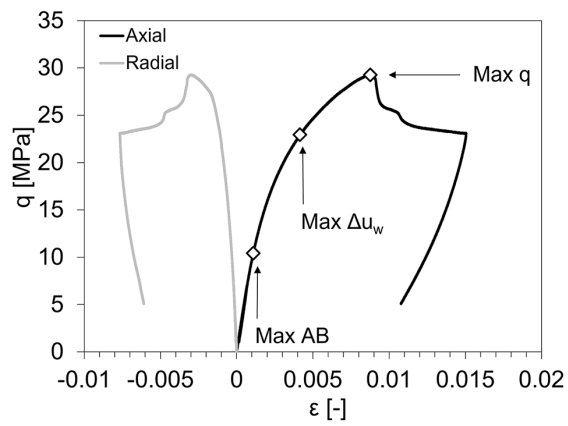
B7_BOZ2_1_427_95P7CTCU



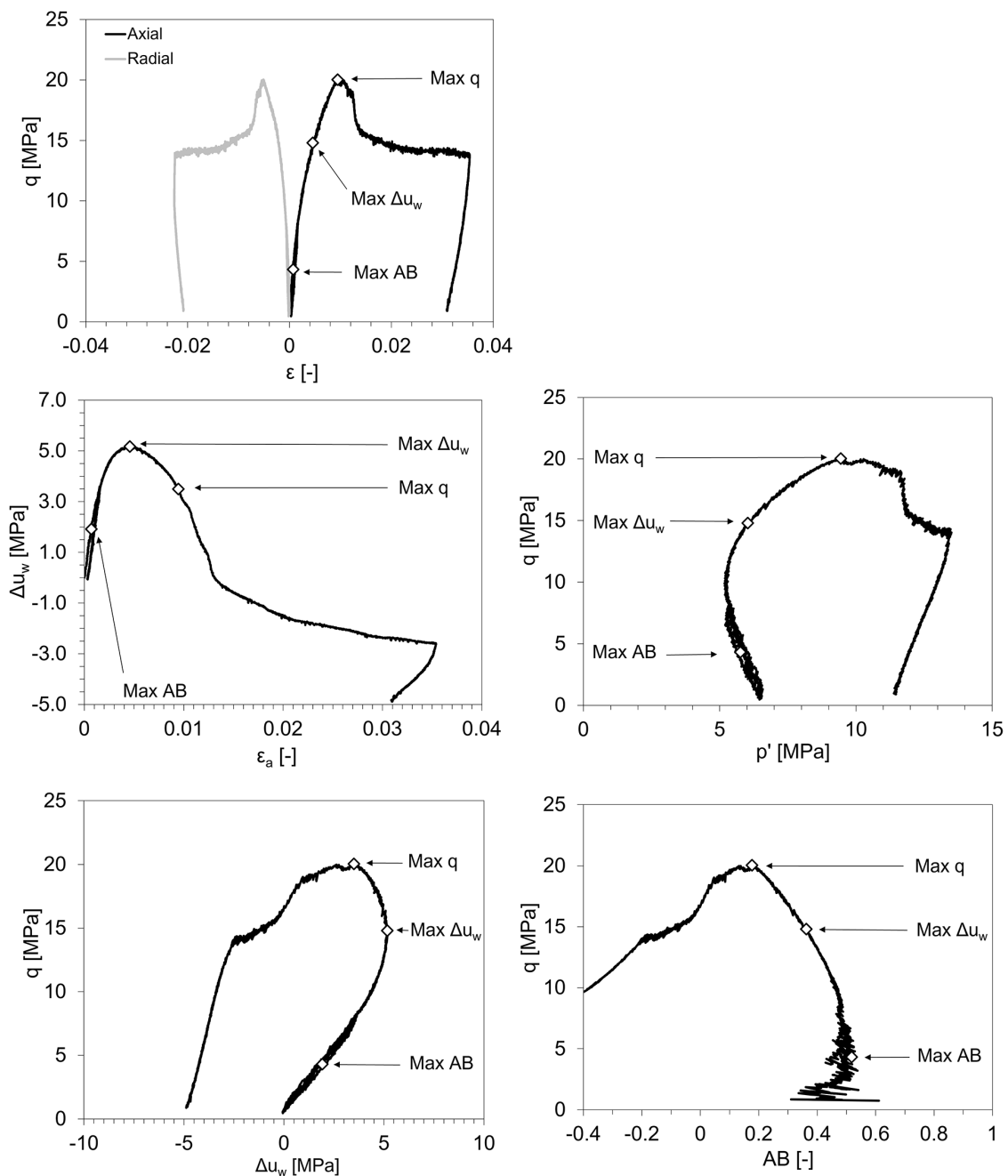
B8_BOZ2_1_453_16S7CTCU



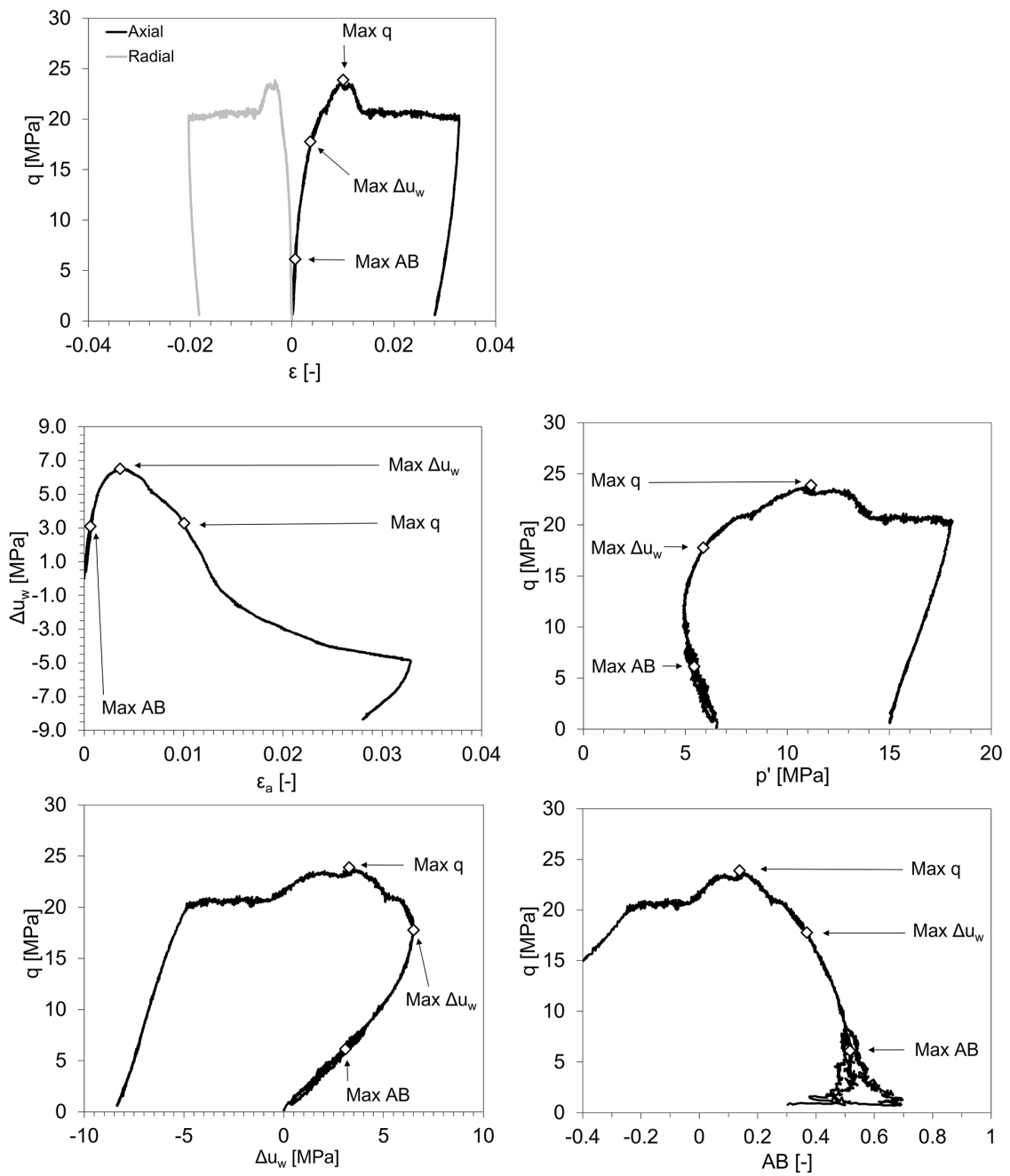
B9_BOZ2_1_453_16S13CTCU



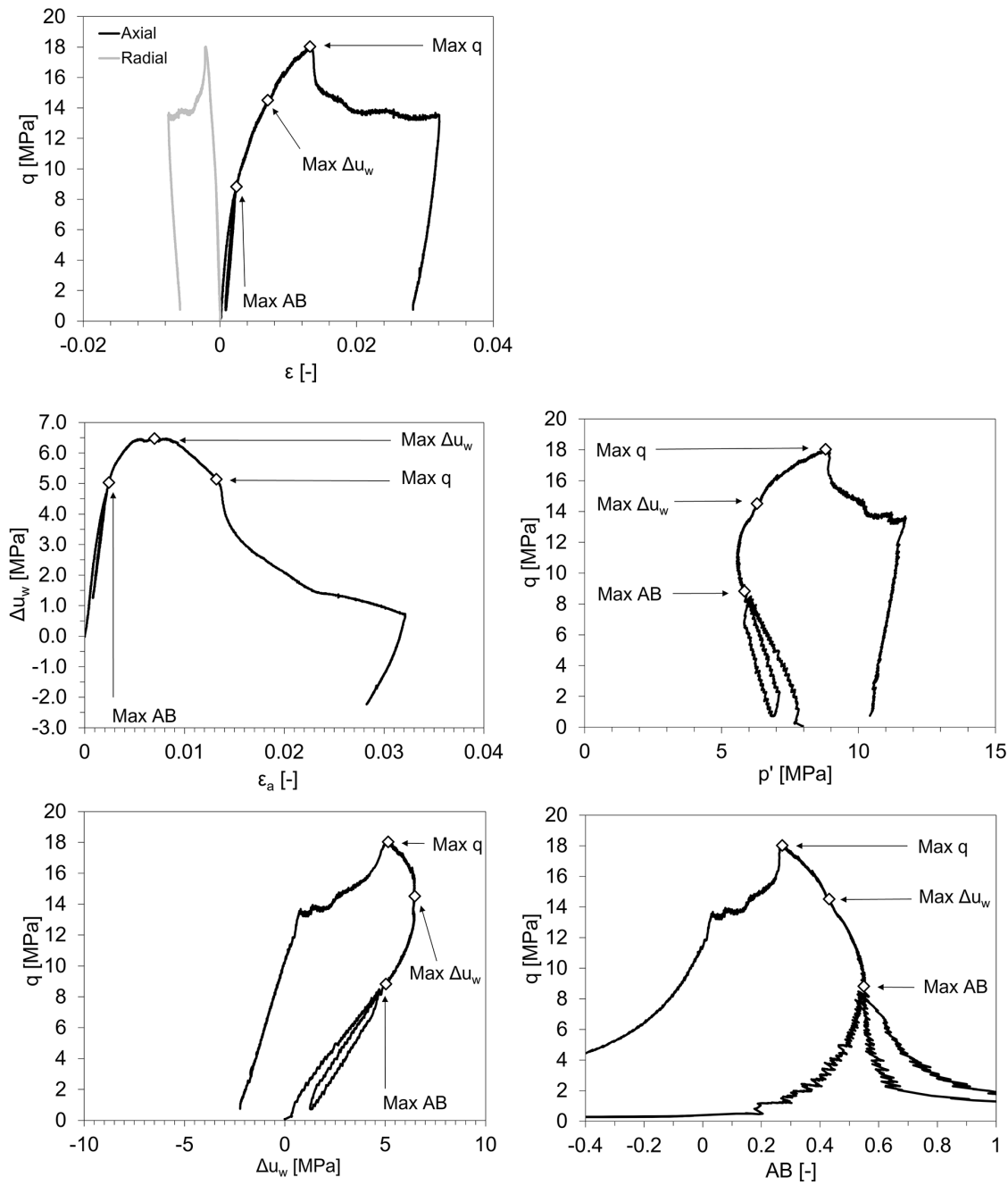
C11_BOZ2_1_504_78S7CTCU



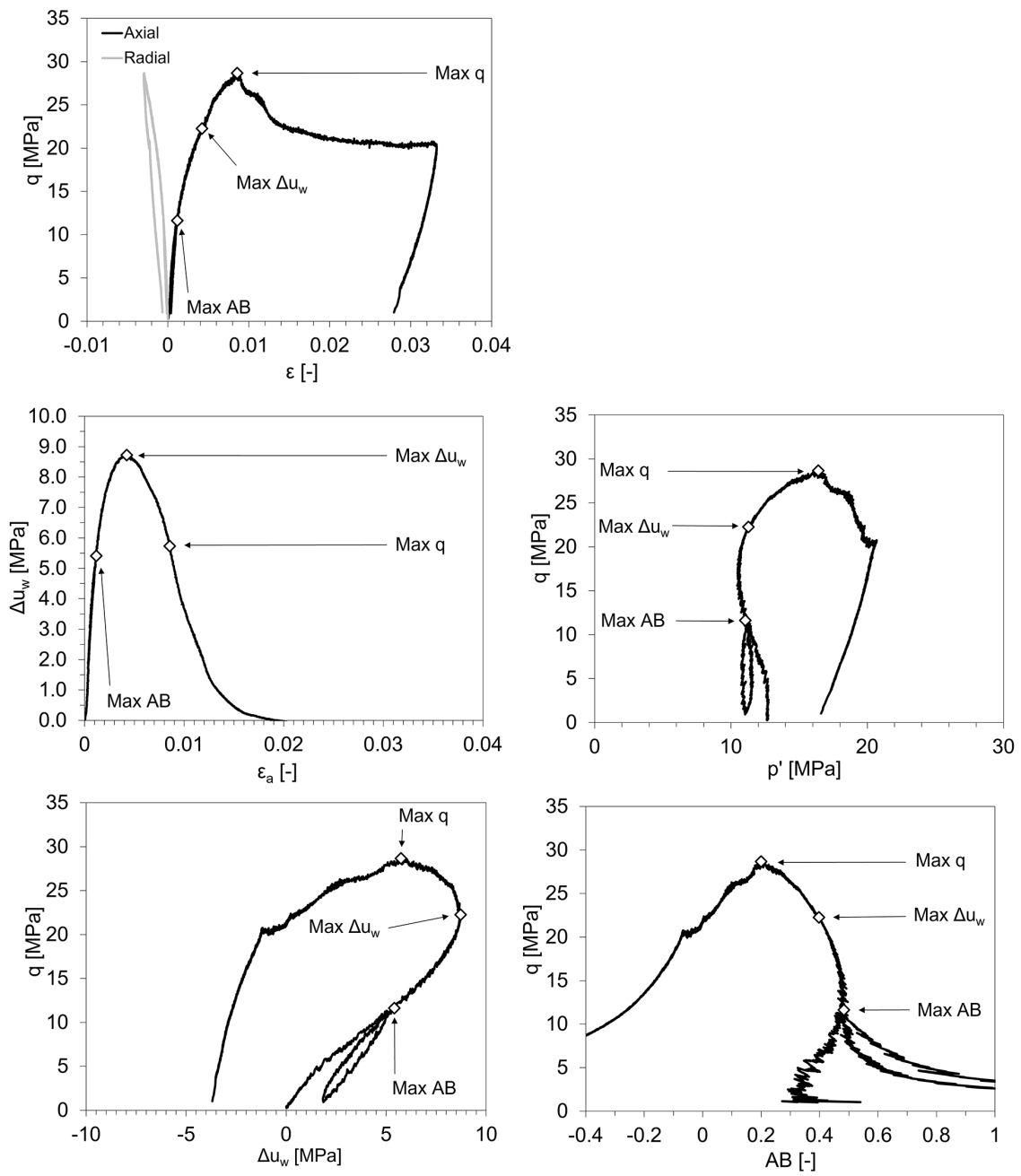
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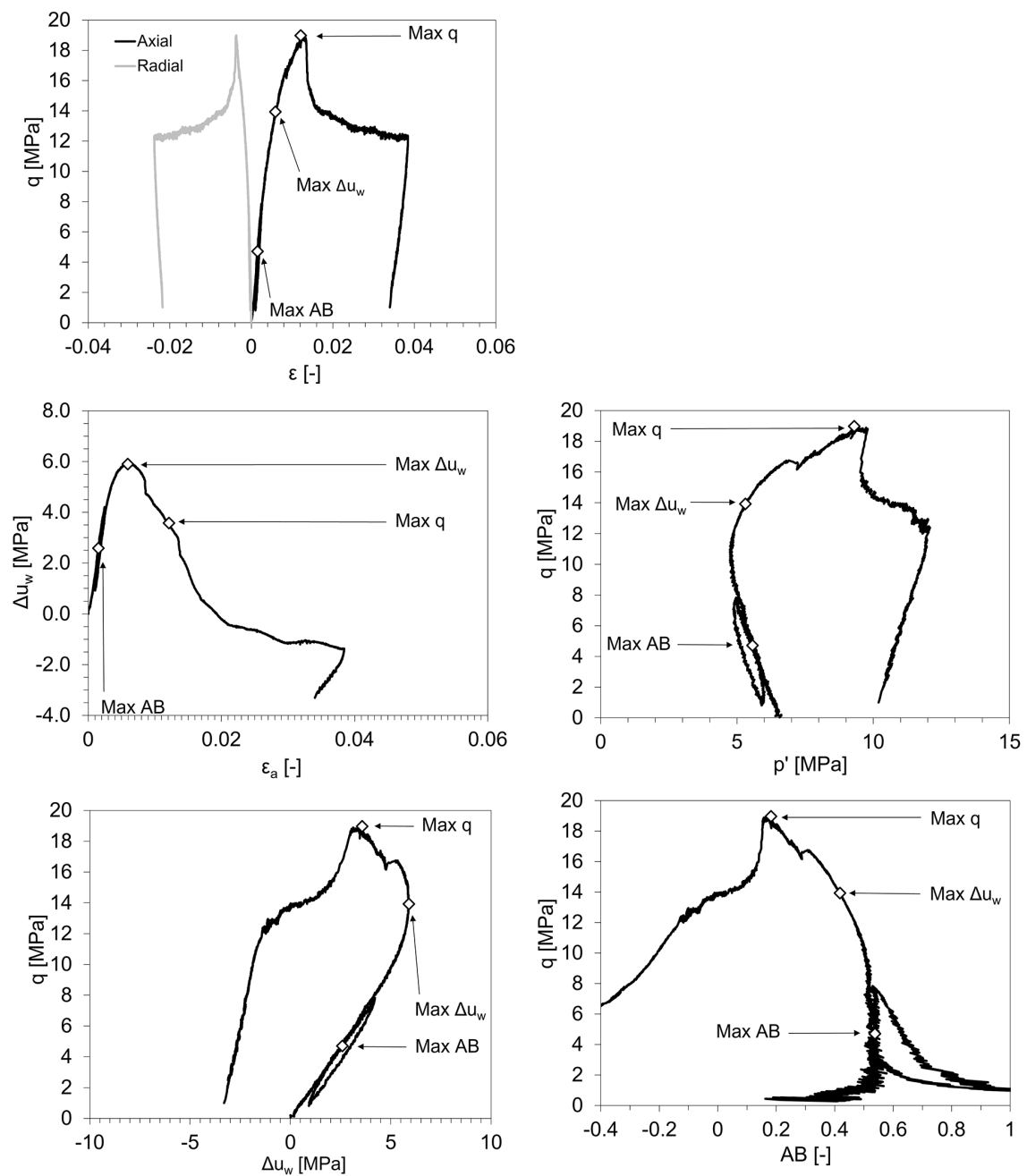
C5_BOZ2_1_504_78S8CTCU



