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Operational Report about Phase 2 of the Collisional Orogeny in the Scandinavian Caledonides scientific drilling project (COSC-2)

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Operational Report about Phase 2 of the Collisional Orogeny in the Scandinavian Caledonides scientific drilling project (COSC-2)

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Abstract

The Collisional Orogeny in the Scandinavian Caledonides (COSC) scientific drilling project characterises the structure and orogenic processes involved in a major collisional mountain belt by multi-disciplinary geoscientific research. Located in western central Sweden, the project has drilled its second fully cored borehole COSC-2 in 2020. It extends the COSC composite geological section through the nappes of the Caledonian Lower Allochthon, the main décollement and the upper kilometre of basement rocks. COSC-2 targets include the characterisation of orogen-scale detachments, the impact of orogenesis on the basement below the detachment, and the Early Cambrian palaeoenvironment on the outer margin of palaeocontinent Baltica. This is complemented by research on heat flow, groundwater flow, and characterisation of the microbial community in the present hard rock environment of the relict mountain belt. COSC-2 successfully and within budget recovered a continuous drill core to 2276 m depth. The retrieved geological section is partially different from the expected geological section with respect to the depth to the main décollement and the expected rock types. The intensity of deformation in the rocks in the upper part of the drill core might impede the analysis of the Early Cambrian palaeoenvironment. However, the superb quality of the drill core and the borehole will facilitate research on the remaining targets and beyond.

Although on-site science was reduced due to Covid-19 related restrictions, COSC-2 drilling was complemented by extensive downhole surveys. However, the geological description of the drill core and the sampling party were severely delayed, with the later being held about two years after drilling, concluding the operational phase of the project.

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Supplementary Data

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Coordinates of main spot: N 63.3124°, E 013.5259°

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Task 'Basement of the Fennoscandian Shield': Dr. Luca Menegon, University of Oslo, Norway.
Task 'Foreland – hinterland – off-shore connection': Prof. Håkon Fossen, University of Bergen, Norway.
Task 'Orogenic style in time and space': Bernard Bingen, NGU, Geological Survey of Norway.
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Drillcon Scandinavia AB

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Dr. Claudio Madonna, ETH Zürich, Switzerland.
Dr. Jenny Anderson, Swedish Geological Survey.

2 Collisional Orogeny in the Scandinavian Caledonides (COSC) project background

The background of the COSC project is described in detail in the operational project about Phase 1 (Lorenz, H. et al., 2015a).

3 COSC-2 scientific objectives

The COSC-2 objectives are derived from the COSC project targets (e.g. Gee et al., 2010) by careful evaluation of the geological premises (site investigations), as well as practical and financial feasibility.

(1) The lower part of the COSC composite geological section, i.e. the COSC-2 drill core, will provide an opportunity for increased understanding of the main Caledonian décollement and associated fault systems, including geometry, stress distribution and rheology. Investigations of it will also shed light on how deformation propagated below this orogen-scale detachment horizon into the basement of the Fennoscandian Shield and whether a deeper deformation system played a role in the tectonic cycle from Iapetus formation to the present day Atlantic.

(2) The origin and nature of the prominent, deep basement reflectors imaged in the seismic profiles and their role during passive margin formation and orogeny is a key-question in the context of point (1). Eventually, these new insights will utilise analogue studies with modern orogens like the Alpine-Himalayan mountain belt.

(3) The Early Paleozoic sediments drilled by COSC-2 were deposited on the continental margin before Scandian orogeny and subsequently, during orogeny, into a foreland basin. As the most distal location in a multiple-site study of this Paleozoic basin, COSC-2 will add unique information on palaeoenvironmental conditions and facilitate the reconstruction of palaeoclimate, global biologic crises, faunal turnover, and major glacial events.

(4) More recent climate evolution is addressed with the study of the ground surface temperature history, based on high-quality, high-resolution borehole temperature profiles. The two COSC drill sites are situated just east of the ice divide of the Weichselian ice sheet in Fennoscandia, but in locations with different (palaeo)environmental and altitude conditions: COSC-1 on the lower slope of a mountain and COSC-2 in a glacial valley. Thus, COSC will contribute to knowledge about the Weichselian glaciation and climate evolution in northern Europe during the Holocene, including industrial age trends.

(5) The hydrogeological and thermal characteristics of mountain belts are defined by their geological history and structure, also for those that are already deeply eroded. Paleozoic orogens exist on all continents and are part of the lithosphere from Central Asia to Europe and western North America. COSC-2 investigates how the deep structure of the Scandinavian Caledonides, including large-scale detachments and basement deformation, affect hydraulic conductivity, pressure heads, and heat transfer in the interplay with groundwater flow and concomitant advective heat transport. Eventually, this will increase the understanding about the origin and genesis of fluids and gases and their impact on seismicity and rheology over time.

(6) Microbiological research focuses on changes in microbial community composition as a function of depth and lithology, as well as to inform about long-term evolutionary change. A secondary target is to benchmark and validate dedicated triple-tube coring and on-site drill-core sampling for contamination-free microbial sampling. Strict contamination control ensures the integrity of the sample collection and provides a testbed for protocols to be used for future scientific boreholes dedicated to microbial research. In addition, fracture mineralisation will undergo detailed geochemical and isotopic characterisation, as this can reveal information on the timing and nature of microbial activity through deep time.

4 Strategy

COSC-2 is the lower part of a composite geological section. The upper and middle parts of this profile include the subduction-related ultra-high-pressure metamorphic rocks of the Middle Seve Nappe (Klonowska et al., 2017) at the top of Åreskutan mountain and the outcrops down to the tree line. Close to the latter, the COSC-1 drill site is located (Fig. 1). This borehole, drilled in 2014, samples the underlying high-grade metamorphic gneisses of the Lower Seve Nappe and penetrates into the underlying thrust zone (Lorenz et al., 2015a,b). COSC-2 is located c. 20 km southeast of COSC-1 at the southern shore of Lake Liten and starts at a tectonostratigraphic level below that of the bottom of COSC-1. It samples the low-grade metamorphic siliciclastics of the Lower Allochthon, the main Caledonian décollement and the Baltoscandian basement.

1.1 COSC-2 site selection

Site selection was based on extensive geophysical investigations, modelling and geological interpretation (Hedin et al., 2012; Juhlin et al., 2016; Yan et al., 2016). The boundary condition that a suitable drill site had to meet was that the borehole at depth has to penetrate at least one of the prominent seismic reflectors in the basement of the Fennoscandian Shield and sample the rock below, while in the upper part it should sample as much of the Lower Allochthon as possible. Suitable locations where these conditions are met within the 2,5 km depth limit of the drill rig exist along the southern shore of Lake Liten, directly on the seismic and magnetotelluric lines. The final selection considered the available level space, firm ground conditions and a land owner with a positive attitude to the project.

