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Drilling into an active mofette: pilot-hole study of the impact of CO_2-rich mantle-derived fluids on the geo–bio interaction in the western Eger Rift (Czech Republic)

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Abstract. Microbial life in the continental "deep biosphere" is closely linked to geodynamic processes, yet this interaction is poorly studied. The Cheb Basin in the western Eger Rift (Czech Republic) is an ideal place for such a study because it displays almost permanent seismic activity along active faults with earthquake swarms up to M_L 4.5 and intense degassing of mantle-derived CO_2 in conduits that show up at the surface in form of mofettes. We hypothesize that microbial life is significantly accelerated in active fault zones and in CO_2 conduits, due to increased fluid and substrate flow. To test this hypothesis, pilot hole HJB-1 was drilled in spring 2016 at the major mofette of the Hartoušov mofette field, after extensive pre-drill surveys to optimize the well location. After drilling through a thin caprock-like structure at 78.5 m, a CO_2 blowout occurred indicating a CO_2 reservoir in the underlying sandy clay. A pumping test revealed the presence of mineral water dominated by Na^+, Ca^{2+}, HCO_3^-, SO_4^{2-} (Na-Ca-HCO_3-SO_4 type) having a temperature of 18.6 °C and a conductivity of 6760 µS cm^{-1}. The high content of sulfate (1470 mg L^{-1}) is typical of Carlsbad Spa mineral waters. The hole penetrated about 90 m of Cenozoic sediments and reached a final depth of 108.50 m in Palaeozoic schists. Core recovery was about 85 %. The cored sediments are mudstones with minor carbonates, sandstones and lignite coals that were deposited in a lacustrine environment. Deformation structures and alteration features are abundant in the core. Ongoing studies will show if they result from the flow of CO_2-rich fluids or not.

1 Introduction

Microbial processes in the "deep biosphere" and their interaction with geological processes are a matter of ongoing debate. Microbial habitats extend down to great depths beneath the earth's surface. However, cell counts and detailed characterizations of the microbial community structure in the continental deep biosphere are rare and mostly related to investigations in oil reservoirs (Youssef et al., 2009), geothermal aquifers (Alawi et al., 2011; Lerm et al., 2013) or gold mines (Deflaun et al., 2007; Takai et al., 2001; Trimarco et al., 2006). A few continental drilling campaigns have focused on the deep biosphere (Fredrickson et al., 1997; Onstott et al., 1998; Zhang et al., 2005), though the state of knowledge reached is still in the early stages. In deep saline aquifers intended for CO_2 capture and geological storage (CCS), changes in the microbial community caused by injected CO_2 can induce mineral dissolution and precipitation or the formation of biofilms (Onstott, 2005; Mitchell et al.,

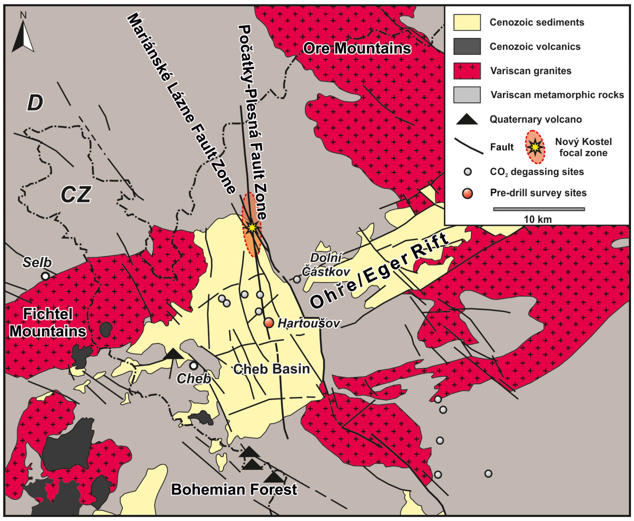

Figure 1. Geological map of the Cheb Basin and surroundings, based on Flechsig et al. (2008) and Dahm et al. (2013).

Figure 2. The major wet mofette in Hartoušov is located in the direct vicinity of the drill site. At the upper and lower part of the mofette bubbles of CO_2-rich gas are visible.

2009), and might affect long-term storage efficiency and reliability (Morozova et al., 2010; Gulliver et al., 2016; Pellizzari et al., 2016).

In the scope of the International Continental Scientific Drilling Program (ICDP) project "Drilling the Eger rift: Magmatic fluids driving the earthquake swarms and the deep biosphere" (Dahm et al., 2013), one focus is to determine to which extent the microbial communities are conditioned by the mantle-derived CO_2 degassing and how the microbial activity is potentially affected by seismic events such as swarm earthquakes. As a pre-examination, a research project "Microbial processes in the deep biosphere of the CO_2-dominated active fault zone in NW Bohemia" started in 2016 and included a 108.5 m deep drilling (Alawi et al., 2015). We assume that in active fault zones, due to an intensified substrate support, microbial processes are significantly accelerated compared to other deep subsurface ecosystems. Similar to black smokers in the deep sea, active fault zones might represent "hot spots" of microbial life in the deep subsurface (Alawi et al., 2015). The combination of intense CO_2-rich mantle degassing, ongoing seismic activity including earthquakes swarms and microbiological activity that occurs in the Cheb Basin (western Eger Rift, Czech Republic; Fig. 1) is exceptional and allows the study of bio–geo interactions as part of active geodynamic processes in the lithosphere (Kämpf et al., 1989, 2005, 2007, 2013; Wagner et al., 2007; Bräuer et al., 2007, 2008, 2011, 2014; Dahm et al., 2013; Fischer et al., 2014, 2017; Alawi et al., 2015; Schuessler et al., 2016).

About 10 km south of the Nový Kostel focal zone epicentral area (Fig. 1), strong subcontinental mantle-dominated CO_2 degassing occurs in the Bublák and Hartoušov mofette fields (Bräuer et al., 2003, 2014; Kämpf et al., 2013; Nickschick et al., 2015, 2017). Mofettes are places where geogenic CO_2 ascends through conduits from the mantle to the surface (Fig. 2). The CO_2 conduits are regarded as important structures of lithospheric mantle–crust interaction via mantle fluids. However, both rock-fluid and geo–bio interactions in these structures are hardly understood.