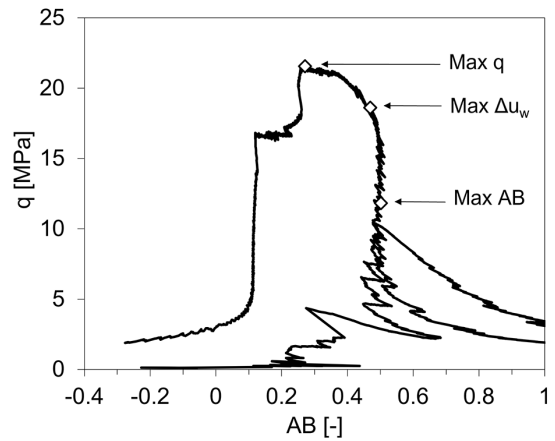
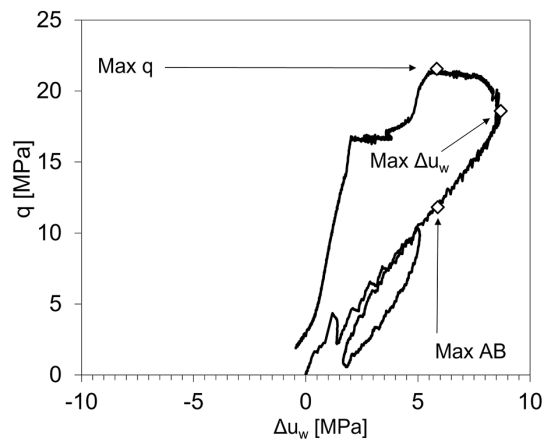
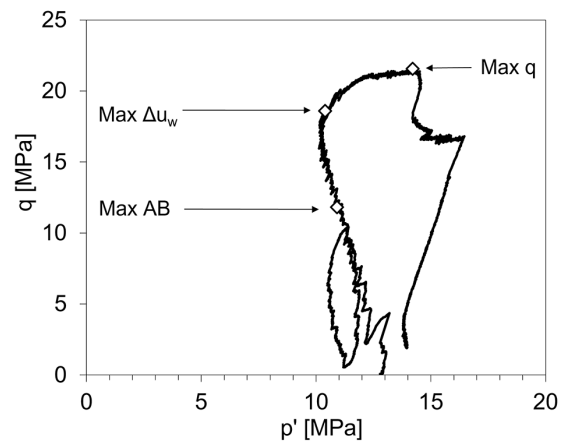
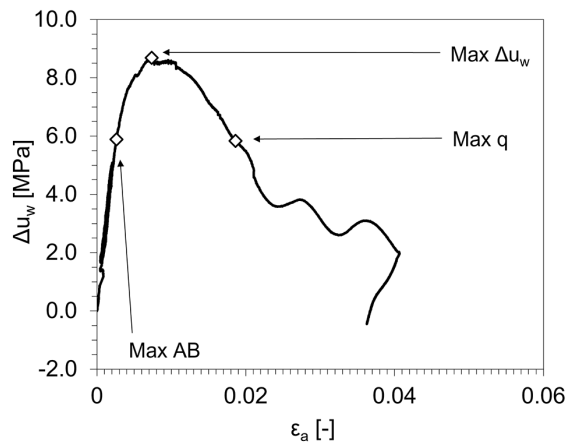
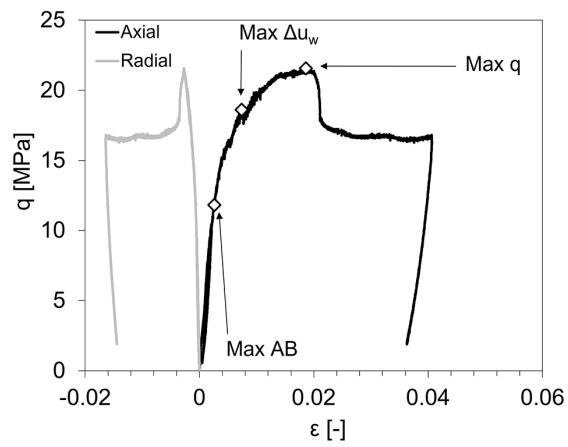
C6_BOZ2_1_504_78S13CTCU



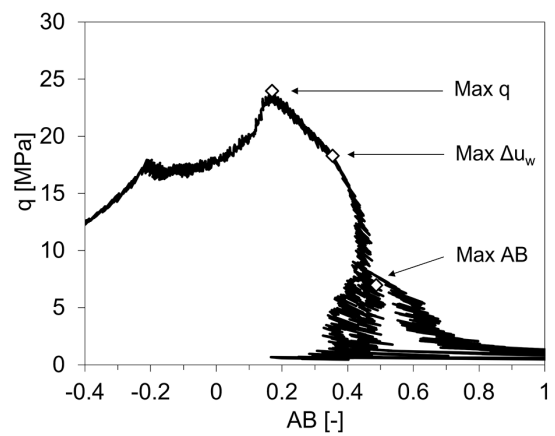
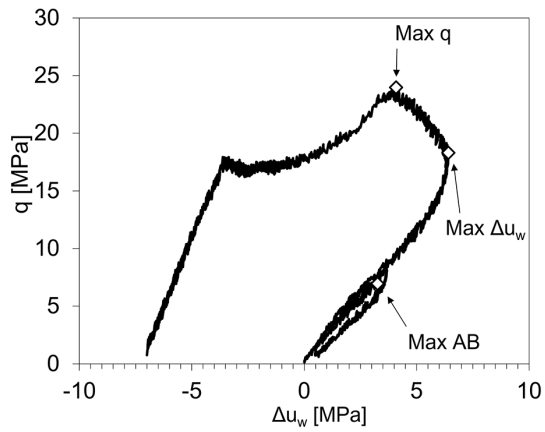
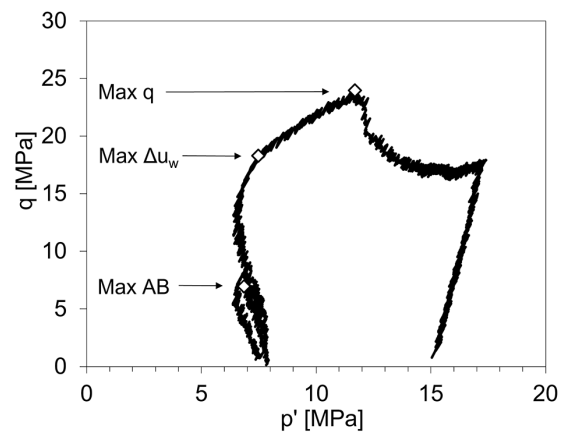
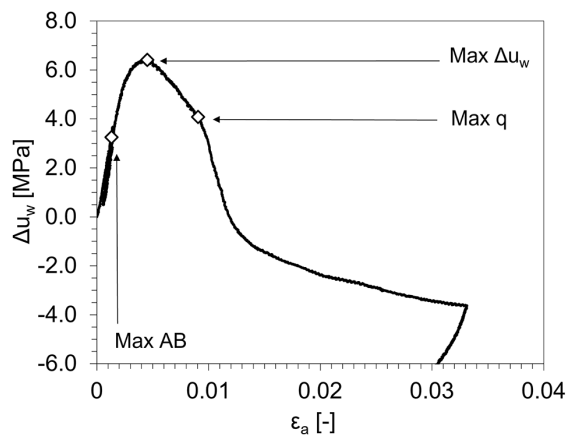
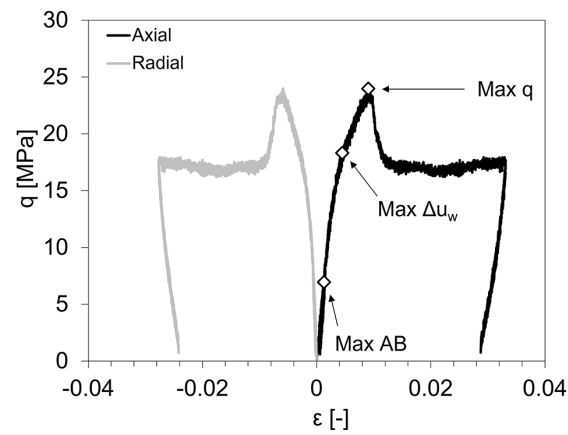
C1_BOZ2_1_504_95S7CTCU