1.2 COSC-2 drilling strategy

Continuous core drilling with triple-tube core assemblies was planned to a target depth of 2500 m. Triple-tube core assemblies include an inner aluminium liner that protects the drill core from mechanical actions of the drill string and inner tube, making it particularly suitable for drilling in fractured rock. For COSC-2, triple tube was chosen because of the unknown rock quality and the aim to retrieve high-quality drill core from major fault zones, including drilling through the main Caledonian décollement. H-size drilling (61 mm core/96 mm hole diameter) was chosen for the upper part of the drill hole, beginning at the lower end of the surface casing (100 m). At 1600 m, or earlier if required by technical circumstances, drilling was planned to continue with the smaller N-size (45mm core/75.7 mm hole diameter) to target depth, with the H-size drill rods left in the hole as a temporary casing. This strategy was designed to provide the COSC science team with an below the surface casing uncased drill hole that allows access to the formation at any depth. Downhole surveys were planned to be conducted during a break when drilling dimension is changed and at total depth (TD).

5 Preparations

The timing of the COSC-2 operations is summarised in Table 1. The drill site was constructed by a local entrepreneur, Hyttstens Schakt & Anlägg AB, adjacent to a private road. Thus, no access road was built. A surface area of approximately 1600 m^2 (40 m x 40 m; Fig. 2) was cleared of trees and bushes. The original topsoil was removed and stockpiled on the sides of the drill site. The site was constructed from local compacted soil materials and surfaced with gravel and angular crushed rock from a local quarry, size 0-250 mm, and levelled with gravel and angular rock, size 0-40 mm. A geotextile was placed on the compacted soil material. The ground below the drill rig was reinforced with gravel and angular rocks, 0-250 mm, from the top of the bedrock up to the designed ground level. A circular cellar construction was built by placing two concrete rings, height 0.6 m and inner-diameter 1.2 m, around the position for the planned COSC-2 borehole (COSC-2 A). Electricity for the drill site, mainly used for cabins, illumination, smaller pumps, etc., was supplied by a 17 kVA generator and a 12 kVA generator was used as back-up. Water was pumped from Lake Liten, located around 50 m from the drill site. Wastewater was disposed of by vacuum truck.

Table 1: COSC-2 operations by time

Date	Task
12th August to 4th September 2019	Construction of the drill site
2nd to 4th March 2020	Installation of conductor casing to 100 m
March & April 2020	Mobilization
14th April 2020	Start of drilling operations
19th April 2020	First core on deck
19th April to 25th May 2020	HQ3 drilling to 1263 m
26th to 27th May 2020	Downhole logging
28th May to 16th June 2020	HQ3 drilling to 1576 m
21st to 22nd June 2020	Downhole logging
23rd to 24th June 2020	Installation of HRQ temporary casing and start NQ3 drilling
13th July 2020	NQ3 drilling to 1883 m
15th July to 7th August 2020	NQ drilling to TD (2276 m)
10th August to 12th August 2020	COSC-2 B HQ3 drilling to 116 m
25th August 2020	Downhole logging COSC-2 B
27th August 2020	Downhole logging COSC-2
7th September to 14th September 2020	Downhole logging
20th September to 29th October 2021	Drill core description
27th June to 15th July 2022	Sampling party
Summer & autumn 2022	Site-restoration and road repairs

5.1 Installation of the conductor casing

The conductor casing was installed by a local drilling company, Jämtborr AB. Initially a 9 m long surface casing with an outer diameter (OD) of 193.7 mm and an inner diameter (ID) of 183.7 mm was installed. Thereafter a hole with 165 mm diameter was drilled down to 100 m using air percussion drilling with a 5-inch down-the-hole (DTH) hammer. No problems with borehole stability or water production zones were observed during the drilling. The surface casing (OD 139.7 mm/ID 129.7 mm) was later installed using a casing advancement method called ODEX115 and cemented from the bottom to the surface. Since no return of cement was observed in the casing annulus, cement was added into the annulus from the surface. In addition, a second casing string was installed down to 9 m depth just outside the well cellar, which first was used as support for the drill rig and later as the conductor casing for COSC-2B. The exact locations of all drill holes are given in Table 2 and shown in Fig. 2.

5.2 Mobilization

In early March, the snow was cleared from the drill site and the privately-owned access road. All heavy equipment was mobilized during the first half of March, i.e. before the frost left the ground and the access road became impassable for heavy traffic. Heavy traffic had to be avoided until the end of May. Technical and scientific site installation started in the second half of March and was finished in the week before drilling commenced. Altogether, nine truckloads of technical and scientific equipment were mobilised.

5.3 Site Overview

The working area of the drill site is nearly quadratic with an area of about 1600 m^2 (Fig. 2). The drill rig, the combined mud tanks and manual pipe handling system and some peripherals such as workshop and mud mixer formed the central part of the drill site. In immediate proximity to the northwest, the generators and an extra fuel tank were located. The eastern part of the drill site was occupied by common facilities and office space. In the northern quarter of the drill site, the on-site science was located. The remaining space was used as storage space for drill rods, logging equipment, and for parking.

Table 2: The COSC-2 boreholes. Locations by RTK GNSS, geodetic datum WGS84 (EPSG:4326), elevation in RH2000 (EPSG:5613). The recovered core is slightly longer than the totally cored length

Name	Designa-tion	IGSN	Driller's depth [m]	Cored length [m]	Core recovered [m]	Latitude	Longitude	Elevation [m]
COSC-2A	5054-2-A	ICDP5054EH40001	2276.05	2175.7	2177.1	N 63.31244584	E 013.52647969	320.25[1)]
COSC-2B	5054-2-B	ICDP5054EH50001	116.25	110.2	110.5	N 63.31244644	E 013.52648032	320.31[2)]

[1)] Elevation reference for borehole in the cellar: ground elevation
[2)] Elevation reference for borehole outside the cellar: top of the casing