Microbial growth in the deep subsurface is limited by factors such as temperature, pH, redox potential, gas concentration, water and substrate availability (Kallmeyer and Wagner, 2014). The conditions for life in the deep biosphere are extreme in comparison to most surface environments: no light is available for photosynthesis, typically much higher temperatures than in surface habitats prevail, the availability of water and of organic carbon is severely restricted, and high gas pressures occur. The exchange of substances is crucially reduced since it is coupled to water availability and to diffusion processes. Therefore, microbial activities are slowed and microbial turnover times are strongly decreased (Lomstein et al., 2012). However, microbes can survive long periods of starvation by reducing their metabolism or forming spores (Goldscheider et al., 2006; Hubert et al., 2009). Interestingly, there are hints that the microbial turnover in active fault zones is significantly accelerated in comparison to the ordinary terrestrial deep biosphere. Eight weeks after an earthquake swarm occurred in the northwestern part of the Cheb Basin, the amount of microbiologically produced methane increased significantly and persisted for more than two years (Bräuer et al., 2005, 2007). The authors assume that hydrogen was released from a fractured granitic aquifer during seismic activity and became available for microorganisms. In the same region, Schuessler et al. (2016) explain recurring changes in iron isotope signatures of mineral spring water by a combination of abiotic and biotic processes triggered by swarm earthquakes. CO_2 as the dominating gas in the Cheb Basin might liberate organic compounds (Glombitza et al., 2009; Sauer et al., 2012); enhance the dissolution, transformation and precipitation of minerals (Rempel et al., 2011); and could thereby affect the availability of substrates for microorganisms. These examples lead to the question of whether and how geodynamic processes such as earthquakes can trigger microbiological activity by transport of substrates and changes in environmental conditions. Our main interests are to determine to which extend the microbial communities are conditioned by the mantle-derived CO_2, how the microbial activity is potentially affected by seismic activity such as earthquake swarms, and if active fault zones, due to an intensified substrate support, lead to significantly accelerated microbial activity compared to other deep subsurface ecosystems.

The present pilot-hole study that precedes the ICDP drilling project "Drilling the Eger Rift" (http://web.natur.cuni.cz/uhigug/icdp; Dahm et al., 2013) focuses on the interaction between lithospheric geodynamic activity driven by magma generation and magma/fluid escape beneath the Cheb Basin in the western Eger Rift and the microbial communities of the deep biosphere in the upper crust.

Here we describe the 108.5 m deep drilling of well HJB-1 into an active CO_2 conduit in the Cheb Basin, located at the northern part of the Hartoušov mofette field. It was intended to core as continuously as possible down to the bottom of the lacustrine succession. The operational challenges were manifold, starting with the logistics and technical feasibility of the drilling to the high standards we require with regard to assessing sample contamination through infiltration of drill mud. Because of the potential risk of a spontaneous gas/fluid blowout during drilling, extra safety measures including the application of a blowout gas preventer, high-density bentonite-based drill mud and gas alarm techniques had to be employed.

2 Geological background

The Cheb Basin represents the shallow western part of the Cenozoic Ohře/Eger Rift, the easternmost segment of the European Cenozoic Rift System that has developed in response to intraplate stresses exerted from the Alps, and possibly to thermal doming (Malkovský, 1987; Rajchl et al., 2009). The basin is located at the intersection of the ENE–WSW trending Eger Rift with the N–S striking Regensburg–Leipzig–Rostock zone respectively its major local segments, the Počatky–Plesná Fault zone and the Mariánské Lázně Fault zone (Fig. 1; Bankwitz et al., 2003). It is underlain by Palaeozoic metamorphics and granites (Hecht et al., 1997; Fiala and Vejnar, 2004) and bounded on its eastern side by the morphologically distinct scarp of the Mariánské Lázně Fault zone (Peterek et al., 2011), and to the west and to the south by the Fichtel (Smrčiny) Mountains and the Oberpfalz Forest.

The fill of the Cheb Basin consists of less than 300 m of continental sediments. Sedimentation started in the Eocene with the local deposition of clays and sands, possibly in maars, referred to as the Staré Sedlo Formation (Fm.; Špičáková et al., 2000; Pešek, 2014). Following a phase of uplift and erosion, sedimentation commenced with the deposition of gravels, sands and clays of the Oligocene (Chattian) to Early Miocene (Early Aquitanian) Lower Argillaceous-Sandy Fm. (Pešek et al., 2014). In the Lower Miocene, the coal-bearing Main Seam Fm. formed in an alluvial landscape enclosing extensive wetlands. Subsequently, a large lake developed in which the clay-dominated Cypris Fm. was deposited (Rojik, 2004). After a hiatus, sedimentation started again in the Pliocene with lacustrine clays, sands and gravels of the Vildštejn Fm. and continued without an obvious break into the Quaternary (Pešek et al., 2014).

In the surrounding of the Eger Rift, volcanism was temporarily active during the Cenozoic. In the Quaternary, volcanic activity formed two small scoria cones with lava flows and a just recently discovered explosive maar structure (Mrlina et al., 2007, 2009; Flechsig et al., 2015; Ulrych et al., 2016). Ongoing tectonic activity in the Cheb Basin is manifested by earthquake swarms that concentrate along the northern segment of the Mariánské Lázně Fault zone (Fig. 1). The strongest registered earthquakes reached local magnitudes of M_L 4.5 (Fischer et al., 2014). Active fault zones very likely represent migration pathways for the degassing of mantle-derived CO_2 that causes intense mofette activity (Kämpf et al., 2013; Nickschick et al., 2015, 2017), while the ascent of magmas and the fluid activity probably constitute the forcing mechanisms of the seismic activity (Bräuer et al., 2003, 2008, 2011, 2014; Dahm et al., 2008; Fischer et al., 2014).

3 Hydrogeological background

Numerous mineral water springs occur in the Cheb Basin. In spa towns such as Františkovy Lázně the springs are used for illness prevention, and rehabilitation and consequently their catchment areas are safeguarded as protection zones. The springs are linked to gas-saturated and highly mineralized waters of an aquifer located at the eastern margin of the Mariánské Lázně Fault zone. Most mineral waters are of the Carlsbad Spa type, i.e., Na-$HCO_3(SO_4Cl)$ to Na(Ca)-$HCO_3(SO_4)$. Total dissolved solids are highly variable and range from a few $mg\,L^{-1}$ to over $20\,g\,L^{-1}$. The components are of a complex origin with both exogenous (oxidative and hydrolytic) and endogenous (hydrolytic and possibly fossil and evaporitic) contributions (Egeter et al., 1984; Dvořák, 1998; Paces and Smejkal, 2004).

4 Microbiological background

Microorganisms involved in all major global biogeochemical cycles exist in the deep biosphere. They are capable of catalyzing reactions between gases, fluids, sediments and rocks, thus enhancing mineral alteration as well as precipitation. Depending on respective subsurface environmental conditions, (hyper-)thermophilic and halotolerant microorganisms were identified. Abundant metabolic groups are for example methanogenic archaea and sulfate-reducing bacteria, and strains from both of these taxa are able to obtain their carbon solely from CO_2 (Alawi et al., 2011). McMahon and Chapelle (1991) highlight that more than 90 % of the 16S ribosomal DNA sequences recovered from hydrothermal waters circulating through deeply buried igneous rocks in Idaho are related to hydrogenotrophic methanogenic microorganisms. Geochemical characterization indicates that hydrogen is the primary energy source for this methanogen-dominated microbial community. These results demonstrate that hydrogen-based microbial communities do occur in earth's deep biosphere. Considering increased hydrogen concentrations during seismic periods in the Cheb Basin (Bräuer et al., 2005) one might conclude that the microbial activity is potentially positively correlated to hydrogen availability, and therefore increased seismicity. We assume that a proliferating primary production based on methanotrophic archaea might provide the starting point for a secondary heterotrophic microbial community. As Alawi (2014) has shown elsewhere, such microorganisms produce energy-rich organic polymers that might be subsequently degraded by fermentative processes and thereby can close the carbon cycle by the emission of CO_2 as well as H_2. Acetate which is produced by acetogenic bacteria may then become a valuable substrate for Fe^{III}, $Mn^{III,IV}$ and SO_4^{2-} reducing microorganisms as well as acetoclastic methanogens (Alawi, 2014). In addition, first analyses of the microbial communities in wetland soils of the Bublák mofette field in the Cheb Basin show that both bacteria and archaea are able to incorporate ^{13}C-labeled CO_2 (Beulig et al., 2015, 2016). Hence, an effect of the increased CO_2 concentrations on the composition of the microbial community seems very likely. Despite various indicators for geo–bio interactions in the deep biosphere, it remains to be understood precisely how geological processes influence microbial activities in the deep subsurface and what role these processes have played in the geological evolution of the earth through time.