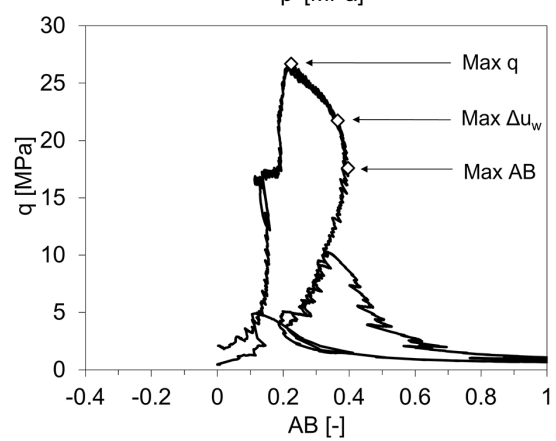
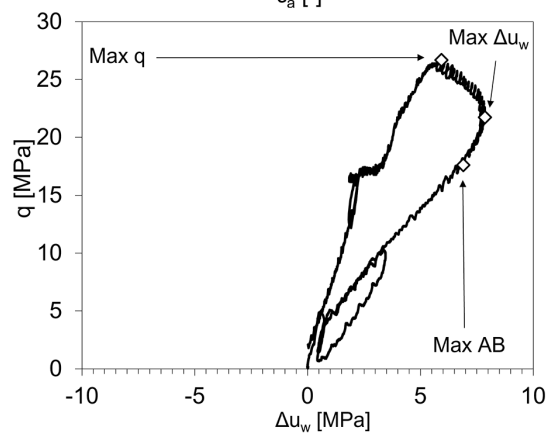
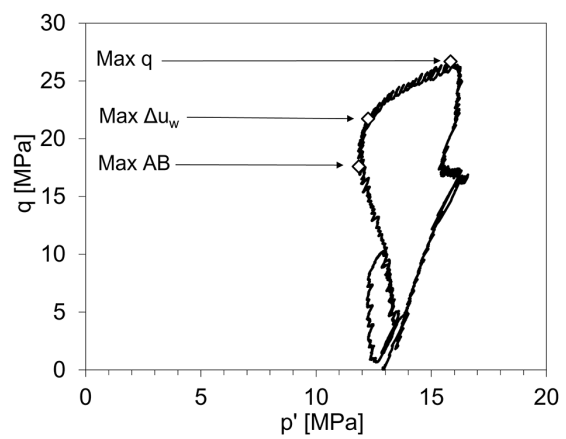
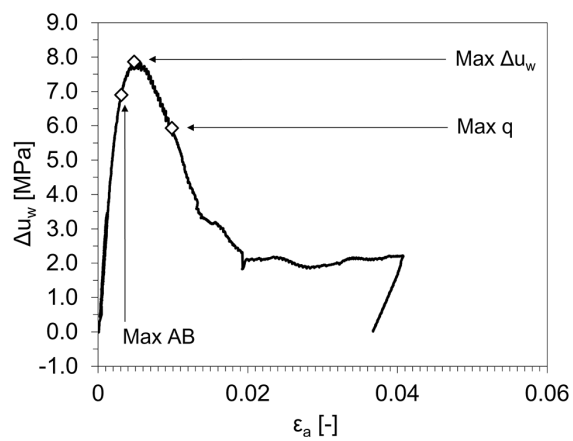
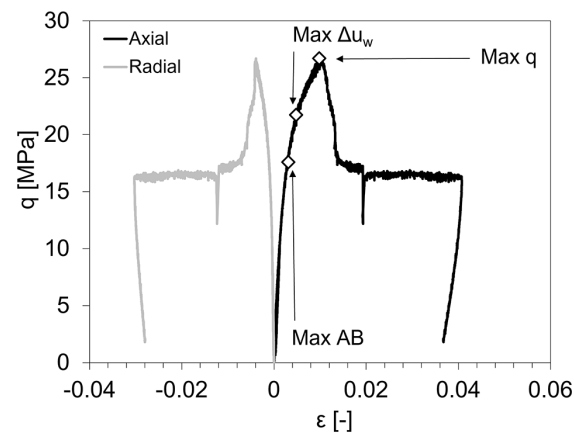
C2_BOZ2_1_504_95S13CTCU



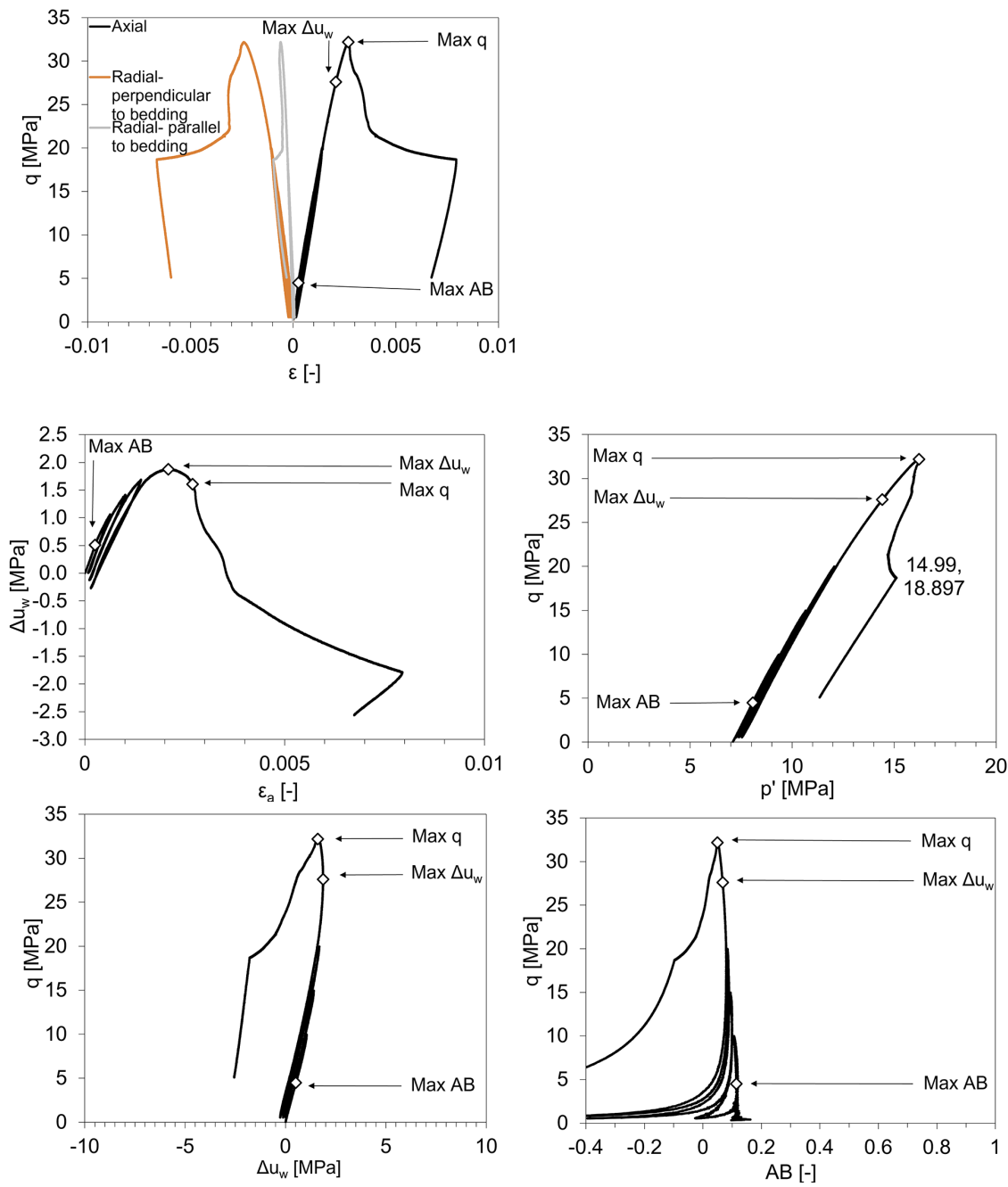
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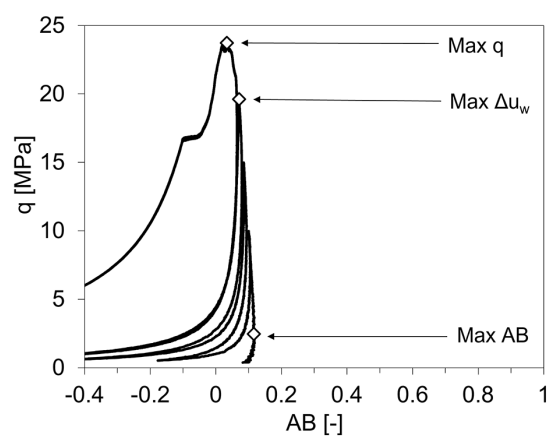
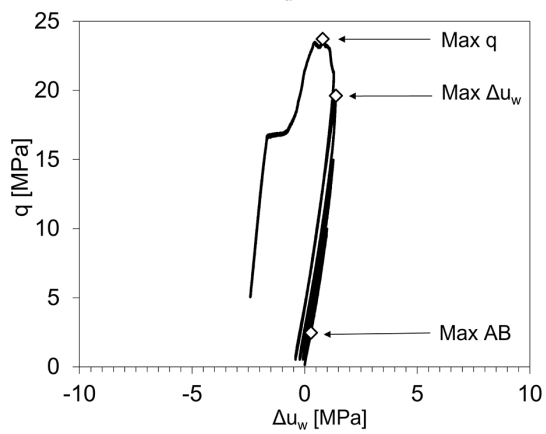
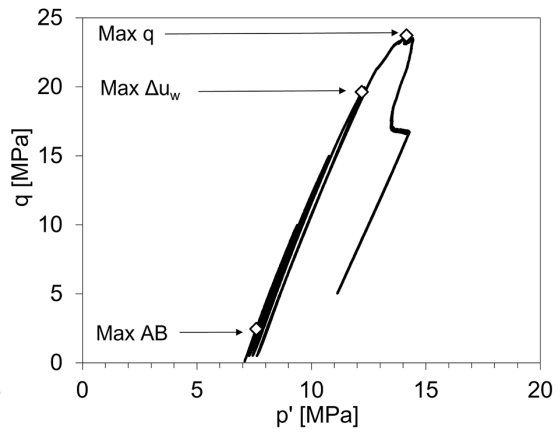
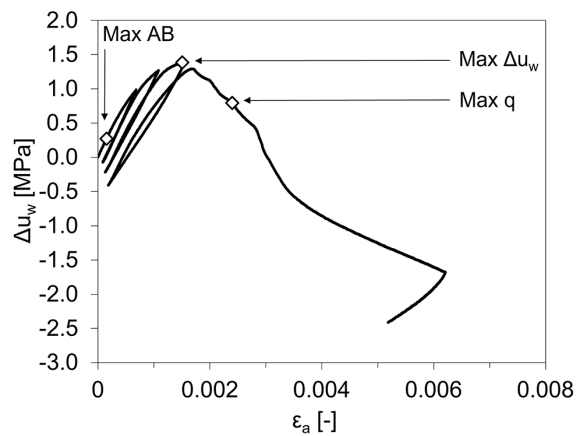
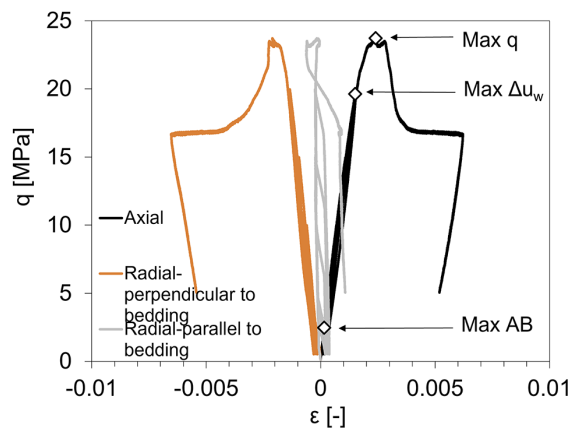
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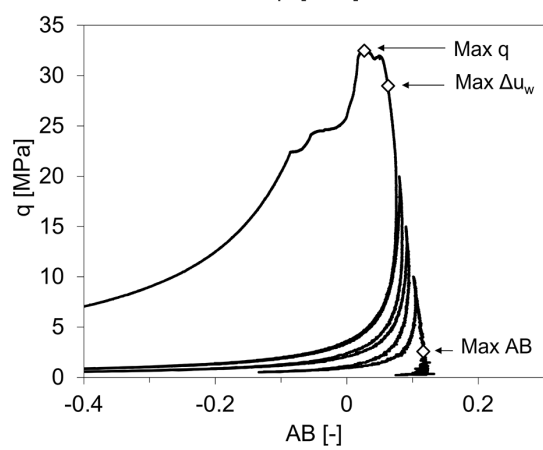
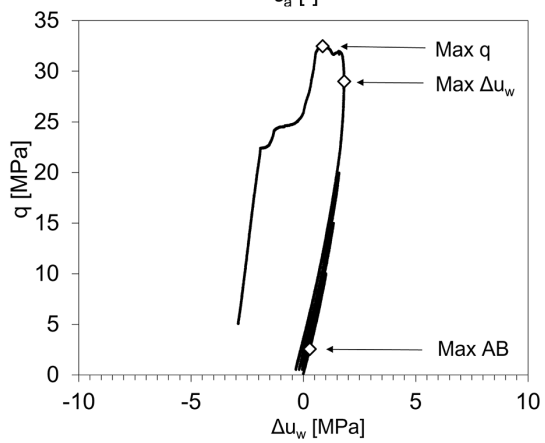
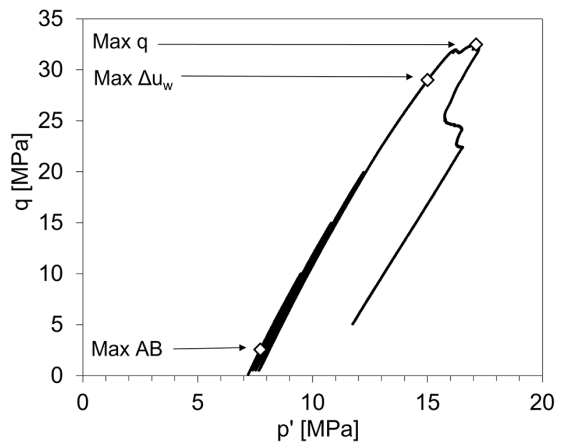
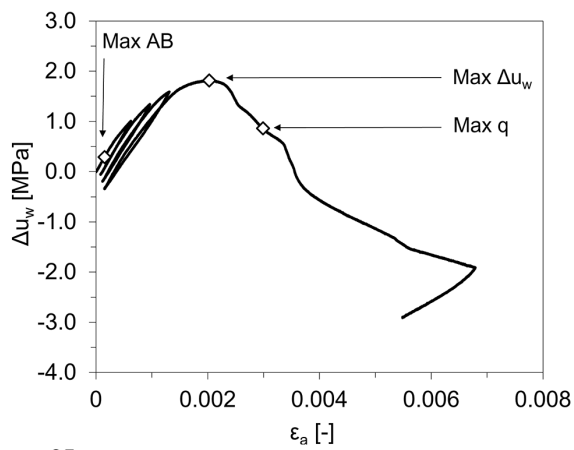
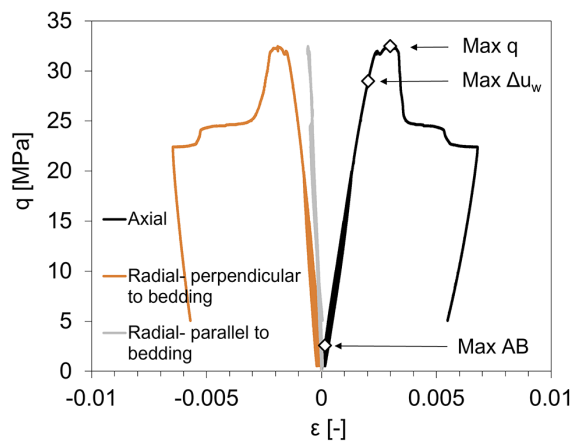
B10_BOZ2_1_515_60P7CTCU