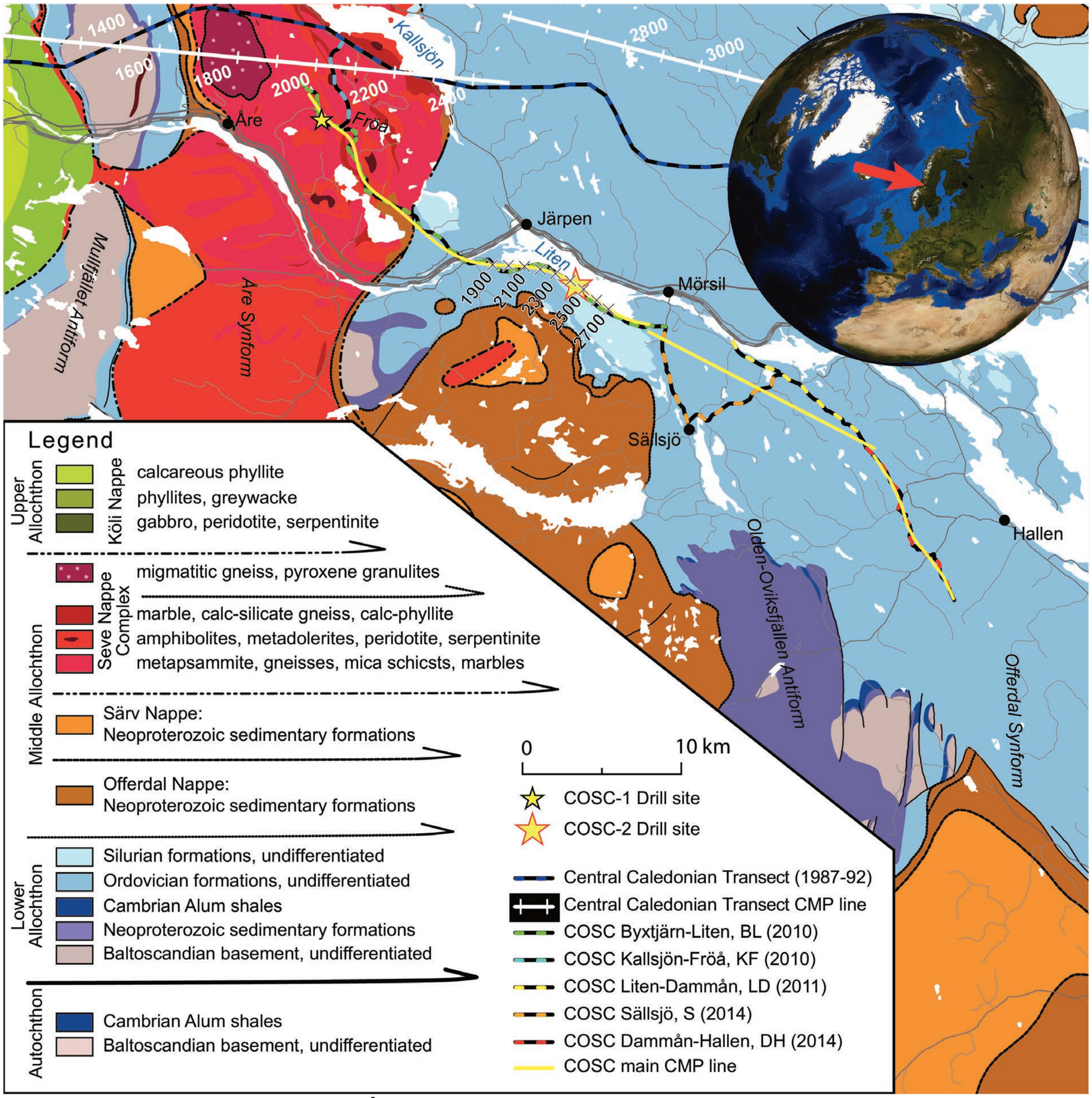


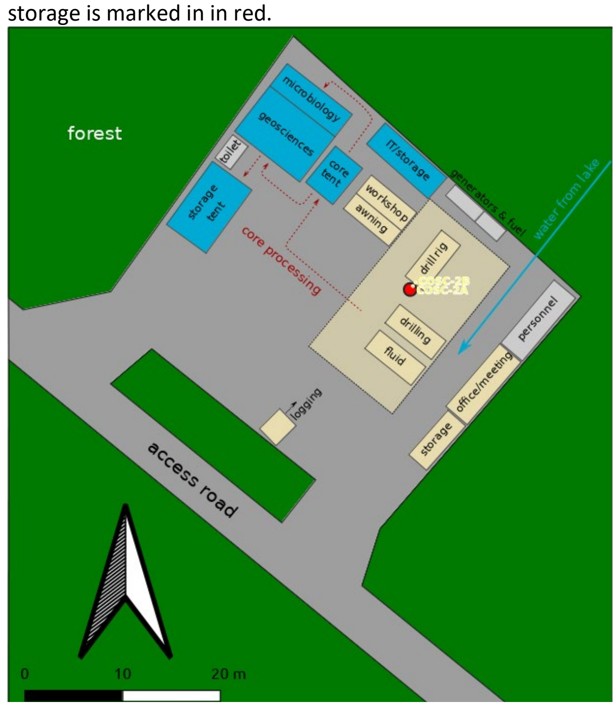
Figure 1: Tectonostratigraphic map of the Åre-Järpen area (based on the 1 : 200 000 scale geological map by the Geological Survey of Sweden, I2014/00601, Strömberg et al., 1984). The map shows the COSC drill sites, the location of the regional seismic profiles of the Central Caledonian Transect (Palm and Lund, 1980; Juhojuntti et al., 2001) and the seismic lines of the COSC site investigations. Note that CDP points on the latter were shifted during reprocessing and thus, are different from Hedin et al. (2012) and Juhlin et al. (2016).The magnetotelluric survey (Yan et al., 2016) followed the track of the COSC seismics. Modified from Juhlin et al. (2016).

6 Technical operations

The technical operations were managed by Lund University, Sweden.

6.1 Drilling equipment

Figure 2: Sketch of the COSC-2 drill site. The area is approximately 1600 m2 large, with the western half used for the science operations (blue), parking and storage, and the eastern half used for the technical operations (yellow) and common facilities. The route of the core from drilling deck to storage is marked in in red.



The Swedish national research infrastructure for scientific drilling "Riksriggen" is operated by Lund University. It is kept at disposition with funding from the Swedish Research Council (Vetenskapsrådet) while projects have to cover the actual drilling costs. The drill rig is a crawler mounted Atlas Copco CT20C. It can handle the three common sizes P, H and N (123/85 mm, 96/63 mm and 76/48 mm hole/core diameter) with depth capacities of around 1050 m, 1600 m and 2500 m, respectively. These capacities assume a vertical water-filled hole and are based on the rig's lifting capacity of 178 kN. Maximum torque is 8150 Nm and maximum spindle speed is 1300 rpm. The rig's mud pump is a Trido140 with a maximum capacity of 140 l/min and a pump pressure of 70 bar. The drilling fluid was recirculated via two mud tanks with a total volume of around 20 m^3. The "Riksriggen" is specially equipped with a data acquisition system (see below) and a torque limiter, but not yet with an automatic rod handling system. A manual rod handling system was constructed at the drill site and welded on top of the mud tanks (Fig. 3). The drill rods were stored in 9 m lengths. A 5'' annular BOP (Fig. 4) was used during the COSC-2 drilling operations.