5 Pre-drilling site surveys

During the last years several geophysical, soil gas and gas flux analyses were performed to understand the patterns of CO_2 degassing at the Hartoušov mofette field. Well sections of prior boreholes drilled in the region, made available by the Czech Geological Survey (http://www.geology.cz/extranet-eng/services/data), provided provisional information on the near sub-surface sediments but detailed data on the mofette field were first acquired in a scientific drill campaign in 2007 (Flechsig et al., 2008). The objective of the pre-drill surveys was to understand the structural and sedimentological control of CO_2 degassing and to determine an optimal drill site of intense degassing underlain by a conduit.

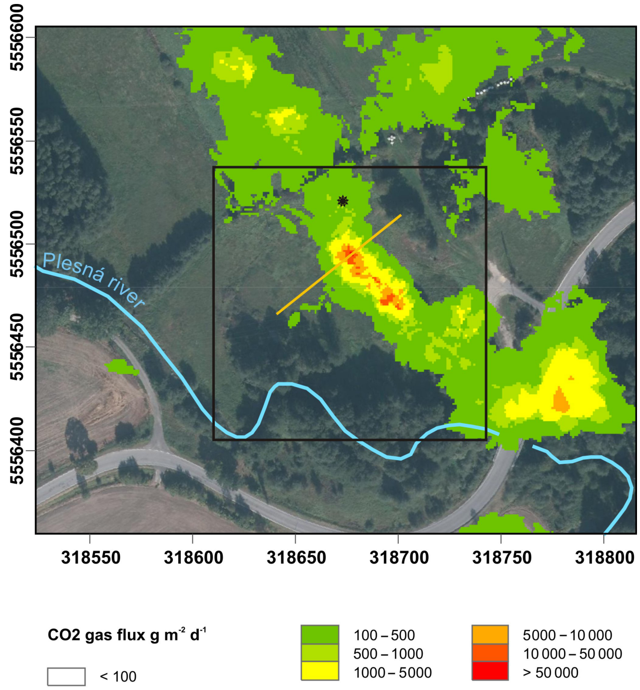

Figure 3. Location of the ICDP drill HJB-1 (black star) in the Hartoušov mofette field, with CO_2 gas flux mapping results of Nickschick et al. (2015). The black rectangle shows the area of passive seismic noise measurements (Fig. 6 and Sect. 5.3; matched field processing, MFP). The location of the geoelectrical profile in Fig. 5 is indicated by the orange line. Coordinates are in UTM zone 33N.

5.1 CO_2 mapping

Mapping of the temporal and spatial pattern of mantle-related CO_2 degassing in the Hartoušov mofette field (Fig. 3) revealed distinct differences in the spatial pattern of emitted CO_2, with low emission rates in a north–south trending zone in the southern part of the mofette field and heavy degassing in the central and northern part (Schütze et al., 2012; Kämpf et al., 2013; Rennert and Pfanz, 2016; Nickschick et al., 2015, 2017). This led Nickschick et al. (2015) to hypothesize that sinistral strike-slip fault movement causes the opening of pull-apart structures, in which intense mantle-derived CO_2 degassing occurs in conduits. For the total area of 0.35 km^2 Nickschick et al. (2015) estimate that between 23 and 97 t of CO_2 are emitted each day.

The results of Nickschick et al. (2015) formed a major basis for the selection of the drill site of HJB-1 (Fig. 3). Located in the central part of the Hartoušov mofette field, CO_2 emission rates here can vary considerably, but are generally high (Nickschick et al., 2015). During a test study in 2012, we measured daily CO_2 gas fluxes on the spot that later became the drill site. Emission rates varied between ~ 14 and 43 kg m^{-2} d^{-1} (Fig. 4) with a mean rate of 27.5 ± 9.5 kg m^{-2} d^{-1} in the observation period. Because of

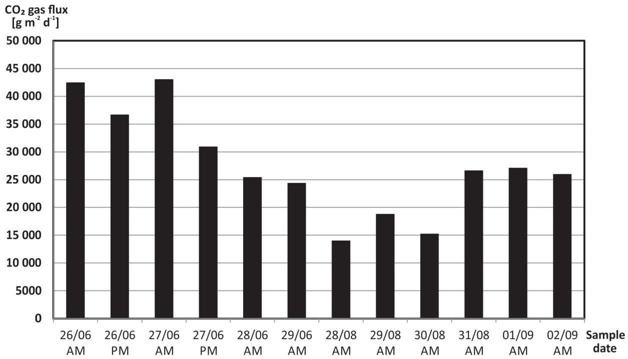

Figure 4. Variations in the CO_2 gas flux at the drill site of HJB-1 measured in 2012.

the continuously high CO_2 gas fluxes, the site proved an ideal location for HJB-1.

5.2 Geoelectrical near-surface surveys

The main objective of geophysical surveys in the Hartoušov mofette field was to detect and characterize subsurface structures that potentially represent fluid pathways or domains of fluid–rock interaction. We used preferentially electrical resistivity tomography (ERT), since the resistivity of rocks is notably sensitive to the presence of fluids. To retrieve a detailed conductivity image of the mofette field, modern ERT inversion and modeling techniques were applied (Günther et al., 2006; Günther and Rücker, 2009).

Combined with sedimentological studies and CO_2 soil gas measurements, the ERT surveys provided an image of near-surface structures down to a depth of ~ 100 m underneath the mofette field (Flechsig et al., 2008, 2010; Schütze et al., 2012; Nickschick et al., 2015, 2017). The detected structures are, most probably, directly or indirectly caused by CO_2 flow because the geophysical subsurface anomalies not only correlate positively with areas of high CO_2 but also with sediment properties such as elevated organic carbon (C_{org}) and pyrite contents, and with the occurrence of dispersed quartz pebbles in fine-grained sediments. The sedimentological properties are likely related to chemical and physical conditions caused by high concentrations of CO_2 in the sediments, and to high gas pressure. Near-surface features such as low-permeability beds seem to influence primarily the variation in CO_2 degassing linked to meteorological conditions. The presence of such beds could cause the temporal accumulation of CO_2 in underlying porous sand layers.