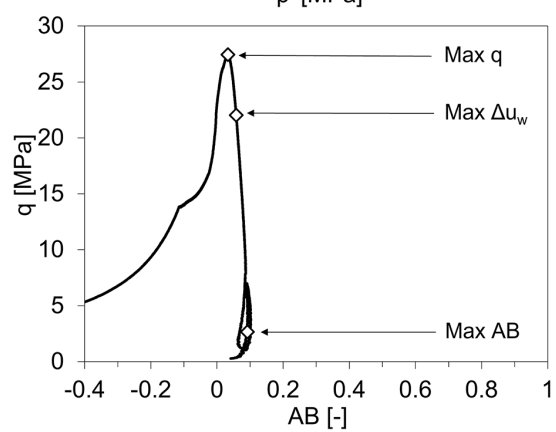
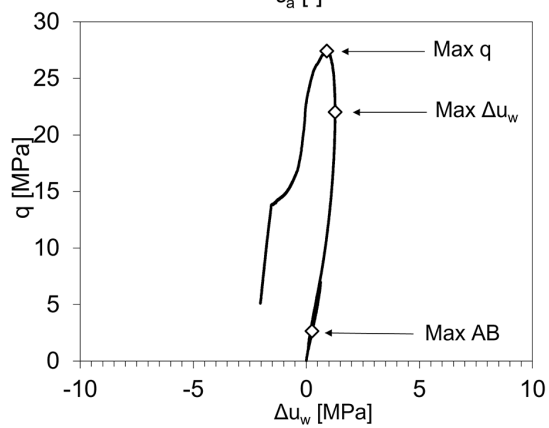
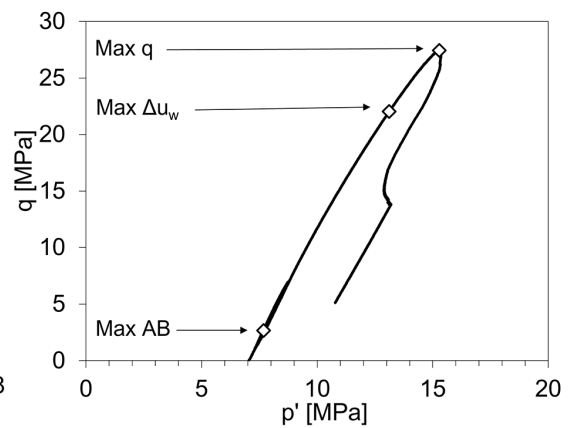
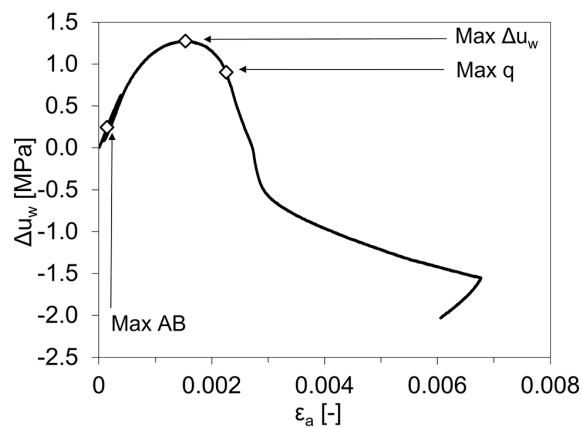
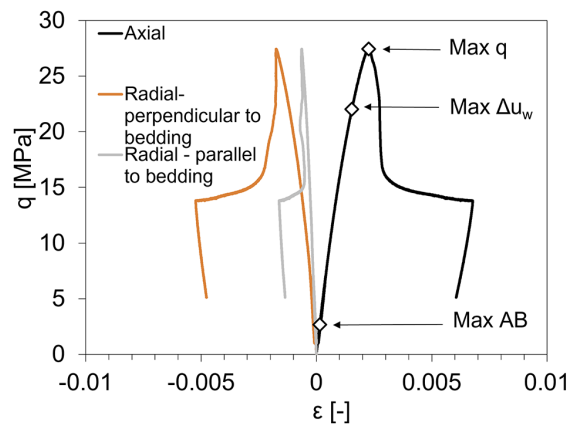
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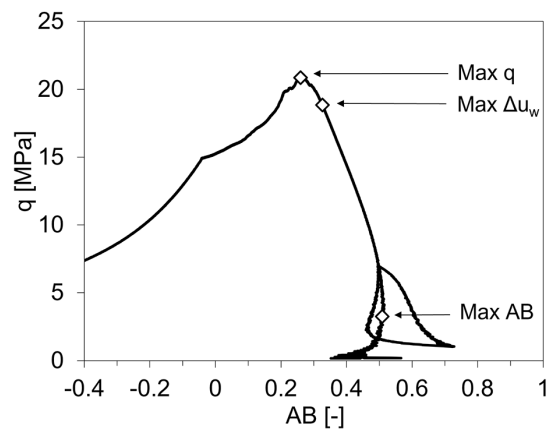
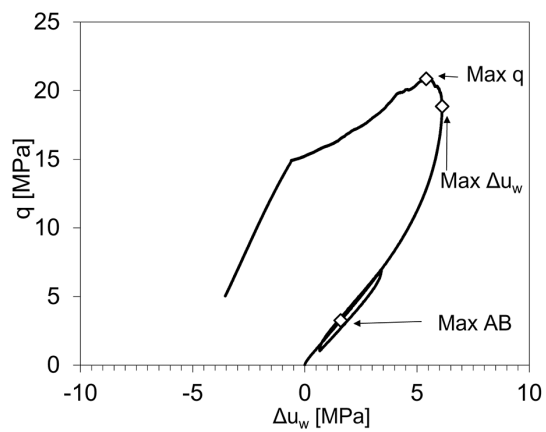
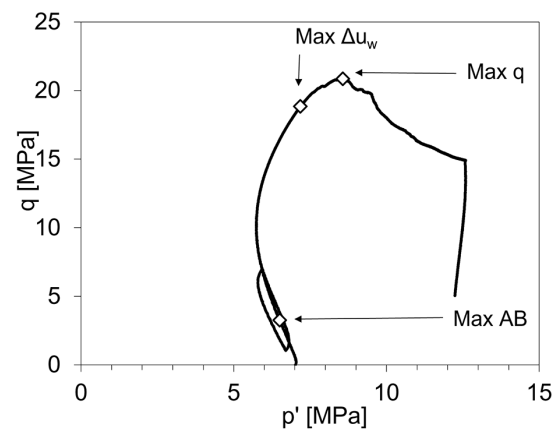
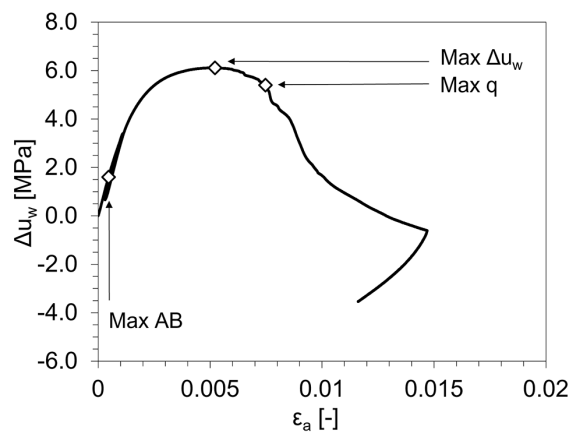
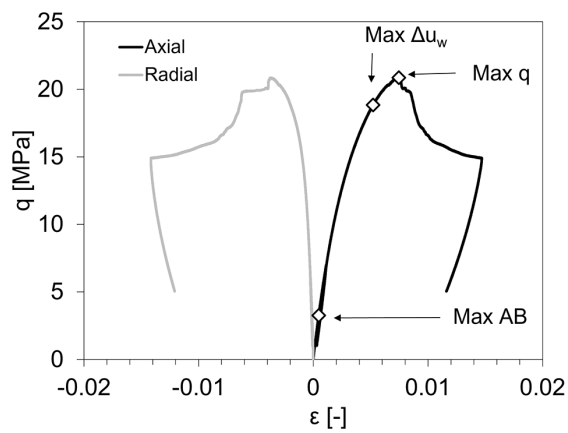
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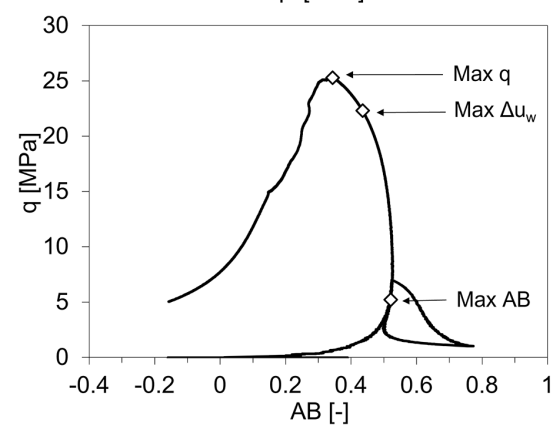
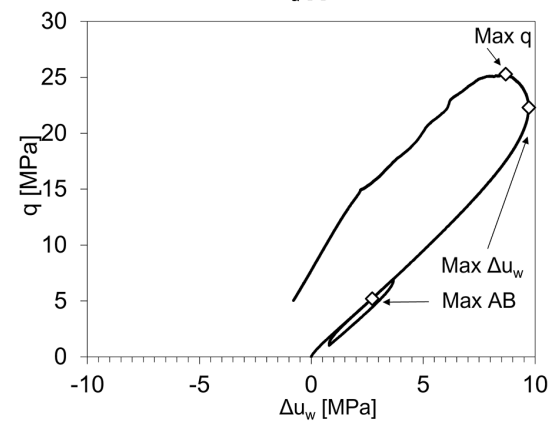
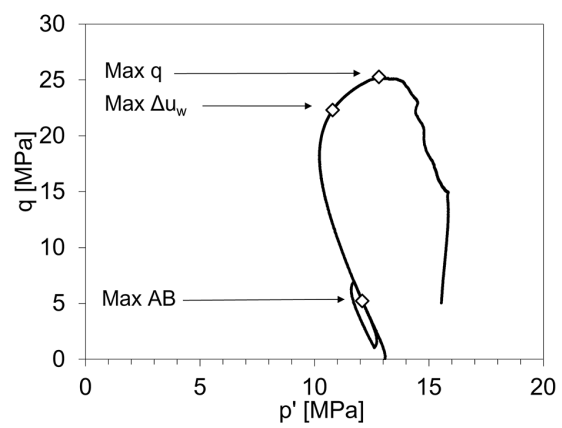
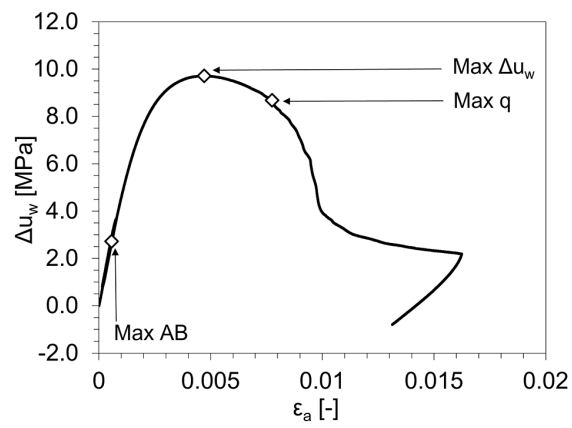
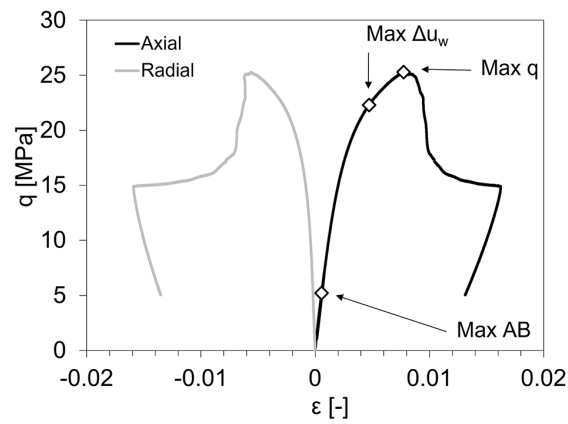
B5_BOZ2_1_519_23P7CTCU