6.2 Drilling

Drilling operations started on 14th April and were completed on 7th August 2020. Driller's depth of COSC-2 is 2276 m.

6.2.1 Drilling crew

A Swedish drilling company, Drillcon, was the drilling contractor. Drilling operations were conducted 24h/day with three crew members, drillers and assistants, per 12 h shift. The shifts started work on Wednesday mornings and worked until around lunchtime on Tuesdays. Hence, there were 18 non-drilling hours that could be used for maintenance and borehole testing. Personnel from Lund University and Larsson Drilling Consulting AB supervised the drilling operations on a daily basis.

6.2.2 Start-up

The first action was to install a second casing string from surface to 100 m. HWT-casing (OD 114.3 mm, ID 101.6 mm) was installed and cemented from the casing shoe to surface. The smaller size of the HWT casing compared to the previous installed casing reduces the risk of damage to the drill rods and guarantees a proper transport of the cuttings to the surface. It also provides a secondary protection for the shallow groundwater. The HWT-casing could be tubed into the hole to around 60 m depth where the top of the cement from the previous surface casing was tagged. Thereafter casing drilling was applied down to around 100 m depth. Before the cementation of the HWT-casing a HRQ drill string was run inside the HWT-casing string to remove any obstacles and drilled around two meters into fresh rock (depth 101.75 m). Thereafter the cementation of the casing was conducted. The cementation of the bottom part of the casing was considered successful, but no cement return was observed at surface. Then the wellhead was installed and the new cement was drilled out. Finally, the wellhead was pressure-tested and no leakage observed.

Figure 3: Riksriggen with the manual rod handling sytem on top of the mud tanks.

6.2.3 Description of core drilling

Wireline core drilling with the following core assemblies was used (inner tube sample length, core diameter, hole diameter):

- H-size triple-tube core barrel assembly (3 m/61.1 mm/96.0 mm)
- N-size triple-tube core barrel assembly (3m/45.0 mm/75.7 mm)
- N-size double-tube core barrel assembly (6 m/47.6 mm/75.7 mm)

A double-tube assembly consists of an outer tube, attached to the drill rods, with an inner tube (core barrel) that captures the core sample. The triple-tube has an additional split tube ("core liner") placed inside of the inner tube. The inner tube is equipped with a spearhead and release mechanism at the top for retrieval and fitted with a core lifter at the bottom. The drill bit and reamers are attached to the outer tube.

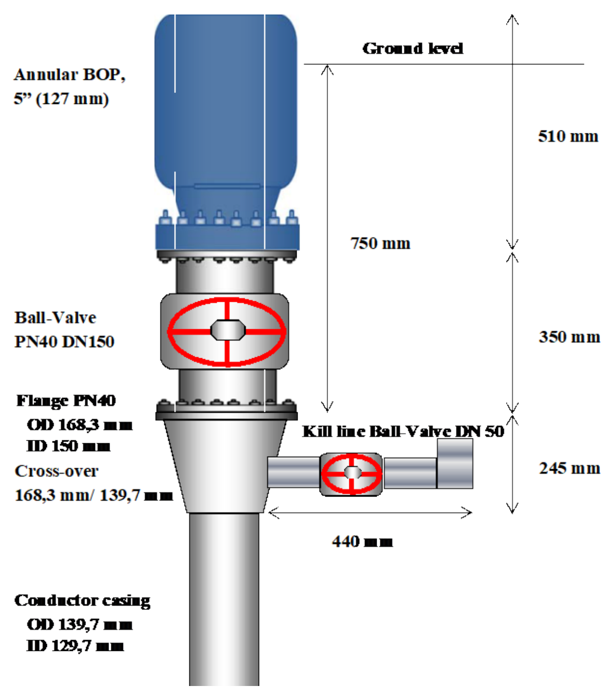


Figure 4: Sketch of the COSC-2 wellhead (similar to the one used at COSC-1). A 5'' annular Blow Out Preventer (BOP) was attached on top of the main valve, a DN150 ball valve. A DN50 ball-valve was used for the kill line.

Core drilling progresses until the inner tube is full.

The driller terminates the drilling and lifts the drill string to break the core at the bottom of the drill hole. An overshot is then lowered into the drill pipe on a wireline cable and the inner tube retrieved. Afterwards, a new inner tube is pumped down the drill string. At the surface, the retrieved inner tube is emptied and the core handling starts.

6.2.4 HQ3 core drilling (100 - 1576 m)

The progress of HQ3 core drilling was in the order of 20-60 m/day when neglecting interruptions by other activities such as bit change, failures, servicing, or testing. Lightweight drill rods with reinforced threads (HRQ V-wall, OD 88.9 mm, ID 77.8 mm, weight 27.4 kg/3 m), diamond impregnated drill bits and surface set reamers on top of the drill bit were employed. In addition, full-hole locking couplings and fluted/broached core lifters were used. The drilling fluid was fresh water. Drilling parameters were recorded both manually and automatically for each core run: rotations per minute, rate of penetration, weight on bit, pumping rate and pump pressure.

6.2.5 Problems with HQ3

The recommended rotational speed of 750 to 950 rpm could be kept during the drilling until around 900 m depth. Thereafter the rotation speed decreased and at the end of the HQ3 drilling the rpm was around 600. Consequently, the rate of penetration had to be lowered. One explanation for higher torque and reduced rotational speed can be that parts of the drill rods were bent beyond tolerance and this resulted in high friction between the drill string and the borehole wall.

6.2.6 HQ3 casing

After HQ3 drilling was completed, the drill string was tripped out of the hole and the core barrel assembly removed and replaced with a HRQ rod shoe. Thereafter the HRQ-drill string was installed as temporary casing from surface down to 1576 m, i.e. the casing/drill string was not cemented to allow for removal after drilling was finished. The annulus between the HRQ-drill string and the already installed HWT-casing was sealed off inside the wellhead to avoid sedimentation of cuttings into the annulus.

6.2.7 Drill bits

In total, 22 impregnated drill bits, adapted for hard to very hard rocks and competent formations, and standard surface set reaming shells were used during HQ3 drilling. This high consumption could have been caused by lacking particle separation in the drilling fluid and also been influenced by the low rotational speed, as explained above. The maximum drilled length by one drill bit was around 199 m and the minimum around 22 m. The bit that lasted only 22 m was caused by an equipment failure. The average drilled length was approximately 67 m/drill bit.

6.2.8 NQ3 core drilling (1576 - 1883 m)

After installation of the HQ3 drill string as temporary casing, drilling continued with a N-size triple-tube core barrel assembly. Too low rotational speed caused by bent drill rods was a major problem during the drilling, see below. The coring progress with NQ3 was in the range of 21-33 m/day, excluding drilling breaks. Drill rods with reinforced threads (NRQ, OD 69.9 mm, ID 60.3 mm, weight 23.4 kg/3 m), diamond impregnated drill bits and surface set reamers were employed. In addition, standard locking couplings with ground carbide pads and fluted/broached core lifters were used. Below 1850 m, a biodegradable polymer (AMC FS 2000) was added to the drilling fluid for reducing the friction along the drill string and to improve the removal the cuttings.