ERT was also used in time-lapse mode to detect temporal changes in subsurface resistivity, caused by fluctuating relations of the gaseous to liquid phase, and was combined with repeated soil gas measurements (Nickschick et al., 2017). To evaluate the stability of subsurface degassing structures over time, repeated measurements were carried out (Nickschick et al., 2017). Two repeated 2D-ERT surveys in 2007 and 2016 at the central mofette (Fig. 5) indicated small-scale near-surface (< 2 m depth) variations in the resistivity, caused by meteorological and seasonal influences, while a distinct anomaly below the central mofette at 45–55 m correlates positively with a zone of high-intensity soil degassing (Fig. 3). The detected changes suggest that CO_2 degassing sites are not steady structures; instead, their architecture changes over time spans of days to years (Nickschick et al., 2017).

5.3 Matched Field Processing (MFP) for noise source localization

Subsurface CO_2 flow is often accompanied by gas bubble collapses that act as ambient noise sources and produce seismic signals. With the help of dense small-aperture instrumental arrays and matched field processing (MFP) techniques, the noise sources can be located (Vandemeulebrouck et al., 2010; Corciulo et al., 2012; Flores Estrella et al., 2016). The data are typically displayed as a 3-D probability map that illustrates the distribution of noise sources within and beneath the array. In this way, degassing spots such as mofettes can be detected, and their corresponding subsurface feeding channels can be imaged (Flores Estrella et al., 2016).

In May 2015 we measured continuous seismic noise with an instrumental array of 25 stations (vertical geophones connected to REF TEK Texan recorders) covering 1 ha surface area in the Hartoušov mofette field. The normalized MFP output shows three clearly defined surface maxima (values ~ 1; Fig. 6a). Including areas with medium MFP amplitude (values between 0.35 and 0.6), the sources form a NW–SE trending zone of increased noise activity. While the northernmost source is only visible down to a depth of 10 m (Fig. 6b), the other two sources are still recognizable in the 10–18 m depth interval but continuously decay below 18 m in amplitude and they widen. In the depth interval 18–30 m another source appears in between, but contrary to the other ones it shows a steady amplitude increase with depth.

The measurements suggest the presence of two major fluid channels to the NE of the array that reach from the surface down to a depth of at least 30 m. Another channel in the northernmost part of the array is limited to the uppermost 10 m. A fourth channel seems to exist between the two major channels starting at 18 m depth and continuously increases in MFP amplitude with depth. The deep-seated channel might form the main feeder channel for the near-surface channels.

5.4 Shallow wells

The borehole HJB-1 was placed in an area in which the two exploratory drillings HJ-3 and HJ-4 were conducted in 1993, exploring the presence of groundwater of deeper aquifers closer to the crossing of faults. Next, direct information on the shallow subsurface sediments in the Hartoušov mofette field was gained in an exploratory drill campaign in 2007 when five shallow wells reached depths of up to 9 m

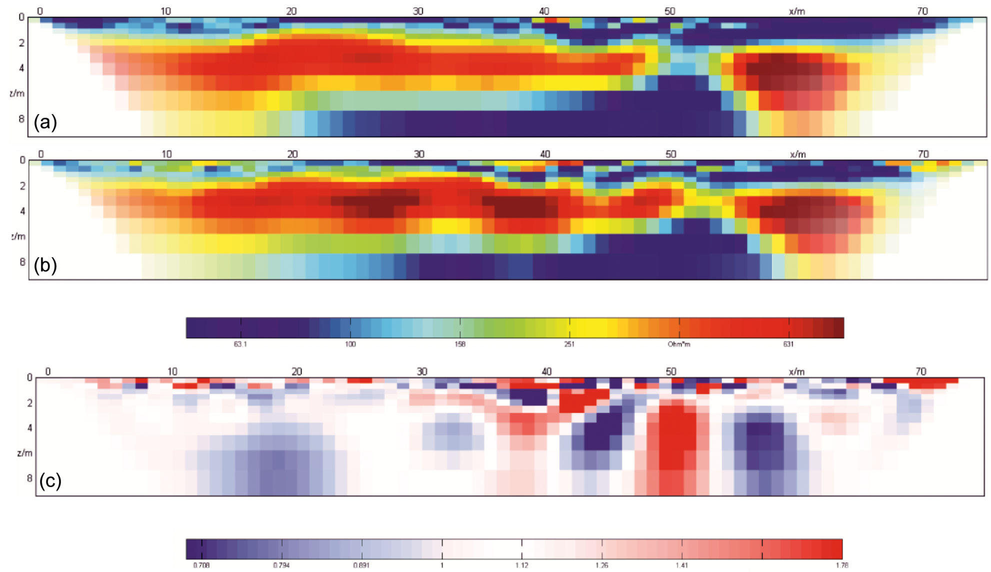

Figure 5. Results of repeated 2-D resistivity surveys at the central mofette in Hartoušov, **(a)** inversion model of the resistivity (Ω m) distribution measured in May 2007, **(b)** inversion model of the resistivity distribution measured in October 2016 (inversion code DC2DInvRes) and **(c)** relative change in the subsurface resistivity by inversion of the ratio of data from the initial (2006) and later (2016) data sets. A variation of 1 means that the resistivity has not changed, a variation of 1.2 represents an increase of 20 %.

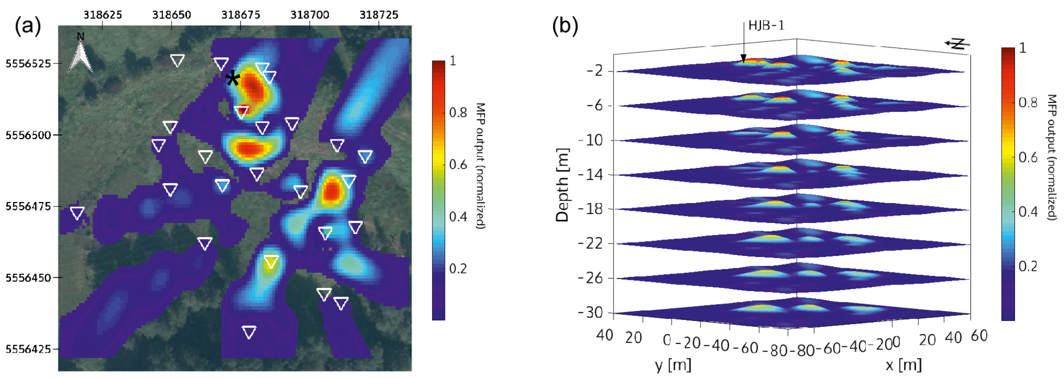

Figure 6. matched field processing (MFP) results (normalized) for the array deployed in May 2015 in the Hartoušov mofette field. **(a)** Surface plot. The white triangles indicate the position of stations. The black star shows the location of HJB-1. **(b)** 3-D depth plot (0–30 m).

(Flechsig et al., 2008). The main objective of the campaign was to compare near-surface sediments underneath an active mofette with sediments in reference sites likely not affected by CO_2 emissions. The authors assumed that sediments in mofette sites are influenced by accelerated silicate weathering due to acidifying and leaching effects of CO_2, decelerated decomposition of organic matter, and enhanced preservation and possibly formation of sulfides and sulfates. Another purpose of the pilot–hole was to corroborate the interpretation of geoelectrical lines measured at that time.