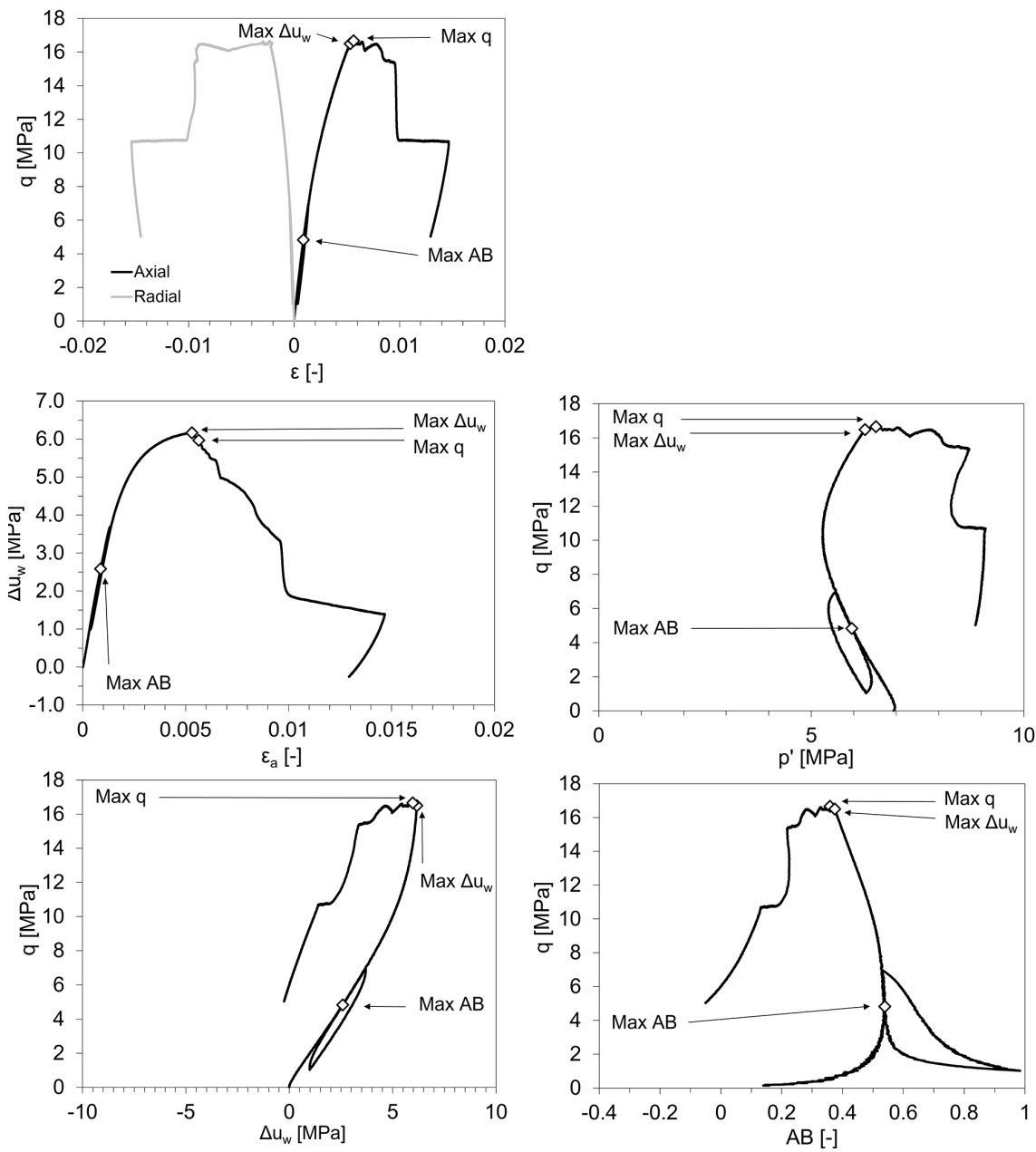
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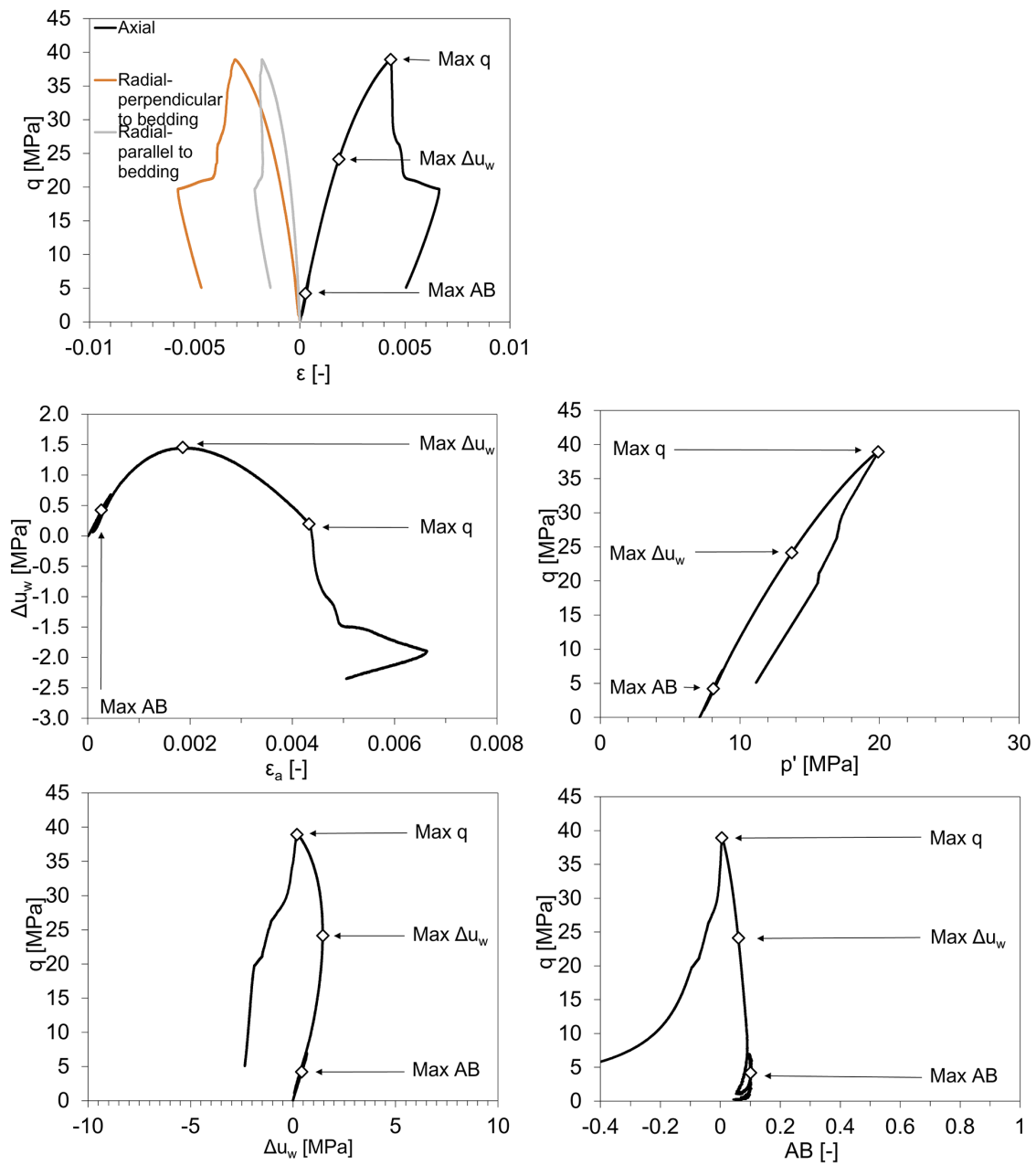
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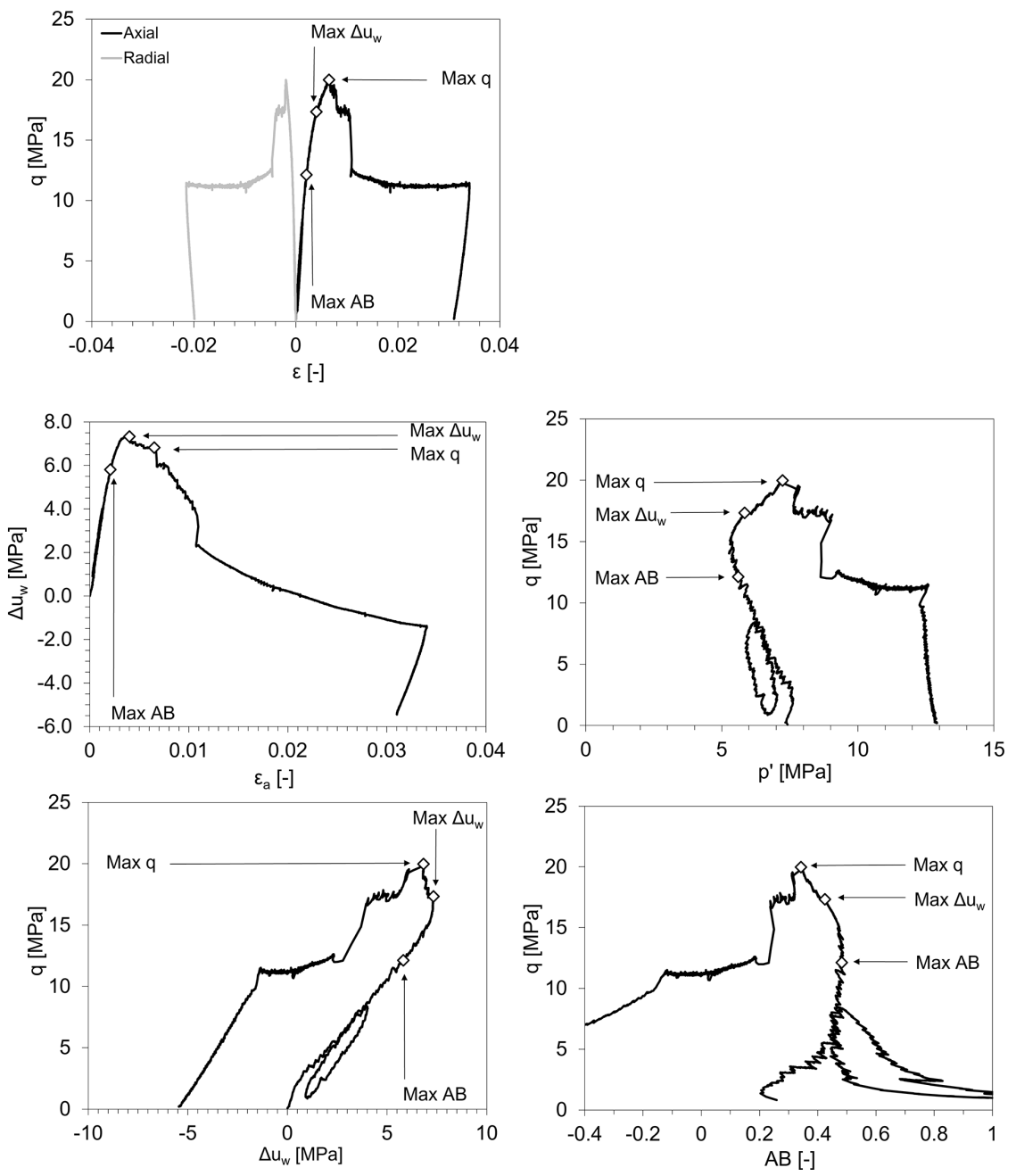
B12_BOZ2_1_519_28S7CTCU_RH



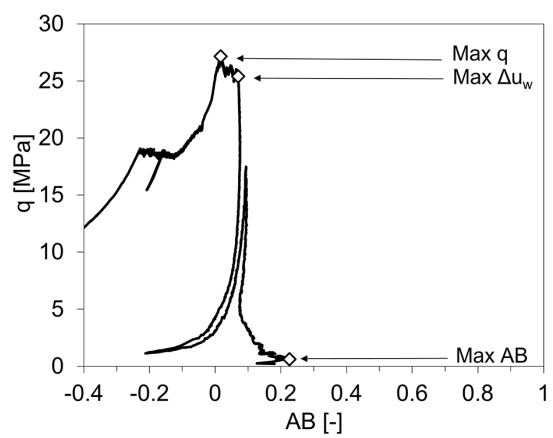
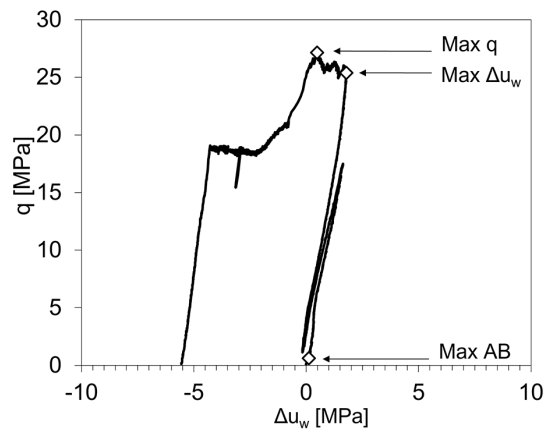
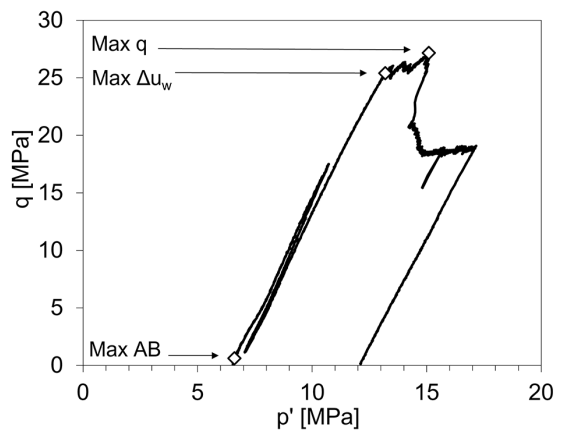
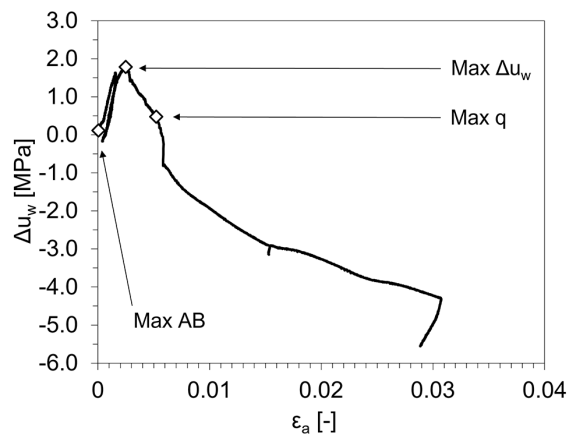
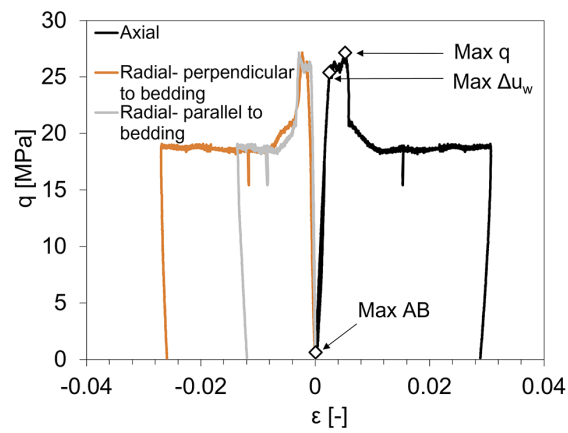
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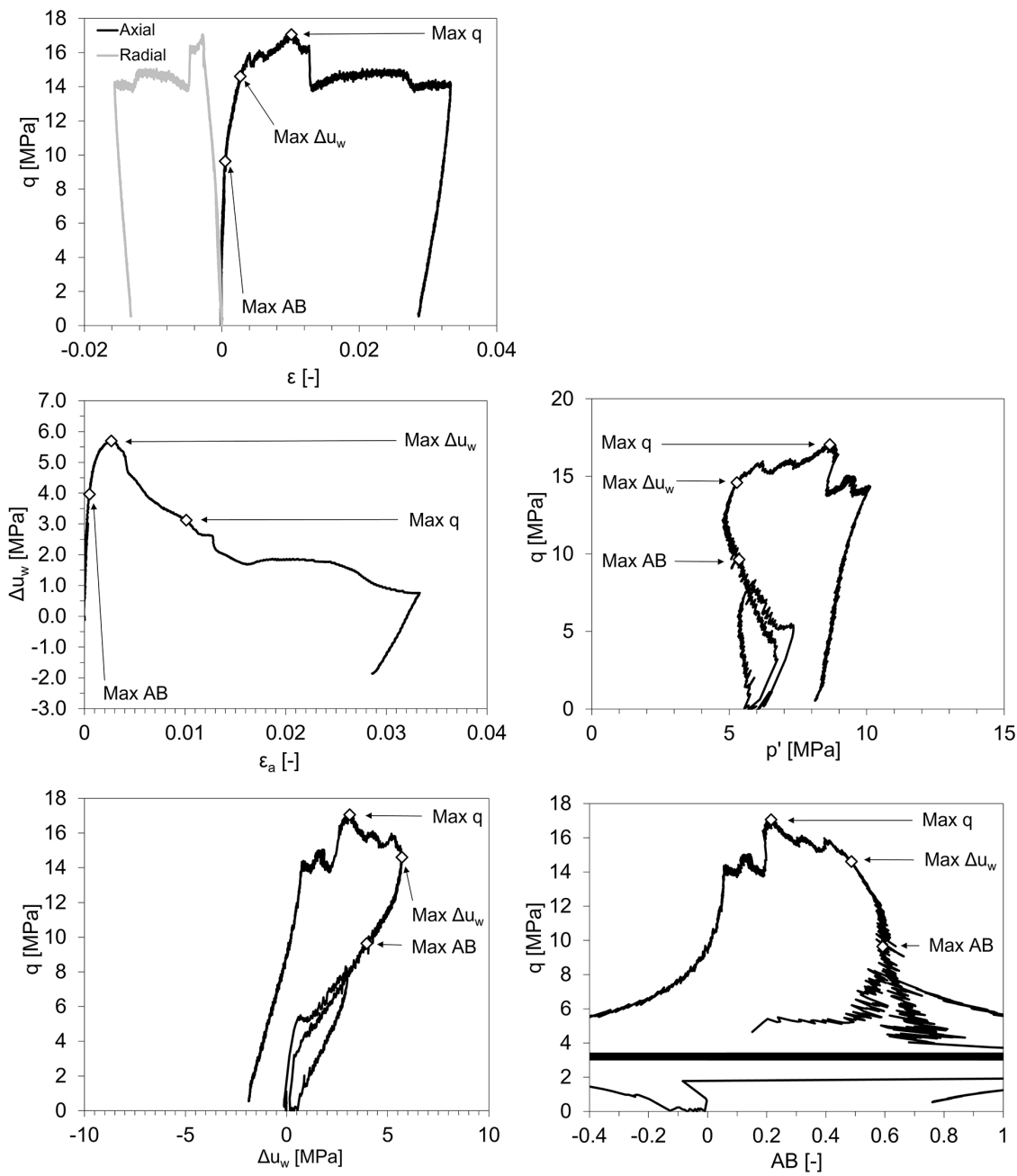
C10_BOZ2_1_566_28S7CTCU