6.2.9 NQ drilling (1883 - 2276 m/TD)
At 1883 m, it was decided to use a double-tube core barrel assembly that could sample 6 m of core to save time compared to using one that samples only 3 m (30-40 % faster). Given the excellent rock quality, it was expected that good core quality would be obtained even with double-tube drilling. The drill rods, types of drill bits and reamers were similar to those used with NQ3. Drilling parameter acquisition continued without changes. The coring progress using NQ was in the range 21-58 m/day, excluding drilling breaks.

6.2.10 Problems during the NQ3 and NQ drilling
Too low rotational speed caused by bent drill rods was a major problem during both the NQ 3 and the NQ drilling. The rotational speed that could be used was between 200 and 400 rpm, which is much lower than the recommended 900 to 1200 rpm. As a consequence, the rate of penetration was lowered and some drill bits wore out faster than expected. Each rod was checked for deformation before it was attached to the drill string and equipment to straighten the rods was built on site. Despite these efforts, higher rotational speed could only be obtained for a short time. A possible explanation is that the drill rods were deformed due to the design of the HRQ V-wall drill rods, where the inner diameter is smaller at the rod-joints compared with the mid-body. There was NW casing at site, but the maximum installation depth for this casing is around 1200 m depth due to risk of casing failure. At that depth it was unclear whether the décollement zone was passed or not and thus, the decision was made to continue with the HQ3-drilling and use the HRQ-drill string as temporary casing.

6.2.11 Drill bits
Nine drill bits were used during N-size drilling, four NQ3 and five NQ drill bits. The selected impregnated bits are suitable for medium to hard, slightly abrasive, slightly fractured to competent formations. The high consumption of drill bits was mainly due to the low rotational speed and suboptimal particle separation in the drilling fluid. The mud system needs to be improved since fine rock fragments may have been recirculated with increased wear on the equipment, including the drill bit, as a result. The maximum drilled interval of a drill bit was around 220 m and the minimum around 6 m. The latter was due to damage to the bit by mechanical action from a drill core piece from the bottom of the previous core run that had remained in the borehole. The average drilled length for the drill bits was 76.8 m/NQ3 drill bit and 78.5 m/NQ drill bit. The time for changing the drill bit at 2000 m was around 19 hours.

6.2.12 Drilling activities after TD
After reaching TD, the NRQ-drill string was placed on the bottom of the hole and disconnected at the surface. Thereafter the wellhead was removed, and the HRQ-drill string (the temporary casing) was successfully retrieved, and the mud-column replaced with freshwater through the NRQ-drill string. Finally, the NRQ-drill string was pulled out of the hole.

6.2.13 General comments about the drilling
To drill 2276 m with full core recovery while retrieving top quality cores is exceptional. In addition, no cementation was carried out during the entire core drilling operation.

Despite the major problem with deformed drill rods, all the strong seismic reflectors that are within the depth capacity of the drill rig were passed before the drilling operation was terminated. However, target depth was reached with a considerable delay because of slower penetration rates and more frequent round trips to replace the drill bit.

The COSC-2 borehole is the second deepest vertically drilled hole in Sweden using H- and N-size and the second deepest hole drilled by Riksriggen. The borehole is only cased down to 100 m, the remaining 2175 m are left as an open-hole completion.

7 Scientific operations

The scientific operations were coordinated by Uppsala University, Sweden. The on-site scientific work was planned to follow the successful COSC-1 setup with some modifications. However, due to Covid-19 restrictions, foreign scientists were prevented from attending the operations and thus, the detailed geological description of the drill core was postponed indefinitely to the core archive. During drilling of COSC-2 A, teams of two on-site geoscientists worked in two 12 h shifts. The on-site microbiology team worked according to its own schedule, which was primarily governed by the sampling schedule. COSC-2 B on-site science was handled by a single geoscientist during the two days of daytime drilling.

7.1 Workflow drill core

The on-site science team received the drill core from the drilling team at the drill rig. Cores drilled with 3 m triple tube core assemblies (HQ3 and NQ3) were transferred to the geologists' working place in the aluminium split-liner. Cores drilled with the 6 m NQ double tube core assembly had to be handled in two halves. To guarantee that core extraction without an inner liner was done in the most careful way, the drilling team hydraulically extracted the core from the core barrel into two 3 m HQ3 split liners (HQ3 because NQ core is larger in diameter than NQ3 core). To accomplish this, the NQ3 core extraction equipment was also used for NQ, which worked very well except for cores with fracture zones (blockage in core barrel). In this way, the drill cores from the double and triple tube systems could be processed in the same way.

At the long table in the core tent (Fig. 2), the core pieces were cleaned (if necessary) and subsequently restored to their original position (with few exceptions where this was not possible). Afterwards, they were marked with two coloured lines for orientation: to the right when looking downwards, a blue reference line is present on all drill cores; the colour of the left line depends on whether core orientation was successful or not: the line is red as far as the position of the core orientation mark at the bottom of the core run could be transferred upwards. In case such a reorientation was not possible, an attempt was made to transfer the orientation from the previous core run. In this case, the line is in yellow colour from the top of the core run. A green line indicates that the core has no orientation information available (unsuccessful reorientation of the core, equipment failure or missing core orientation equipment as, e.g., in COSC-2 B). Once reorientation and marking was finished, other tasks on the drill core could commence: (1) measuring the total length of the drill core along the blue line, (2) placing the drill core into core boxes, and (3) registration of the drill core in the mDIS.

From the core tent, full core boxes were transferred to the geosciences container (Fig. 2). Unrolled core scans were acquired for each section after drying with a hair dryer and the images were added to the mDIS. Afterwards, each core box was photographed on a repro-stand and the photos added to the mDIS. Subsequently, geophysical parameters of the core sections were logged on a Geotek MSCL-S core logger (provided by ICDP). A short geological characterisation of each section was registered in the mDIS as support for the project management's decision making and for an initial geological assessment.

7.2 Sampling

All samples in the COSC scientific drilling project are marked with an International GeoSample Number (IGSN; International Generic Sample Number from 2023), a hierarchical unique identifier that is used to track samples and relationships between samples (see also https://www.igsn.org/).