The drillings showed that the uppermost sediments in the mofette field consist of Quaternary fluviatile channel and flood plain deposits of the Plesná river, while the lower section is made up of Pliocene lacustrine clays. Drilling in the central mofette site revealed the occurrence of dispersed pebbles in fine-grained sediments and confirmed the presence of a domal uplift of the Pliocene clays already recognized in geoelectrical data (Flechsig et al., 2008). Laboratory analyses showed increased C_{org} and pyrite contents of the sediments in areas of high CO_2 degassing. The results of the drilling campaign supported the hypothesis that in areas of high CO_2 degassing, such as mofettes, physical and mineralogical properties of sediments can be significantly influenced by CO_2.

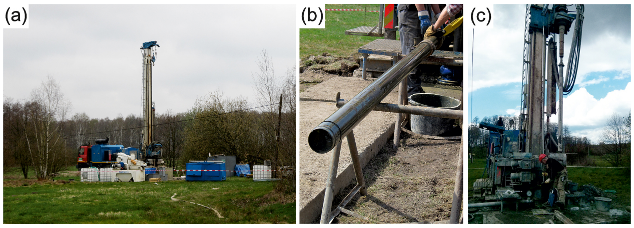

Figure 7. **(a)** Drill site of HJB-1 in Hartoušov; **(b)** core barrel display after recovery; **(c)** geophysical logging operations.

6 Drilling and coring, hydraulic and geochemical analyses, logging operations, and sampling

The drill site of HJB-1 (Fig. 7) is located in the protection zone of natural healing resources of the spa town of Františkovy Lázně (Franzensbad) but likewise in the protected area of natural water accumulation of the Cheb Basin and the Slavkovský Forest. Thus, drilling permissions had to be obtained from the State Land Office of the Czech Republic, Ministry of Public Health, Regional Authority of the Karlovy Vary Region (OŽPaZ) and the District Mining Bureau for the region of Karlovy Vary. Because of difficult terrain conditions, it was necessary to build a gravel track to allow the heavy drilling lorry to access the drilling location. The drilling operator was the company SG Geoprůzkum České Budějovice.

6.1 Drilling and coring

Drilling started on 30 March 2016 and lasted until 27 April 2016. First, a steel casing with a diameter of 324 mm was cemented down to a depth of 8 m. Next, a conductor pipe of diameter 219 mm was fitted and cemented down to 15.50 m below surface level. On the inner casing (219 mm) a preventive slide valve (preventer) DN 300 mm was installed. Then the hole was drilled near-vertically and reached a final depth of 108.50 m utilizing a core drilling system Drillmec G-25 with a cutting diameter from 450 to 275 mm installed on a Tatra 815 drilling lorry. For the coring, a Terracore S Geobor wireline core barrel system (Atlas Copco) was used (inner diameter 96.1 mm). Cores were retrieved in PVC liners of 3 m length. Pure bentonite was used as a drilling mud additive. Drilling was conducted under strict contamination control using fluorescein in the drilling mud as a contamination tracer, as tested before at the CO_2-sequestration site in Ketzin (Brandenburg, Germany) (Pellizzari et al., 2013). The concentration of fluorescein in the drilling mud was kept constant at 5 mg L^{-1}.

Drilling was performed through the gate valve so that the drilling crew was able to overcome problems of pressurized CO_2 in the drilling shaft. Pressure signs, which were expected in the project, occurred in the form of smaller and larger gas eruptions after drilling through the ceiling formed by the Cypris Fm. The first eruption of CO_2 occurred at a depth of 78.5 m when about 0.3 m^3 of clay was flushed to surface, and acoustic signs of CO_2 emission became loud. Afterwards, until the final depth was reached, dense bentonite mud ($\sim$ 1150 kg m^{-3}) was used, while the drilling mud initially had a density of $\sim$ 1100 kg m^{-3}. Mud loss was high in the Quaternary deposits and in the claystones of the Cypris Fm., and particularly in the interval of 27 to 45 m.

On the 28 April 2016 the drilling string was pulled out of the hole and geophysical logging was performed. On the 2 May 2016 the first borehole cleaning was realized by using airlift of debris; an annulus was used for filling the stem with drinking water and the air was pushed using airlift tubes with a diameter of 72 mm. The stem was purified from the residual mud and dressed with a PVC-U casing with a diameter of 114 mm. In sections 58.50 to 63.50 m, 68.50 to 83.50 m and 88.50 to 103.50 m a perforated PVC-U casing was fitted. The bottom of the borehole was equipped with a full casing with a length of 5 m. Subsequently, the casing was backfilled using washed gravel. Pressure on the gridiron is monitored online (on average 510 kPa or 5.1 bar) by H. Woith (GFZ Potsdam). Today, the wellhead is closed by a gas-tight seal and flange mounted gauge. During the drilling, the groundwater level was irregularly monitored. A very shallow aquifer was reached at 0.60 m below surface, then an aquifer in the upper part of the Cypris Fm., and finally a deep aquifer below 81.50 m in the Main Seam Fm. 24 h after reaching the final depth, the groundwater level in the well was at 4.20 m below surface. Hydraulic properties of the aquifer system were checked using short-time pumping and recovery tests. The borehole was left open for long-term online monitoring of the casing-head pressure. Until today, the borehole forms an active ascent path for gases. Since no cores were recovered in the uppermost 9 m, a dry drilling (HAR-2R) was performed immediately after HJB-1 was drilled. The dry drilling allowed the retrieval of uncontaminated shallow-core samples.

6.2 Hydraulic and geochemical analyses

A 24 h pumping test was performed after a mechanical gas-separator and an automatic measuring station were fitted to the wellhead to monitor groundwater level and flow, conductivity and temperature of pumped water. Subsequently, short-time hydrodynamic tests with a maximum tapping phase of 22 h were completed using a submersible pump (Grundfos SQ 2 70). The effective yield value of the liquid phase was 0.15 L s^{-1}, while the yield of the gaseous phase was significantly higher, on average 0.5 L s^{-1}, with a maximum of 2.92 L s^{-1}. The coefficient of determination between the water level and the yield of the gaseous phase amounted to 0.67; the coefficient of determination between the yields of liquid phase and gaseous phase yields was at 0.89 during the short-term tests. The specific yield value amounted to 2.9×10^{-5} m^2 s^{-1}. Transmissivity was around 7.8×10^{-6} m^2 s^{-1} during non-steady flow at the end of the short-term hydro-

Table 1. Comparison of the chemical parameters of the recovered mineral water in HJB-1. The sampling date was 10 May 2016 (20:00 LT, end of recovery test). A comparison to the chemistry of two typical mineral waters from western Bohemia is shown (Karlovy Vary: spring Vřídlo (Sprudel), borehole BJ-35, 55.2 m deep and Františkovy Lázně: spring Adler, borehole 33 m deep).