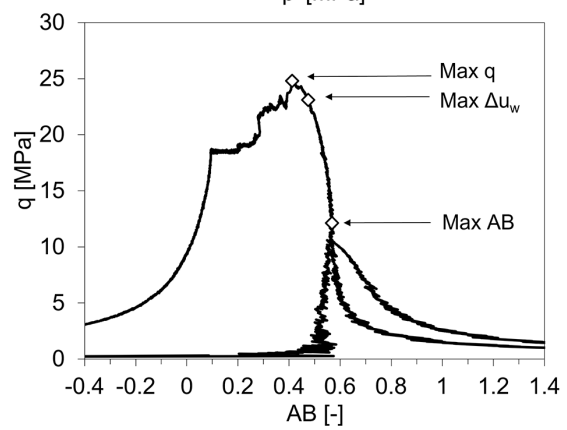
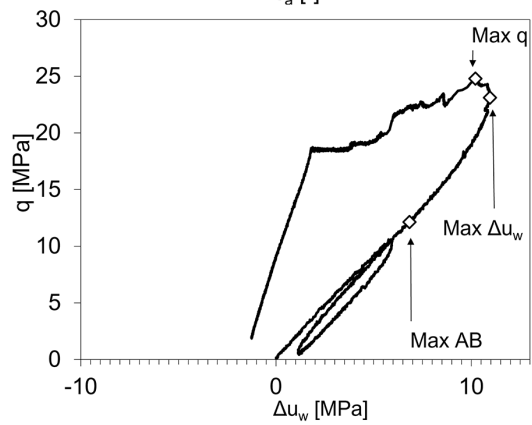
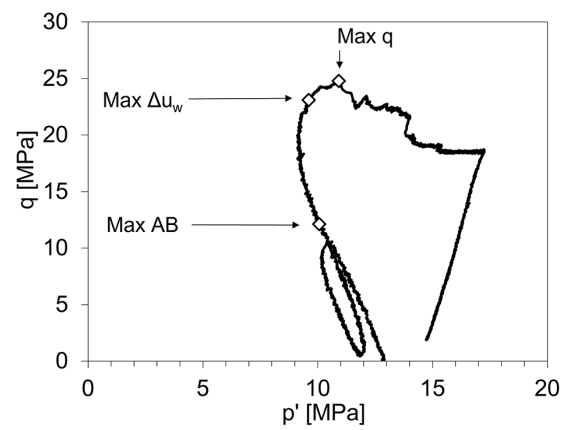
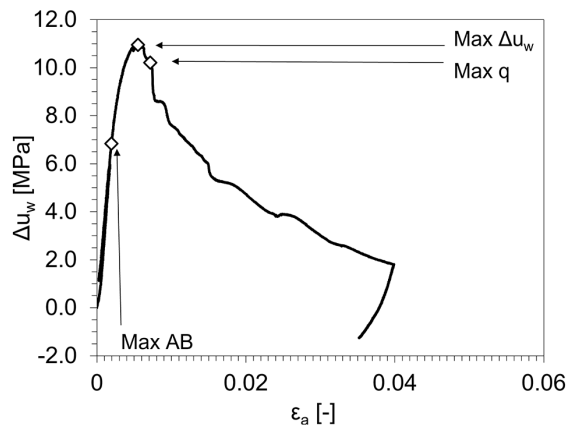
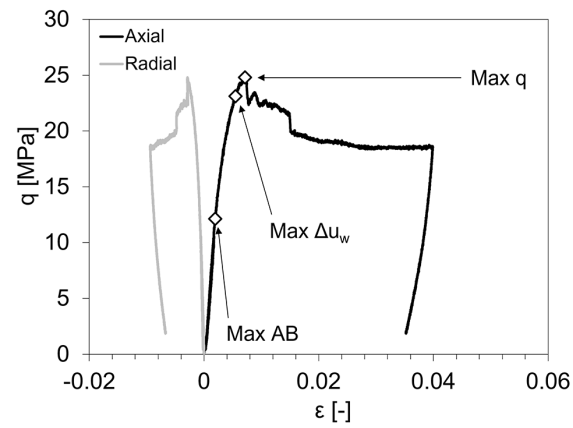
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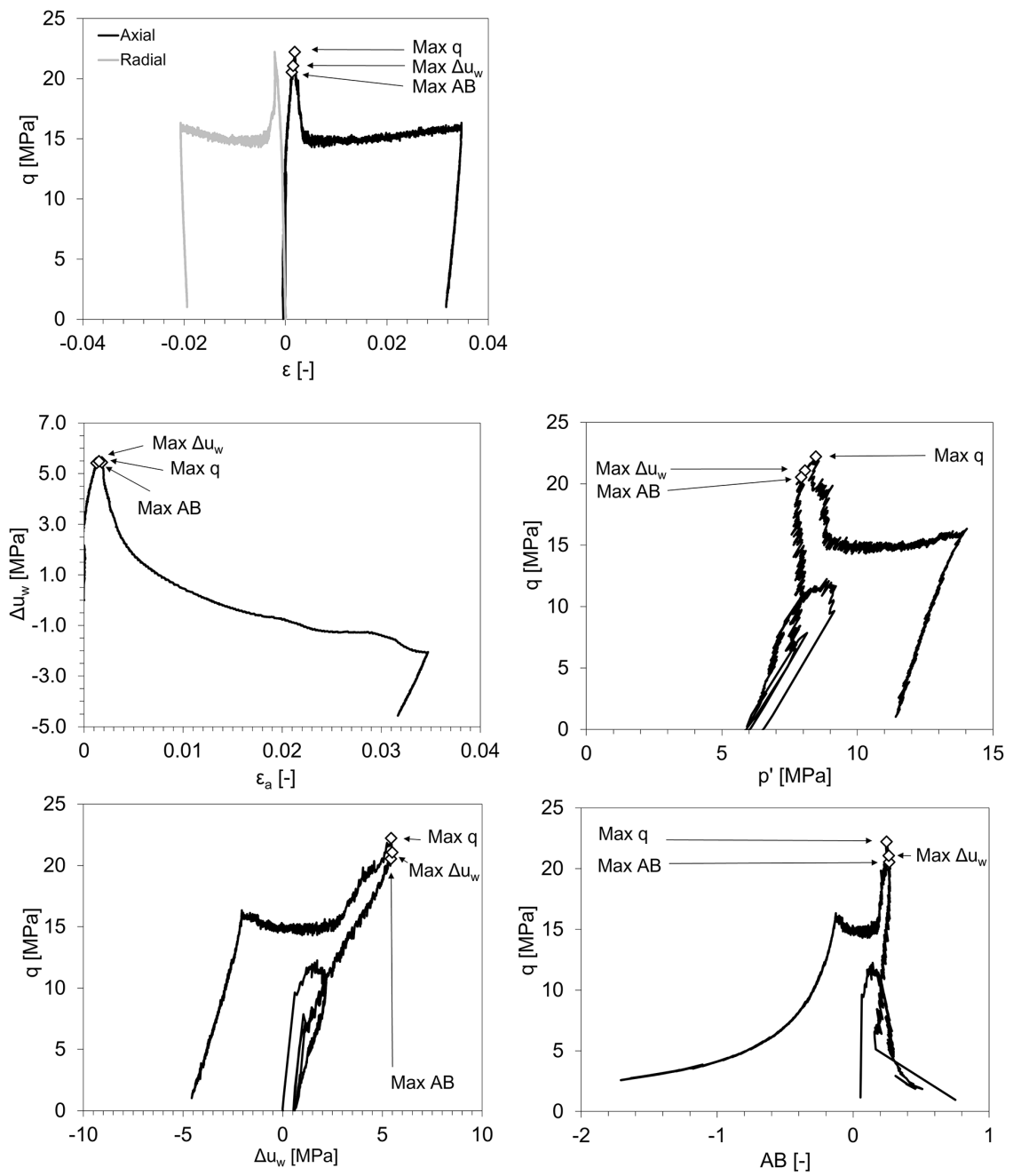
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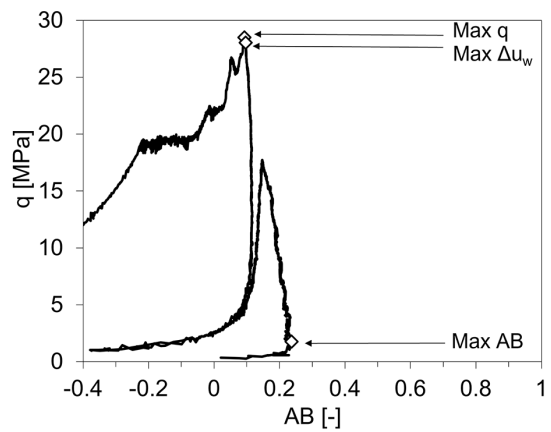
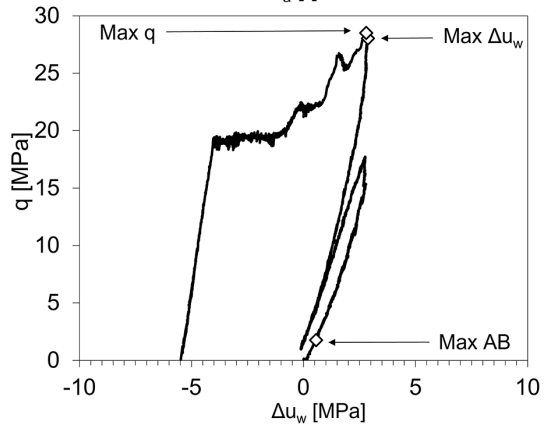
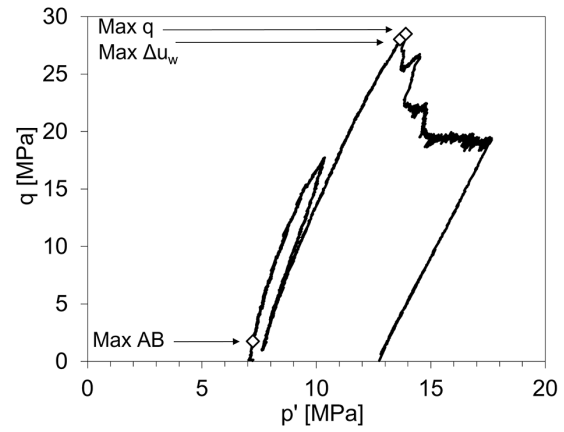
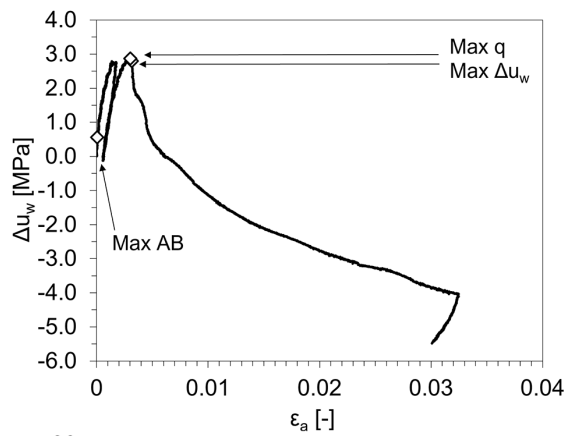
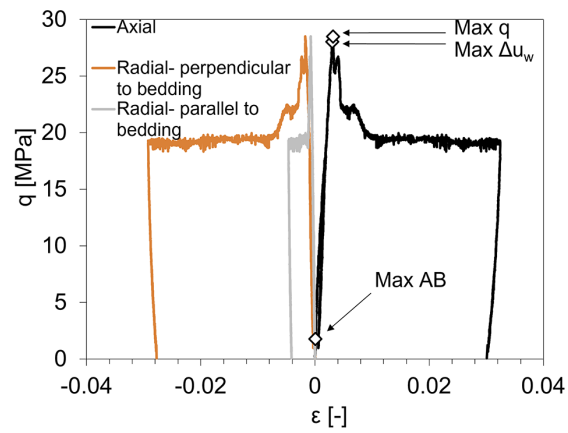
C4_BOZ2_1_566_28S13CTCU



C8_BOZ2_1_566_28S7CTCU



C14_BOZ2_1_566_58P7CTCU



Appendix D Mineralogical analysis of the tested samples

Mineralogical analysis and grain density performed by the University of Bern on a series of specimens. Mineralogical analyses were performed on specimens that were not used in the mechanical programme, or negatives and chunks from the specimen preparation. The ID of one of the specimens sourced from the same depth is reported. ^a Sample for mineralogy sourced below the mechanically tested sample in a section with high variability (see CT scan in Appendix B).