On-site sampling of the drill core was very restricted and only permitted for geomicrobiology and rock mechanics:

For the microbiology, core samples 20-30 cm in length were collected from a depth of 100 m to 2250 m at 50 m intervals, resulting in a total of 50 cores. After sample registration in the mDIS (Drilling Information System), the surface of the core was washed with sterile MilliQ ultrapure water and brought to the on-site microbiology laboratory. The bench tops used for core processing were chemically disinfected followed by flame sterilisation. The surface of the core was flamed to combust contaminating nucleic acids from microbes present in the drilling fluid. To assess the success of surface decontamination, fluorescent microspheres (AFN-09, Radiant Color NV) 0.25 – 0.45 ⍰m in diameter were added to the drilling fluid at a final concentration range of 108 to 109 beads ml-1. The concentration of the microspheres in the drilling fluid was determined every six hours using a fluorescent microscope (CyScope HP equipped with a 470 nm LED set) as previously described (Friese et al., 2017). Simultaneous with core recovery, 50 ml of the drilling fluid was sampled in a sterile Falcon tube and immediately frozen at -80 °C for characterisation of the microbial community in the drilling fluid and thus, to determine which taxa should be considered as contaminants. Evaluation of the core surface sterilization was carried out as previously described (Friese et al., 2017) or via an adapted surface sterilisation protocol described as follows. Briefly, a surface fragment of 2 – 3 g was collected using a sterile chisel and washed for 5 min in sterile MilliQ water (1 ml water g-1 rock) using a vortex. The liquid was filtered on a polycarbonate membrane filter and bead concentration on the core's surface was estimated by counting 30 random fields of view using fluorescent microscopy. Flame sterilization of the core surface was repeated until at least 99.9 % of the microspheres in the drilling liquid had been quenched (quenching of the microsphere fluorescence occurs upon heating above 100 °C). Once the core was deemed free from contamination, it was sampled for subsequent CARD-FISH (fluorescence in situ hybridization with catalysed reporter deposition) analysis (Escudero et al., 2020). Briefly, the core was transferred to the clean part of the on-site laboratory to sample the inner core by aseptically removing small fragments followed by fixing the material in 4 % (vol/vol) formaldehyde in Mackintosh minimal media. The fixed sample was stored at 4 °C until transport back to the home laboratory where it was kept at -20 °C. Finally, the core was packaged in a foil sleeve, partially sealed, flushed with 0.2 ⍰m filtered nitrogen gas, completely sealed, and stored in a -80 ºC freezer present on site. Due to adhesion of the fluorescent microspheres to clay particles in the drilling fluid, the beads were no longer added to the drilling fluid after reaching 700 m depth. As an alternative decontamination control procedure, the microbiology core was immediately after retrieval submersed in a liquid containing the fluorescent microspheres in a concentration of 108 to 109 beads ml-1 followed by the same decontamination procedure as described above. In addition to the 50 m sample interval, natural fractures were sampled by first rinsing the surrounding material with autoclaved MilliQ water whereafter the material was collected with either a flame-sterilized chisel or spatula. The material was subsequently washed in 5 ml autoclaved MilliQ water using a vortex and stored at -80ºC. The drilling fluid was sampled directly after sampling the fracture in an identical manner as described above. For natural fracture samples, it was not possible to flame the surface as this would combust all biomolecules in the sample. Consequently, there is a higher risk of contamination of this material compared to the surface-sterilised cores; the significance and influence of this contamination will be assessed during characterisation of the microbial communities. Finally, all samples stored on site at -80 °C were transferred to the home laboratory on dry ice and kept at -80 °C before processing.

Seventeen samples for rock mechanical tests, each between 20 and 30 cm long, were taken from the Alum Shale Formation and across the main Caledonian décollement, which corresponds to approximately one sample per core run in the depth range from 780 m to 820 m. Each sample was placed in a plastic pipe with diameter slightly larger than the core diameter and orientation marks were copied from the core to the pipe’s outside. The pipe, whose bottom is closed, was then filled with laminating epoxy until the sample was covered completely. The cured epoxy preserves both the sample’s fluid content and its structural integrity during transport to the laboratory.

7.3 Mud logging

Due to the relative simplicity of the mud composition, mud logging was restricted to pH, temperature and conductivity measurements at irregular intervals. Some samples were preserved and stored with the drill core.

7.4 OLGA

The planned OnLine Gas Monitoring (OLGA) during COSC-2 operations was cancelled entirely because the equipment was inaccessible due to Covid-19 restriction.

Table 3: Summary of COSC-2 and COSC-2B downhole logging

Logging campaigns in COSC-2 (2020)
26th – 27th May at 1235.7 m driller's depth (Lund University campaign 1)
• Caliper with total natural gamma (2.09 m – 1199.10 m)
• Electric rock resistivity short, long normal, SP, temperature, single point resistance, total natural gamma (110.15 m – 1233.5 m)
• Acoustic borehole televiewer (1° resolution), total natural gamma (160.87 m -1234.59 m)
21st -22nd June at 1090 m driller's depth (Lund University campaign 2)
• Electric rock resistivity short, long normal, SP, temperature, single point resistance, total natural gamma (1200.00 m – 1574.25 m)
• Sidewall density, total natural gamma, temperature (3.63 m -1572.10 m)
• Acoustic borehole televiewer (1° resolution), total natural gamma (95.02 m -180.5 m (because of technical problems during campaign 1) and 1200.45 m – 1575.21 m)
27th August at 2276 m driller's depth (Lund University campaign 3)
• Electric rock resistivity short, long normal, SP, temperature, single point resistance, total natural gamma

9th to 12th September at TD (ICDP-OSG and Lund University)

- Dipmeter (0 – 2275 m)
- Magnetic susceptibility (1 – 2275 m)
- Electric rock resistivity dual laterolog (deep and shallow radius of measurement; 3,6 – 2276 m)
- Spectral gamma, total natural gamma, full waveform sonic (3,5 – 2276 m)
- Acoustic borehole televiewer, total natural gamma (1162 – 2270 m)
- Gyro (0 – 2276 m)

Logging campaigns in COSC-2B (2020)

25th August (Lund University)

- Caliper with total natural gamma (0.73 m – 116.34 m)
- Electric rock resistivity short, long normal, SP, temperature, single point resistance, total natural gamma
- (5.71 m -116.34 m)
- Acoustic borehole televiewer (1° resolution), total natural gamma (1.03 m – 115.97 m)

7.5 Downhole investigations

Lund University performed two logging campaigns during a drilling break and before installation of the temporary casing. This was done for safety reasons, to secure data in case of a hole loss while drilling and in case the temporary casing could not be pulled out of hole at the end of the operations. A comprehensive downhole logging- programme to TD was conducted in collaboration with the ICDP Operational Support Group (OSG). The COSC-2 A and B downhole logs are listed in Table 3.