Water source	K ($mg\,L^{-1}$)	Na ($mg\,L^{-1}$)	Ca ($mg\,L^{-1}$)	Mg ($mg\,L^{-1}$)	Cl ($mg\,L^{-1}$)	SO_4 ($mg\,L^{-1}$)	HCO_3 ($mg\,L^{-1}$)	Fe ($mg\,L^{-1}$)	Mineralization ($mg\,L^{-1}$)
HJB-1	44.2	1080	411	85.1	229	1470	2420	13.7	5870
Karlovy Vary	90.2	1670	118	42.9	592	1610	2180	1.3	6422
Františkovy Lázně	21.9	921	48.4	11.2	398	1119	671	14.3	3306

dynamic test, just before eruption. Thus, the Variscan mica schists and basal Cenozoic sediments seem to be weakly to slightly permeable. Less permeable rocks were reached after approximately 10 h of pumping. The tests suggest the presence of a major fluid ascending channel located in a permeable fault zone. Reaching a significant fault in basal layers of the basin and its fundament is also supported by a large spreading of the gas phase after penetrating the ceiling formed by less permeable strata of the Cypris Fm.

Starting at a depth of approximately 78.5 m, after penetrating a carbonate-rich layer approximately 30–40 cm in thickness, significant circulation of gas-saturated groundwater was observed, and bursts of gaseous CO_2 and water occurred at the wellhead. Gas analysis measured 99.90 vol. % CO_2, 0.0831 vol. % N_2 and 0.00558 vol. % O_2. We assume that the sand-bearing sediments directly underneath this caprock-like structure form a reservoir for mantle-derived CO_2. Physicochemical parameters of groundwater recovered from the basal aquifer (approximately at a depth of 79–85 m) were measured during the pumping tests (Table 1). After cleaning the borehole, samples were taken for chemical and microbiological analysis of liquid and or gaseous phases. The subthermal mineral water had a temperature of up to 18.6 °C. The water was highly gas-saturated with about 1892 $mg\,L^{-1}$ of free dissolved CO_2, and heavily mineralized with an electrical conductivity of around 6800 $\mu S\,cm^{-1}$. The pH was about 6.4.

The content of H_2SiO_3 in the groundwater of the basal aquifer is very high, with up to 112 $mg\,L^{-1}$, as is the Fe content with up to 13.7 $mg\,L^{-1}$. The groundwater of the basal aquifer is of the Na-Ca-HCO_3-SO_4 type, typical of the Františkovy Lázně Spa and its mineral waters. Its composition is mainly influenced by intense hydrolysis of aluminosilicate minerals probably caused by CO_2, and, given the relatively high concentration of chloride ions, by a fossil component (Na-Cl) related to an evaporitic closed lacustrine basin represented by the claystones of the Cyris Fm. (unit 3 in Fig. 8). A high content of sulfate is typical of Karlovy Vary Spa mineral waters and might reflect, at least partly, the dissolution of evaporites such as Na_2SO_4 (Paces and Smejkal, 2004).

6.3 Logging operations

Logging data were acquired in eight runs to ensure complete well coverage without losing data due to sensor offsets in stacked tool strings. Most tools were combined with a gamma ray (GR) probe to allow an accurate depth alignment. Since borehole stability was a concern, the spectral GR was run before pulling out the drill pipe, logging downwards at 2 $m\,min^{-1}$. A bismuth germanate (BGO) scintillation crystal within the tool allowed us to determine the amount of natural radioactivity within the formation and additionally a splitting into thorium (Th), potassium (K) and uranium (U) based on discrete energy peaks. After run 1, the drill pipe was pulled and all consecutive measurements were acquired in open hole. Run 2 consisted of a probe recording the environmental parameters of the borehole fluid including temperature, pressure, conductivity, salinity, pH, oxygen saturation and chloride content. A magnetic susceptibility probe was run in combination with GR in runs 3 and 4 in two intervals. An overlap was logged to allow for proper depth alignment and splicing of the two runs. In run 4, a different gain was used for the susceptibility probe. To compensate for the difference between both measurements, a multiplier was utilized to homogenize the data before splicing. Due to the presence of a conductor pipe at approximately 15 m, no open hole data could be gained above that depth. Since the data of run 3 and 4 were acquired logging upwards and in open hole, they were used as depth reference. All other measurements were matched with these runs using either a linear or an interactive depth shift. Run 5 provided a focused electric resistivity measurement followed by formation velocity in run 6. The sonic data were reprocessed by picking the first arrivals of the near and far detectors and recalculating delta time compressional and primary velocity (V_p). A dipmeter probe was logged in run 7 providing four pad conductivities in four directions, caliper data and borehole navigation data. Microsusceptibility was the last measurement proving to be a higher-resolution log than the standard susceptibility in runs 3 and 4, with a vertical resolution of about 2 cm. It will be used in the future for a better correlation with core data. To complete the logging suite, Prague University acquired gamma density and neutron porosity data.

The composite log is presented in Fig. 8 together with a lithology obtained from core data. The core depth and lithological boundaries were adjusted on the basis of the logging data, especially in areas of low core recovery. The borehole was drilled vertically with a slight north trend and a deviation of 1–2°. The GR log indicates a gradual decrease in clay content towards the surface. Especially the weathered schists near total depth feature high thorium contents. Susceptibility is generally low but shows several peaks throughout Miocene deposits. Within the weathered Paleozoic schist an increase in gamma ray, sonic velocity and resistivity can be noted indicating higher clay content and likely a higher compaction. The dipmeter shows several conductivity spikes within the Miocene that could be related to minor fractures or cracks. The sonic wavelets indicate several chevrons that probably developed for the same reason.

6.4 Sampling

At the well site, the laboratory container of GFZ Potsdam (BUGLAB) was installed to allow subsampling under optimal conditions. Equipped with refrigerators as well as with −80 °C freezers, the container permitted optimal storage conditions for biological samples. Below 20 m depth, the sediment was too consolidated for subsampling with cutoff syringes and consequently whole round cores (8 cm long, still in plastic liner) were cut. To preserve the samples, different techniques were used. Core material assigned for cultivation-based analyses were stored in CO_2-flushed gastight bags, while samples intended for geochemical analyses were stored in N_2-flushed bags, and samples reserved for molecular biological studies were frozen in the field at −80 °C. By now, segments of the core have been transferred to project partners to analyze the microbiology, sedimentology and mineralogy as well as to perform geochemical analyses. Because the perimeter of the core most likely was contaminated by drilling mud, it was discarded. This so-called inner coring was performed under aseptic conditions at the GFZ Potsdam. More than 300 samples are currently processed in this way. From each core meter about 60 cm were retained as whole round cores for sedimentological and mineralogical analyses and to perform core logging. All cores were photographed at the GFZ (Fig. 9).

6.5 Contamination control

To assess drill-mud penetration into cores the tracer fluorescein was extracted from the cut-off rim and the inner core according to the protocol from Pellizzari et al. (2013; Fig. 10). Sediment samples were ground using a mortar so that 0.250 g of the powder was mixed with 600 µL buffer (50 mM TRIS, pH 9) in a 2 mL reaction tube. The tubes were placed on a vortex and mixed for 30 min at maximum speed. Then, the sediment samples were centrifuged at 20 800 × g for 10 min and the supernatant was transferred to a 1.5 mL reaction tube. The extraction procedure was then repeated. The supernatants were combined, centrifuged and transferred to a clean tube. The fluorescein content was measured in triplicate using 96-well plates processed using a filter fluorometer (CLARIOstar® OPTIMA, BMG LABTECH, Germany). The quantification of fluorescein indicates that 5 out of 45 inner core samples (after inner-coring) were contaminated by drill mud. Generally sandy (highly permeable) samples showed a higher degree of contamination in comparison to clay-rich samples.