Specimen ID from same depth	Depth [m]	S [wt.-%]	C(inorg) [wt.-%]	C(org) [wt.-%]	Quartz [wt.-%]	K-feldspar [wt.-%]	Plagioclase [wt.-%]	Calcite [wt.-%]	Dolomite/Ankerite [wt.-%]	Siderite [wt.-%]	Pyrite [wt.-%]	Clay minerals [wt.-%]	Grain density [g/cm ³]	Grain density STDEV [10 ⁻⁴ /cm ³]
B7_BOZ2_1_427_95P7CTCU	427.94	0.2	0.9	1.1	30.2	3.2	2.8	7.6			0.4	54.7	2.689	5
B8_BOZ2_1_453_16S7CTCU	453.16	0.3	2.1	1.2	31.2	1.4	1.9	17.5			0.6	46.2	2.678	8
D3_OED_BOZ2_1	464.35	0.2	3.3	0.5	30.1	1.4	1.9	25.1		2.8	0.4	37.9	-	-
D5_OED_BOZ2_1	464.38	0.1	3.4	1.1	30.8	1.7	2.1	26.1		2.6	0.2	35.5	2.694	4
C5_BOZ2_1_504_78S8CTCU	504.78	0.5	2.3	1.2	27.3	1.6	1.4	12.4	3.2	3.9	1.0	48.0	2.691	6
C1_BOZ2_1_504_95S7CTCU	504.95	0.5	1.7	1.1	27.1	1.6	1.7	8.8	3.0	2.8	0.9	53.0	2.705	3
B10_BOZ2_1_515_60P7CTCU	515.60	0.1	1.3	1.0	26.6	1.6	2.1	10.8			0.2	57.7	2.671	13
B11_BOZ2_1_515_91P7CTCU	515.91	0.1	1.7	1.0	26.6	1.9	1.8	11.4		3.2	0.2	54.0	2.668	7
B5_BOZ2_1_519_23P7CTCU	519.23	0.1	0.4	1.4	20.4	3.5	3.0	3.0			0.1	68.6	2.694	8
B1_BOZ2_1_519_28_S7CTCU	519.30	0.1	1.0	0.9	21.4	2.0	2.7	4.3		4.6	0.2	63.8	2.690	7
B6_BOZ2_1_519_39P7CTCU ^a	519.42	0.1	1.1	1.3	22.6	3.9	3.5	8.8			0.1	59.9	2.713	5
D1_OED_BOZ2_1	529.58	0.4	0.9	0.6	20.9	2.0	2.7	5.2		2.6	0.7	65.1	2.717	6
D2_OED_BOZ2_1	529.83	<0.1	1.2	1.0	18.8	2.2	2.8	4.8		6.0	<0.2	64.5	2.711	9
C3_BOZ2_1_566_28S7CTCU	566.28	0.6	0.8	1.4	17.6	1.4	1.3	4.2		2.6	1.2	70.3	2.693	3
C14_BOZ2_1_566_58P7CTCU	566.60	0.5	1.0	1.2	15.2	1.1	1.1	5.8		3.0	1.0	71.6	2.696	6
D01_PERM_BOZ2_1	646.02	<0.1	<0.1	<0.1	41.0	8.5	9.4				<0.2	41.2	2.667	6

Appendix E Triaxial test results

Tab. E-1: Wave velocities recorded at the beginning of the shearing phase

Specimen ID, specimen geometry, mean effective and deviatoric stress (if applicable) at which the measurements were performed, P and S waves in the cylinder axis direction (V_p , V_s), P wave measured in the horizontal direction V_{ph} . For specimen geometry see Fig. 4-1.

Specimen ID	Specimen geometry	p' [MPa]	q [MPa]	V_p [m/s]	V_s [m/s]	V_{ph} [m/s]
B7_BOZ2_1_427_95P7CTCU	P	7.0		3'682	2'031	3'275
B8_BOZ2_1_453_16S7CTCU	S	7.0		3'301	1'361	4'576
B9_BOZ2_1_453_16S13CTCU	S	13.0		3'402	1'618	
C11_BOZ2_1_504_78S7CTCU	S	8.3	4.0	3'336	1'625	
C12_BOZ2_1_504_78S7CTCU	S	8.2	3.5	3'530	1'869	
C5_BOZ2_1_504_78S8CTCU	S	14.5	4.6	3'366	1'729	
C6_BOZ2_1_504_78S13CTCU	S	16.1	9.3	3'333	1'633	
C1_BOZ2_1_504_95S7CTCU	S	7.7	3.4	3'148	1'600	
C2_BOZ2_1_504_95S13CTCU	S	16.2	9.6	3'218	1'551	
C7_BOZ2_1_504_95S8CTCU	S	9.4	4.9	3'213	1'741	
C9_BOZ2_1_504_95S13CTCU	S	16.6	10.7	3'292	1'766	
B10_BOZ2_1_515_60P7CTCU	P	7.0		3'923	2'301	4'145
B11_BOZ2_1_515_91P7CTCU	P	7.0		4'068	2'664	
B11b_BOZ2_1_515_91P7CTCU	P	7.0		4'148	2'114	4'408
B5_BOZ2_1_519_23P7CTCU	P	7.0		4'029	2'228	
B1_BOZ2_1_519_28_S7CTCU	S	7.0		2'940	-	2'940
B2_BOZ2_1_519_30S13CTCU	S	13.0		3'054	-	
B12_BOZ2_1_519_28S7CTCU_RH	S	7.0		2'928	1'597	
B6_BOZ2_1_519_39P7CTCU	P	7.0		3'936	2'294	3'210
C10_BOZ2_1_566_28S7CTCU	S	8.5	4.6	3'052	1'515	
C13_BOZ2_1_566_28P7CTCU	P	8.8	5.5	4'140	2'060	
C3_BOZ2_1_566_28S7CTCU	S	8.7	5.1	2'929	1'362	
C4_BOZ2_1_566_28S13CTCU	S	11.1	9.2	3'073	1'405	
C8_BOZ2_1_566_28S7CTCU	S	8.3	4.0	3'030	1'362	
C14_BOZ2_1_566_58P7CTCU	P	8.7	5.0	4'032	2'087	

Specimen ID and corresponding initial characteristics are reported in Tab. 6-2, along with the results from the triaxial tests from the pre-shearing phases. Tab. E-2 includes:

- Specimen ID
- Core depth
- Formation
- Specimen geometry
- Bulk modulus ρ_{bulk} [g/cm³]
- Initial void ratio, computed using a reference solid density of 2.70 g/cm³
- Initial and final water content
- Measured values of the Skempton's B check, without correction (average B value over multiple determinations and corresponding mean effective stress)
- Swelling pressure obtained at the end of the saturation (radial and axial)
- Consolidation coefficient, obtained during the consolidation phase, and corresponding mean effective stress

Tab. E-3 presents the results from the shearing phases, including:

- Undrained elastic properties: Elastic modulus [GPa], Small Strain elastic modulus [GPa], Ratio of radial to axial strain [-], Ratio of radial (parallel to bedding) to axial strain [-] (only for P-samples), Mean effective stress at which the elastic properties were computed [MPa]
- Peak strength: Mean effective stress and deviatoric stress at peak
- Maximum *AB* value: Mean effective stress and deviatoric stress at the maximum *AB* value
- Maximum pore pressure: Mean effective stress and deviatoric stress attained at the maximum pore pressure
- Post peak strength: Mean effective stress and deviatoric stress

Tab. E-2: Triaxial test results (part 1)

For specimen geometry see Fig. 4-1.

Specimen ID	Specimen geometry	ρ_{bulk} [g/cm ³]	e_0 [-]	Water content		B check		Swelling pressure		Consolidation phase		Strain rate $\dot{\epsilon}$ [s ⁻¹]	Stress path
				Initial [%]	Final [%]	p' [MPa]	B [-]	Axial [MPa]	Radial [MPa]	p' [MPa]	c_v [mm ² /s]		
B7_BOZ2_1_427_95P7CTCU	P	2.504	0.140	5.72	6.06	15.0	0.85	17.4	16	7	5.7E-04	7.0E-08	CTCU
B8_BOZ2_1_453_16S7CTCU	S	2.512	0.124	4.57	4.96	13.8	0.83	13.76	8.6	7	1.9E-03	9.0E-08	CTCU
B9_BOZ2_1_453_16S13CTCU	S	2.513	0.126	4.75	4.98	14.2	0.86	14.2	9.5	13	2.0E-03	9.0E-08	CTCU
C11_BOZ2_1_504_78S7CTCU	S	2.508	0.122	4.25	4.44	6.0	0.93			17	2.1E-03	1.0E-07	CTCU
C12_BOZ2_1_504_78S7CTCU	S	2.551	0.103	4.17	4.05	15.3	0.76			12.3	1.0E-03	5.0E-08	CTCU
C5_BOZ2_1_504_78S8CTCU	S	2.533	0.113	4.43	4.32	3.0	0.93			8	3.4E-04	1.0E-07	CTCU
C6_BOZ2_1_504_78S13CTCU	S	2.533	0.113	4.43	4.35	4.0	0.90			13	4.4E-04	1.0E-07	CTCU
C1_BOZ2_1_504_95S7CTCU	S	2.509	0.129	4.91	4.89	3.0	0.93			7	2.5E-04	1.0E-07	CTCU
C2_BOZ2_1_504_95S13CTCU	S	2.509	0.131	5.07	5.01	10.0	0.79					1.0E-07	CTCU
C7_BOZ2_1_504_95S8CTCU	S	2.524	0.123	4.92	4.75	17.0	0.76			7.4	5.1E-04	1.0E-07	CTCU
C9_BOZ2_1_504_95S13CTCU	S	2.521	0.118	4.39	4.49							5.0E-08	CTCU
B10_BOZ2_1_515_60P7CTCU	P	2.523	0.123	4.91	5.38	20.0	0.79	19.2	19	7	5.3E-04	7.0E-08	CTCU
B11_BOZ2_1_515_91P7CTCU	P	2.515	0.130	5.26	5.67	22.0	0.83	21.7	22	7	6.8E-04	7.0E-08	CTCU
B11b_BOZ2_1_515_91P7CTCU	P	2.541	0.109	4.40	4.75	18.0	0.83	17.6	18	7	5.2E-04	7.0E-08	CTCU
B5_BOZ2_1_519_23P7CTCU	P	2.498	0.145	5.88	5.91	20.0	0.85	20.2	20	7	5.5E-04	7.0E-08	CTCU
B1_BOZ2_1_519_28_S7CTCU	S	2.505	0.140	5.79	6.11	20.2	0.85	20.3	14.3	7	1.3E-03	9.0E-08	CTCU
B2_BOZ2_1_519_30S13CTCU	S	2.513	0.136	5.70	5.83	19.4	0.88	19.4	12.9	13	1.1E-03	9.0E-08	CTCU
B12_BOZ2_1_519_28S7CTCU_RH	S	2.487	0.149	5.82	6.57	6.5	0.95	-	-	-	-	9.0E-08	CTCU
B6_BOZ2_1_519_39P7CTCU	P	2.547	0.117	5.38	5.55	20.0	0.80	19.9	20	7	6.4E-04	7.0E-08	CTCU
C10_BOZ2_1_566_28S7CTCU	S	2.507	0.133	5.23	5.33	13.0	0.65					1.0E-07	CTCU
C13_BOZ2_1_566_28P7CTCU	P	2.492	0.141	5.29	5.28	17.0	0.75			7	2.6E-04	5.0E-08	CTCU
C3_BOZ2_1_566_28S7CTCU	S	2.493	0.145	5.71	5.46	3.0	0.93					1.0E-07	CTCU
C4_BOZ2_1_566_28S13CTCU	S	2.488	0.139	4.99	4.94	10.0	0.86			13	4.7E-04	1.0E-07	CTCU
C8_BOZ2_1_566_28S7CTCU	S	2.514	0.133	5.44	5.23	16.0	0.75					5.0E-08	CTCU
C14_BOZ2_1_566_58P7CTCU	P	2.482	0.158	6.45	6.13	17.0	0.78				5.7E-04	5.0E-08	CTCU