8 The COSC-2 drill core and geology

The COSC-2 drill core was retrieved from two closely spaced boreholes (< 1 m at the surface),

- COSC-2 A, where core drilling commenced at 100.32 m and continued to 2276.05 m , and
- COSC-2 B, were core drilling commenced at 6.08 m and continued to 116.25 m

(all depths are drillers' depth). Total core recovery was close to 100 %, with only minor core loss documented at a small number of fracture zones.

Turbiditic greywackes (possibly equivalent to the Föllinge Fm.) were drilled from the bedrock surface down to c. 780 m (light blue in Fig. 5). Here, the borehole encountered a strongly sheared black shale formation, which is in accordance with the magnetotelluric site investigations. After c. 45 m, the black shales give way to a unit characterised by sandstones and conglomerates in a turbiditic background sedimentation, which extends downwards to c. 1250 m (orange in Fig. 5). At this depth, volcanic porphyries were encountered for the first time in the borehole. They show only minor signs of deformation and are present in different varieties (green to reddish, different grain size) down to the total depth (red in Fig. 5), interrupted by major (and some minor) dolerite intrusions between c. 1600 and c. 1930 m (green in Fig. 5).

After the downhole logging operations, the drill core was depth-corrected to the depth master log. Thus, sample material, drill core data and downhole data share a common depth system.

9 COSC-2 base data

The following paragraphs describes the datasets included in the COSC-2 base data. These datasets that are listed in tables 4 and 5 are available from the COSC-2 data repository (Lorenz et al. 2022 at https://doi.org/10.5880/ICDP.5054.003). Explanatory remarks are available at the data repository.

9.1 Datasets originating from the drilling operations

A PLC (programmable logic controller) based data acquisition system is installed on "Riksriggen". In the configuration used during COSC-2 it measured hydraulic pressure signals (feed, holdback), rotational speed, chuck position, mud flow rate (inbound), pump pressure and wireline winch position. On reading per second was collected in a SQL database. These data are not included in the data repositories and only available on request, due to inherit problems with how to interpret the dataset when combined with scientific data.

9.2 Datasets based on the drill core

9.2.1 Originating from the mDIS

The mDIS contains descriptive information about the drilling project, primary data and links to primary data (e.g. imagery). Available data sets are:

1 Drill core metadata. Number of core run, depth, length of core run, sections, length of sections, core recovery, the location of sections in core boxes. The value of the corrected depth (MCD, mean composite depth) is the depth in metres after the sections were manually correlated with the depth-

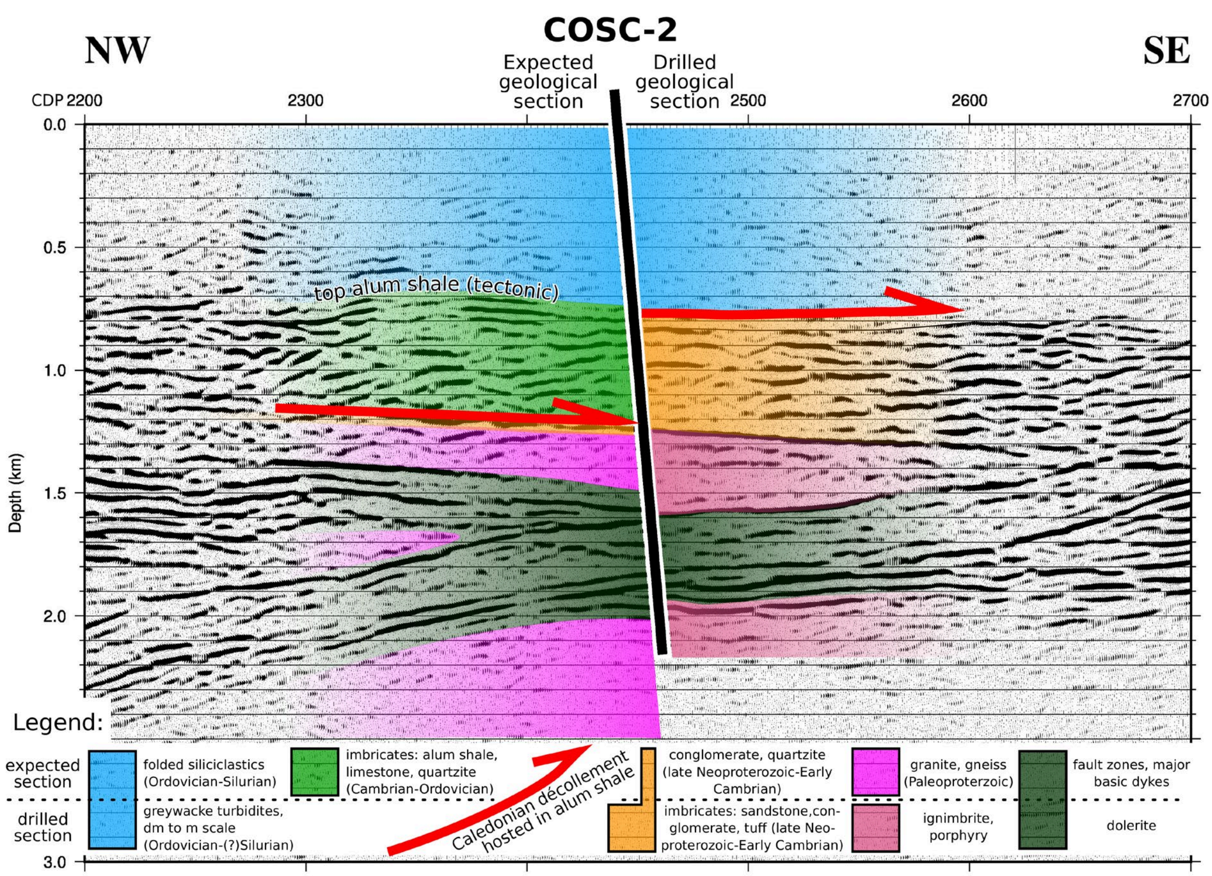


Figure 5: The COSC-2 expected geology (left) and the drilled geology (right) superimposed on the depth converted seismic section that represents the rock in the vicinity of the COSC-2 drill site. See Fig. 1 for location and note that due to reprocessing, CDP points are shifted when compared with the original publications (Hedin et al., 2012; Juhlin et al., 2016).

matched televiewer imagery (see Section 9.3.1).

2 Unrolled core scans, i.e. the drill core was rolled below a line-scan camera on a DMT CoreScan3 scanner (provided by ICDP), which resulted in images of the whole drill core surface (360° around core axis) at a spatial resolution of 10 pixels/mm and a spectral resolution of 8 bit/channel. The images are available in TIFF and JPEG formats.

3 Core box images. The core boxes were photographed with a Nikon D800 camera and Zeiss Distagon T 1:2/35 mm lens.

9.3 Datasets based on downhole surveys

The depth reference for the COSC-2 drill hole is a composite log of total natural gamma radiation that was measured from total depth to the surface in a single run. These reference data are located in the Temp.MS_GRmaster column of the data file 5054_2_A COMPOSITE log.asc.