7 Initial core description

In total, 85 % of the 108.5 m hole was available in the form of core halves for inspection and sampling. Major gaps exist primarily in the uppermost 30 m. The core was split in half lengthwise and subsequently photographed at the GFZ Potsdam, followed by a visual core description. The recovered core is severely affected by drilling disturbance. Partly, it shows a conspicuous banding composed of relatively dark mudstones typically 2–5 cm thick and of lighter colored homogeneous and comparatively soft mud mostly 0.5–2.5 cm thick (Fig. 9g and f). Although the banding resembles rhythmic bedding, close inspection reveals that it results from the injection of drilling mud along preexisting bedding planes. Drilling mud was also injected into the core along subvertical, natural and drilling-induced fractures, while in the basal interval of the core the mud has intruded highly-altered or weathered mica schists. Thus, careful examination of the core is vital to identify artificial "false bedding" and to differentiate natural and drilling-induced deformation structures.

The core is composed of five units (Fig. 9):

The lowermost unit 1 from ∼ 108.5 to ∼ 89.8 m consists of highly altered or weathered Palaeozoic mica schists (Fig. 9a). According to preliminary XRD measurements, the schists are principally composed of kaolinite, muscovite/illite, siderite and quartz. Kaolinite likely has formed under near-surface weathering conditions during Mesozoic-Early Cenozoic time (Störr, 1976). The common presence of siderite might either be related to an alteration under reducing conditions and elevated $p\mathrm{CO_2}$, hence possibly to fluids rich in CO_2, or to a formation during the influence of an overlying freshwater swamp.

Unit 2 from ∼ 89.8 to ∼ 79.0 m is made up primarily of massive to crudely bedded grey to brown and sandy to peaty mudstones with abundant mottles and nodules (Fig. 9b). The mineralogy is dominated by kaolinite, siderite, quartz and anatase. Thin lignite layers and abundant lignite coal fragments as well as the presence of root structures and possible soil horizons suggest deposition in a swamp environment. The unit might represent the Main Seam Fm. (Lower Miocene).

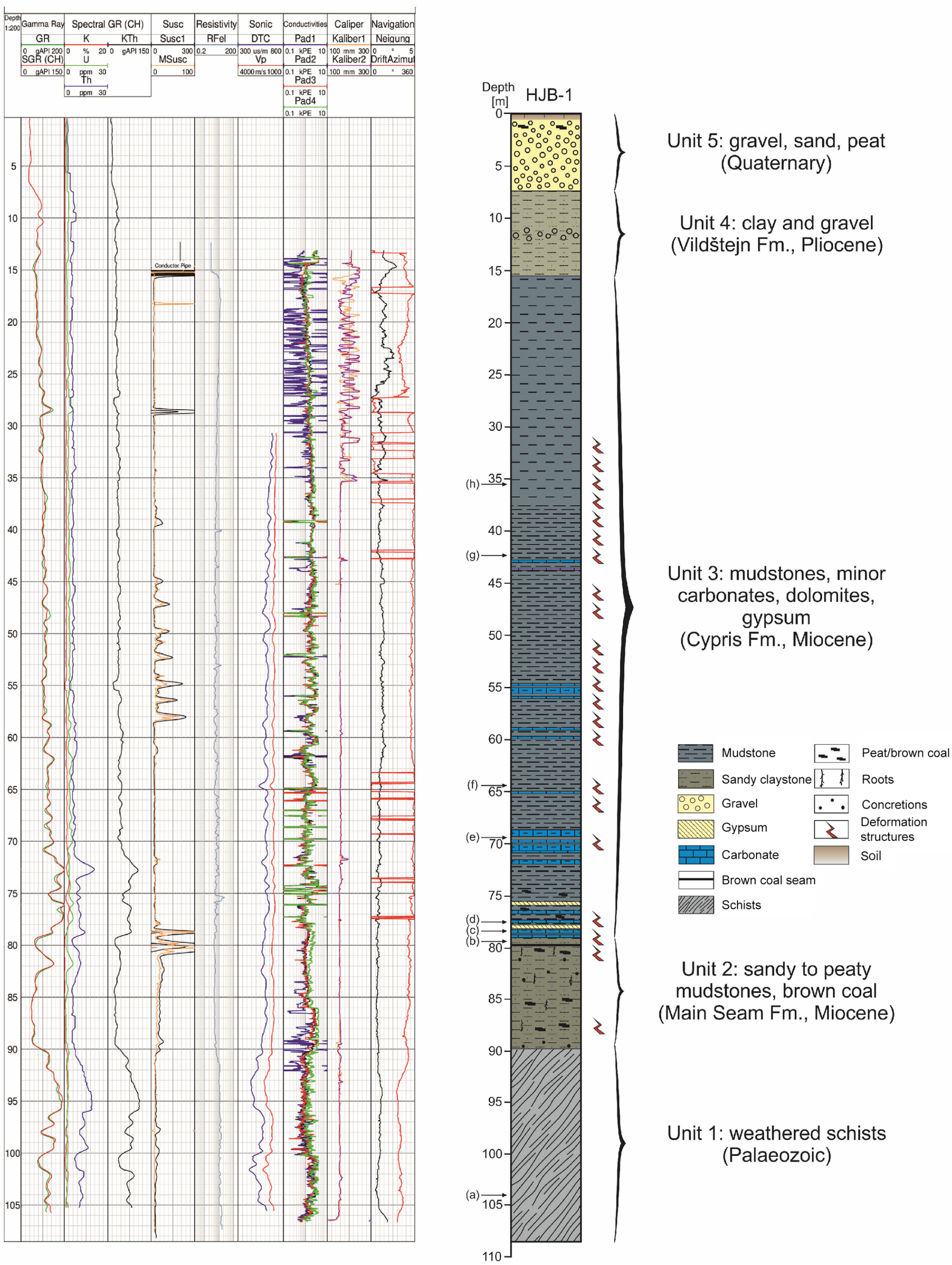

Figure 8. Logging data of well HJB-1 and summary stratigraphy based on initial core description results. Positions of cores in Fig. 9 are indicated by corresponding labels (a–h) and arrows.