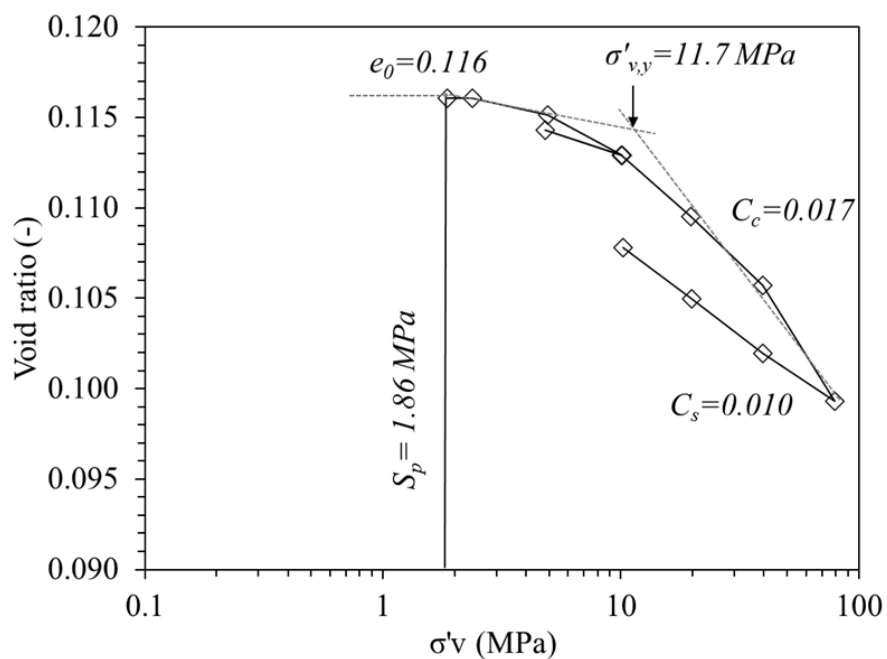
Tab. E-3: Triaxial test results (part 2)

Specimen ID	Undrained elastic properties					Peak strength [MPa]		Max. AB value [MPa]		Max. pore pressure [MPa]		Post peak strength [MPa]		Post peak elastic properties	
	p' [MPa]	Elastic modulus [GPa]	Small Strain modulus [GPa]	Ratio radial to axial strain [-]	Ratio radial (parallel to bedding) to axial strain	q [MPa]	p' [MPa]	q [MPa]	p' [MPa]	q [MPa]	p' [MPa]	q [MPa]	p' [MPa]	p' [MPa]	E [GPa]
B7_BOZ2_1_427_95P7CTCU	8.5	12.0	15.4	0.49	0.34	30.6	17.7	4.5	8.0	19.6	11.8	17.2	15.0	14.8	5.9
B8_BOZ2_1_453_16S7CTCU	6.8	8.9	11.5	0.41		20.3	9.7	3.4	6.9	17.7	8.3	12.1	11.9	12.3	5.7
B9_BOZ2_1_453_16S13CTCU	5.3	8.9	12.8	0.25		29.3	17.2	10.4	11.8	22.9	12.5	23.6	19.7	21.1	6.7
C11_BOZ2_1_504_78S7CTCU	5.3	6.0	9.7	0.35		20.0	9.4	4.3	5.9	14.8	5.9	14.0	13.0	13.3	3.7
C12_BOZ2_1_504_78S7CTCU	5.2	9.7	11.4	0.21		23.9	11.1	6.1	5.5	17.8	5.8	20.6	14.1	18.1	5.6
C5_BOZ2_1_504_78S8CTCU	6.0	5.8	7.7	0.38		18.0	8.8	8.8	5.8	14.5	6.3	13.6	10.9	11.7	4.4
C6_BOZ2_1_504_78S13CTCU	11.2	11.7	14	0.55		28.7	16.6	11.6	11.0	22.3	11.3	20.0	20.2	20.5	5.7
C1_BOZ2_1_504_95S7CTCU	5.0	5.1	7.3	0.31		19.0	9.3	4.7	5.5	13.9	5.4	13.8	10.7	12.0	3.7
C2_BOZ2_1_504_95S13CTCU	11.3	7.1	10	0.28		21.6	14.2	11.8	10.9	18.6	10.2	16.4	15.5	16.3	4.5
C7_BOZ2_1_504_95S8CTCU	6.8	6.5	12.5	0.50		24.0	11.5	7.0	6.9	18.3	7.5	16.9	14.9	17.2	4.9
C9_BOZ2_1_504_95S13CTCU	12.8	11.3	11.2	0.35		26.7	15.7	17.6	11.9	21.7	12.1	17.0	15.6	16.1	6.0
B10_BOZ2_1_515_60P7CTCU	9.4	17.0	22.6	0.60	0.31	32.2	16.2	4.5	8.1	27.6	14.4	18.9	15.0	21.1	12.3
B11_BOZ2_1_515_91P7CTCU	9.2	15.8	19.2	-	-	23.7	14.1	2.5	7.6	19.6	12.2	16.7	13.7	14.2	12.5
B11b_BOZ2_1_515_91P7CTCU	8.8	17.0	21.6	0.43	0.30	32.5	17.1	2.6	7.7	29.0	15.0	24.9	15.8	16.5	14.8
B5_BOZ2_1_519_23P7CTCU	8.7	17.1	22	0.53	0.44	27.4	15.3	2.7	7.7	22.0	13.1	14.4	13.0	13.2	12.2
B1_BOZ2_1_519_28_S7CTCU	5.9	7.1	8.5	0.31		20.9	8.6	3.3	6.5	18.8	7.2	16.3	11.0	21.1	4.1
B2_BOZ2_1_519_30S13CTCU	11.7	9.0	10.2	0.32		25.3	12.8	5.2	12.1	22.3	10.8	15.8	15.5	15.8	3.9
B12_BOZ2_1_519_28S7CTCU_RH	5.57	6.03	7.3	0.27		16.7	6.5	4.8	6.0	16.5	6.3	10.7	8.7	9.1	3.8
B6_BOZ2_1_519_39P7CTCU	8.7	12.6	22.6	0.50	0.20	38.9	19.9	4.2	8.1	24.1	13.7	20.9	15.7	15.6	10.2
C10_BOZ2_1_566_28S7CTCU	6.2	6.9	9.2	0.31		20.0	7.2	12.1	5.6	17.3	6.1	12.0	9.0	12.4	4.5
C13_BOZ2_1_566_28P7CTCU	10.7	16.0	20.1	0.53	0.34	27.1	15.0	0.6	6.6	25.4	13.2	18.3	15.0	17.1	11.0
C3_BOZ2_1_566_28S7CTCU	5.9	9.5	12.2	0.00		17.1	8.6	9.6	5.3	14.6	5.3	13.9	8.8	21.1	4.4
C4_BOZ2_1_566_28S13CTCU	10.5	7.6	8.4	0.27		24.8	11.0	12.1	10.0	23.1	9.7	19.0	14.7	17.2	5.8
C8_BOZ2_1_566_28S7CTCU	-	-	-	0.67		22.2	8.5	20.5	7.9	21.1	8.1	14.7	9.2	13.1	5.4
C14_BOZ2_1_566_58P7CTCU	10.3	13.7	17.7	0.44	0.33	28.5	13.8	1.8	7.2	28.0	13.6	19.8	14.9	17.6	10.9

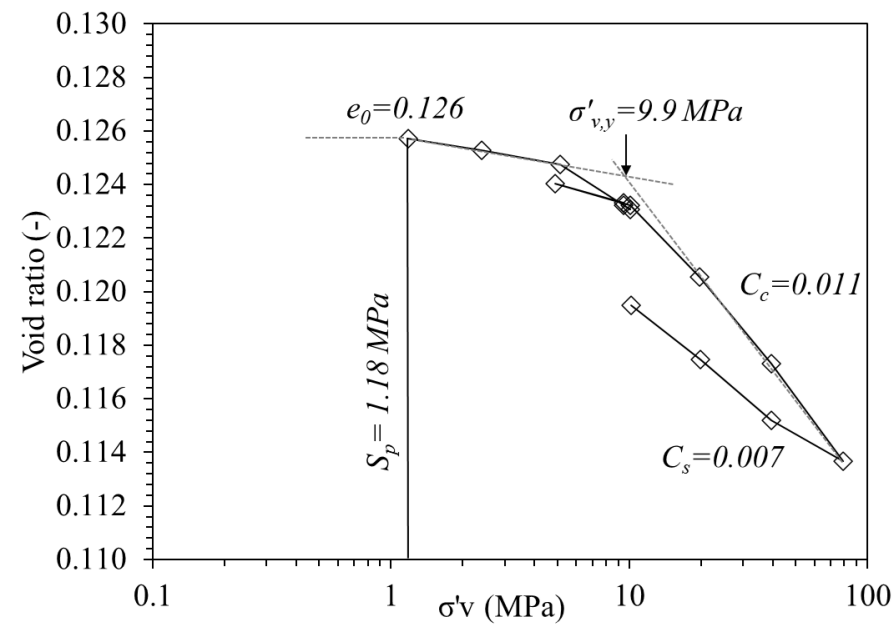
Appendix F Test results in oedometric conditions

Results of the oedometric test results are here reported in terms of oedometric curves (void ratio at the end of the primary consolidation) obtained for each test. In each graph the void ratio (e) versus the vertical effective stress (σ'_v) are reported. In each graph, it is highlighted the initial void ratio, the swelling pressure attained at the end of the resaturation phase (S_p), the yield stress ($\sigma'_{v,y}$) obtained through the Casagrande's construction, the compressibility (C_c) and the unloading (C_s) indexes. Results ordered by samples source depth.

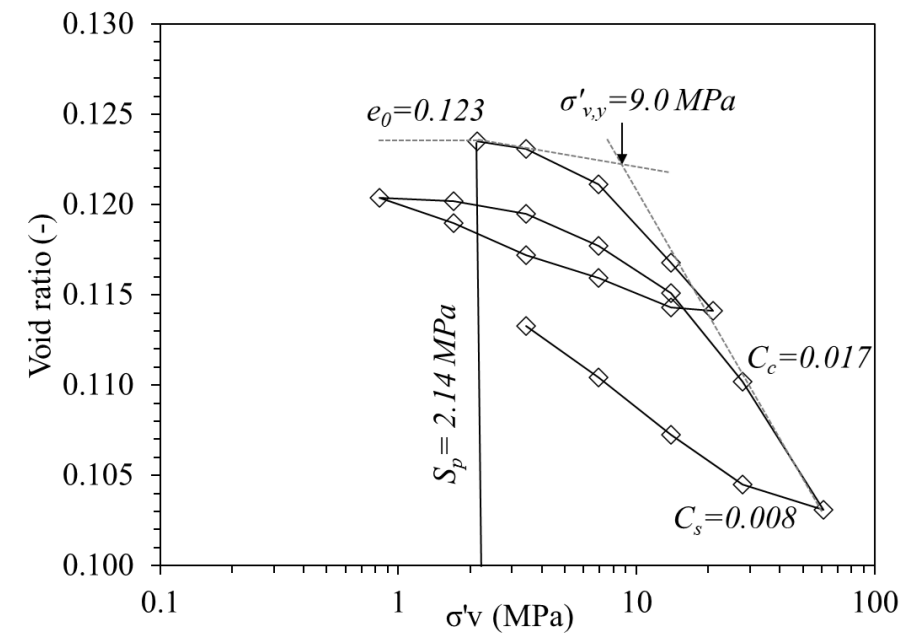
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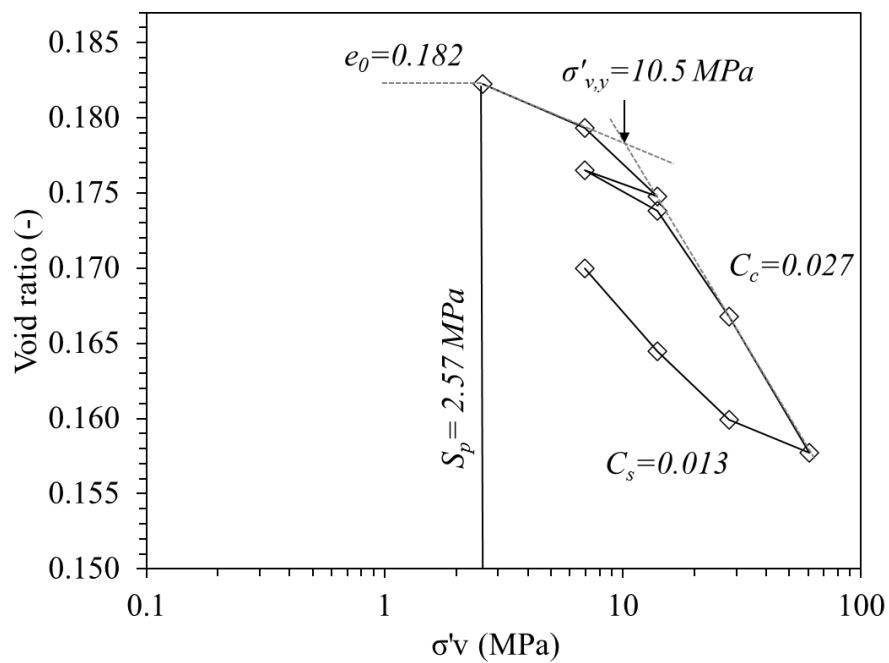
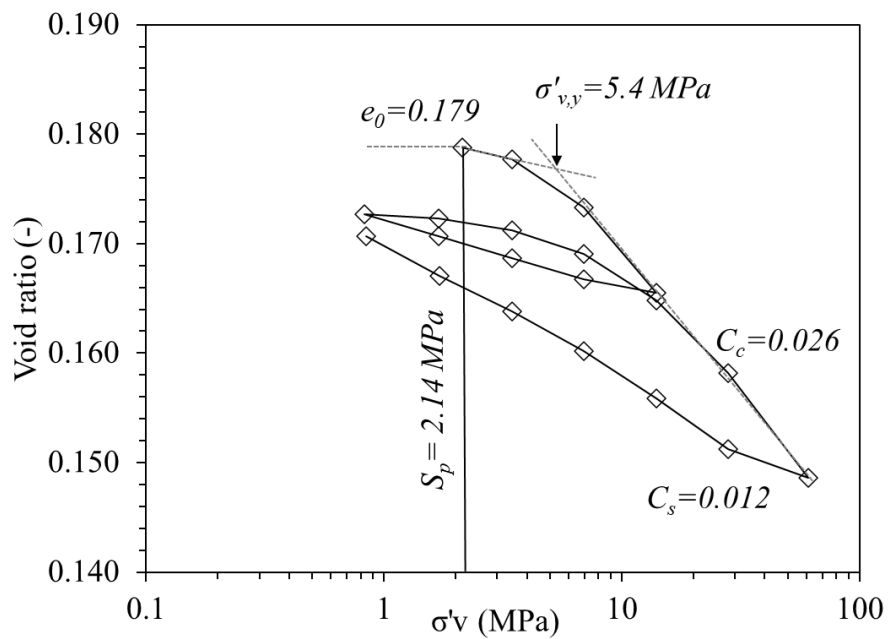


D05_OED_BOZ1_1



D06_OED_BOZ2_1



D04_OED_BOZ2_1**D02_OED_BOZ2_1**

D07_OED_BOZ2_1