9.3.1 Depth-matched downhole data

ICDP OSG logging data (COSC-2 A) were depth-matched by the OSG and compiled into several composite logs, which are available in ASCII (txt) format. Logging data from Riksriggen/Lund University were depth matched to the COSC-2 A depth master log. All logging data in COSC-2 B were acquired by Riksriggen/Lund University and are provided as a depth-matched composite log.

Table 4: Available files with data from COSC-2

	DATA	Extend	Format
1	All Data	All Data	ASCII/TXT
2	Site Locations	All Sites	ASCII/TXT
3	Hole Locations	All Holes	ASCII/TXT
4	Cores	All Holes	ASCII/TXT
5	Core Sections	All Holes	ASCII/TXT
6	Core Boxes	All Holes	ASCII/TXT
7	On-Site Lithological Description	All Holes	ASCII/TXT
8	Lithological Description (Core Repository)	All Holes	ASCII/TXT
9	Samples	All Holes	ASCII/TXT
10	Mud Samples	All Holes	ASCII/TXT
11	Sample Requests	All Sample Requests	ASCII/TXT
12	Corelyzer Files	All Holes	Software specific files and instructions
13	Borehole Measurement Datasets: Logging Data Riksriggen	All Holes	ASCII/TXT
14	Borehole Measurement Datasets: Logging Data OSG	All Holes	ASCII/LAS/WellCAD/PDF print
15	Magnetic Properties of the Core	Selected intervals	ASCII/TXT-
16	README: Core marking	All Holes	-

All data are depth corrected to the COSC-2 depth master.

9.3.2 MSCL

MSCL geophysical core logging was performed with the following sensors: gamma attenuation, magnetic susceptibility and natural gamma, resulting in processed data for density (calculated from gamma attenuation and core diameter), magnetic susceptibility and natural gamma. Core sections were fed through the sensors in polycarbonate half-liners to avoid transport problems like core pieces that jam the in front of a sensor. All data were processed under the assumption that the drill core has the nominal inner diameter of the diamond core bit it was drilled with, because of consistent problems with drift in the thickness deviation sensor. Due to the immense work that is required to divide MSCL output files on a core section basis and by hand remove the boundary effects between core sections, the MSCL data were never curated and are only available on request. The depth-matched downhole datasets provide easy access to similar information at a slightly inferior resolution.

1.3 Drill core description

To compensate for the limitations of the on-site geological work due to Covid-19 restrictions, a separate drill core description was organised for the core repository. After several Covid-19 related delays, it could be conducted in September and October 2021 by a core group of five scientists, assisted by other science team members who visited for shorter periods. The resulting data (number 8 in Table 4) complement the depth-matched downhole data and should be used instead of the On-site Lithological Description.

10 Core repository and sampling party

The COSC-2 drill core is archived at the Core Repository for Scientific Drilling at the Federal Institute for Geosciences and Natural Resources (BGR), Wilhelmstr. 25-30, 13593 Berlin (Spandau), Germany. The sampling party was conducted during three weeks in late June and July 2022, after new delays due to Covid-19 related regulations at the core repository. At the sampling party, approximately 1000 samples were taken from the drill core and distributed to the science team.

11 Site restoration

The access road to the drill site was repaired and the drill site restored during summer and autumn 2022. At the drill site, the gravel was removed, the top soil placed back and trees planted. A four-metre-wide corridor was spared and provides access to the boreholes for future studies.

12 Preliminary Scientific Assessment

A preliminary scientific assessment of the findings in the COSC-2 operational phase is presented in Lorenz et al. (2022). The latter predates the core description at the repository, and thus, the latest findings are provided here, cited from the abstract of Lehnert et al. (2022) to the IODP/ICDP colloquium 2022):

The geological core description shows that there is a continuous sedimentary succession on top of the weathered basement (saprock & saprolith). Its cover of regolith is overlain by basal conglomerates, followed by a few meters of heterogeneous sediments, including marls with trilobites, which indicate a Lower Cambrian age instead of a Neoproterozoic one. This indicates the unusual development of an Early Cambrian basin that initially was filled, most likely very rapidly, by mainly coarse-grained sediment gravity flows. This sedimentation was interrupted by a longer quiet period of Alum Shale deposition

Table 5: Available imagery from COSC-2

IMAGES	Low Resolution	High Resolution
Core Overviews	All Holes	All Holes
Cores	All Holes, unrolled scans	All Holes, unrolled scans
Core Boxes	All Holes	All Holes

(Middle Cambrian/Maolingian through Lower Ordovician/Tremadocian; e.g., Zhao et al. 2022), which transitioned into turbidite sedimentation. The resulting sedimentary sequence shows fining upward and indicates a general deepening of the basin (Tremadocian and younger?). The turbidites were previously regarded as a foreland basin fill. However, the locally sourced material in the gravity flows below the Alum Shale and the long-time of deposition suggest continuous sedimentation in a long-lived pull apart basin that has been well preserved beneath the Caledonian nappe pile.

13 Conclusion

COSC-2 successfully sampled the lower part of the Scandinavian Caledonides tectonostratigraphy and the underlying basement with nearly 100 % core recovery. All operational targets were reached despite surprises with the encountered geology. The scientific community now has access to a high-quality drill core to work on the project's scientific targets, a work that gradually has started during the last year, when the pandemic situation allowed. Primary tasks will be to establish geological time along the entire cored section, investigate the geological surprises like the type of the basement and the nature of the basement cover below the Alum shale, and to describe, quantify and date the deformation.

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15 Glossary

ASCII	American Standard Code for Information Interchange
BOP	blow out preventer
COSC	Collisional Orogeny in the Scandinavian Caledonides
DIS	Drilling Information System
DMT	company name (Deutsche Montan Technologie)
GFZ	German Rearch Centre for Geosciences (Deutsches GeoForschungsZentrum)
HRQ	wireline drill rods in H-size (HQ) with reinforced thread
HWT	flushing joint casing in H-size
ICDP	International Continental Scientific Drilling Program
ID	inner diameter
IGSN	International GeoSample Number
LAS	Log ASCII Standard
LU	Lund University
Ma	million years (mega anni)
MSCL	multi-sensor core logger
MWD	measurement-while-drilling
OD	outer diameter
OLGA	on-line gas monitoring
OSG	the operational support group of ICDP
PDF	Portable Document Format
PLC	programmable logic controller
RPM	revolutions per minute
ROP	rate of penetration
SQL	Structured Query Language
TD	total depth
VSP	vertical seismic profiling
WOB	weight on bit
XRF	x-ray fluorescence

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