Upward, following unit 3 from about 79.0 to ∼ 15.5 m is dominated by grey to green mudstones. The relatively heterogeneous lower part of the unit consists of calcareous, sandy or peaty mudstones that are interbedded with thin peloidal or bioclastic carbonates, dolomite beds and gypsum layers (Fig. 9c, d, e). The overlying part up to ∼ 37.5 m consists primarily of laminated or thin bedded mudstones (Fig. 8, while the uppermost part of the unit up to ∼ 15.5 m is made up of massive to crudely bedded mudstones. Laminated mudstones were most likely deposited in a relatively deep lake with dysoxic to anoxic bottom-water conditions. The planar lamination from a few millimeters up to 2 cm thick might have formed due to seasonal changes in the bioproductivity or in the water stratification, whereas thin detrital carbonate beds up to 5 cm thick possibly represent event layers such as turbidites. The mudstones of the whole core interval are made up of clay minerals such as muscovite/illite, kaolinite, smectite and mixed-layers, and of quartz, K-feldspars, pyrite,

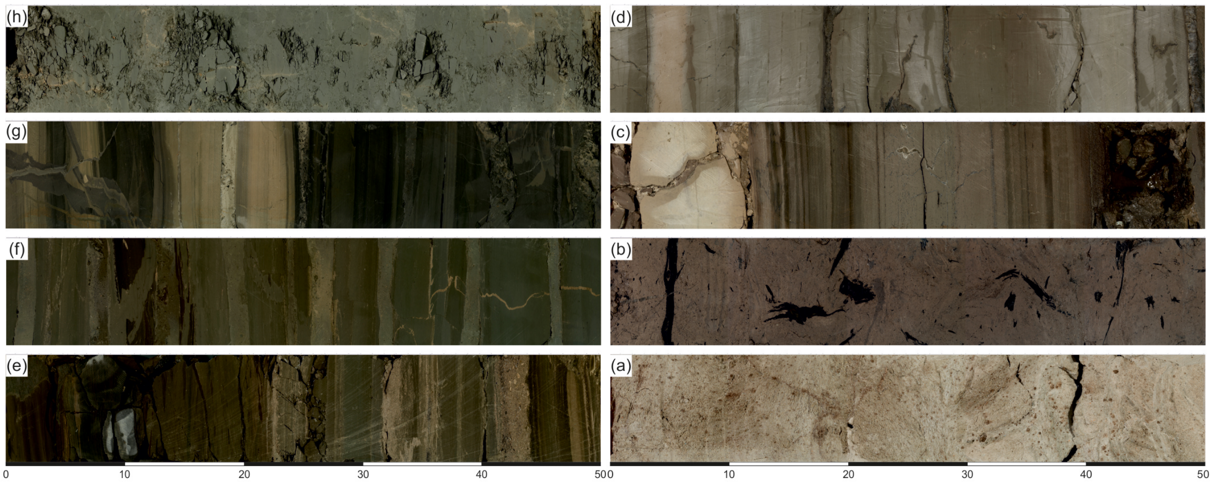

Figure 9. Representative lithologies in core HJB-1. **(a)** Palaeozoic schists with siderite concretions (104.16–104.66 m); **(b)** sandy mudstone with lignite coal (79.50–80.00 m); **(c)** interbedded sandy mudstones, calcareous mudstones and carbonates (78.50–79.00 m); **(d)** calcareous mudstones with gypsum layers and injection structures (77.61–78.11 m); **(e)** interbedded laminated mudstones and peloidal to bioclastic carbonates (69.56–70.06 m); **(f)** "false bedded" mudstones (light colored regular banding represents injected drilling mud) with natural injection structures (64.55–65.05 m); **(g)** laminated mudstones with natural deformation structures and "false bedding" (∼ 42.00–42.46 m and **(h)** massive mudstones (∼ 35.15–35.60 m). Scale is in centimeters.

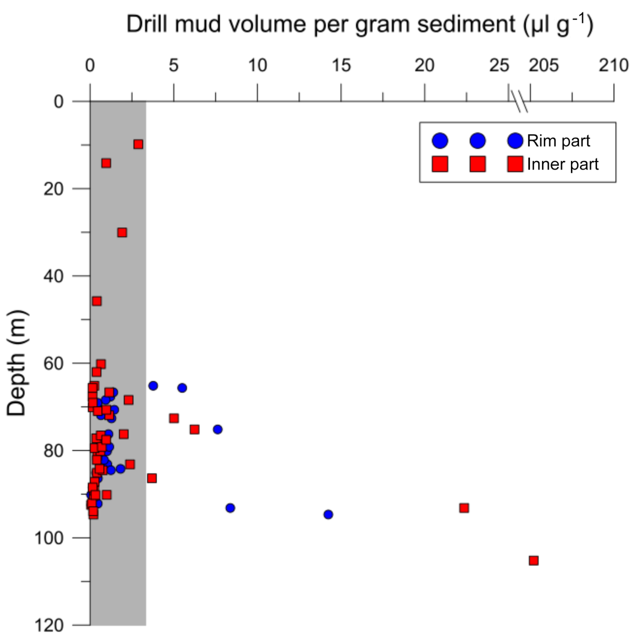

Figure 10. Contamination assessment of drill mud in cores. The grey area indicates the background noise of the fluorometric measurements of fluorescein (evaluated with core material obtained at the same site but without addition of fluorescein). 5 out of 45 inner core samples (red squares) are contaminated by drill mud.

zeolites, gypsum and analcime. Greigite occurs in several layers in the middle part of the mudstone interval according to petrophysical well site observation (magnetic susceptibility), but its presence is not yet confirmed by XRD. The presence of gypsum and analcime suggests a saline-alkaline lacustrine depositional environment, while the common occurrence of pyrite implies suboxic conditions during early diagenesis. However, the formation of these minerals might also be influenced by CO_2-rich fluids or microbial activity during diagenesis (e.g., Chen et al., 2016). The whole mudstone-dominated unit 3 likely correlates to the Cypris Fm.

Unit 4 between ∼ 15.5 and ∼ 7.2 m consists of green to brown clay and of minor gravel probably correlative to the Vildštejn Fm. Unit 5, representing the uppermost sediments down to a depth of ∼ 7.2 m, is made up of predominantly moderately to poorly sorted sand to gravel with minor peat, most likely Quaternary channel and floodplain deposits of the nearby Plesná river.

Natural deformation structures such as microfaults, dikes and sills as well as irregular intrusions are abundant in several core intervals but are best visible in the laminated mudstones of unit 3. Most of the structures seem to have formed by hydrofracturing, sediment fluidization and injection as a result of excessive pore fluid pressure. Carbonate and gypsum cements are infrequently associated with the deformation structures and the host rock in the surrounding partly has changed its color or is bleached. Whether the deformation structures, cements and color changes are related to the flow of CO_2-rich fluids is the subject of ongoing investigations.

8 Conclusions, ongoing studies and open questions

Pilot hole HJB-1 drilled into an active mofette has proved as a successful test for upcoming well projects planned in the scope of the ICDP project "Drilling the Eger Rift" (http://web.natur.cuni.cz/uhigug/icdp). First microbiological investigations including activity tests for microbial methane production, DNA extractions and cultivation experiments are ongoing. Microbial DNA was extractable from all samples and is currently analyzed through Illumina MiSeq 16S rDNA sequencing and quantitative PCR. A new procedure for the recovery of DNA from deep subsurface sediment samples was recently established by Alawi et al. (2014). With this method, DNA can be extracted from sediments with a low bacterial abundance, where commercial DNA extraction kits fail. Furthermore, with this technique it is possible to separate extracellular and intracellular DNA, and therefore to distinguish between fossil and modern microbial communities. Additionally, it is planned to perform community analyses based on Shotgun metagenomic sequencing for selected samples (in cooperation with P. Kyslik, Academy of Sciences of the Czech Republic). This method allows the identification of genes from all organisms present in the sediment, regardless of their taxa and specificity of PCR primers. For anaerobic culturing, the focus is set on methanogenic archaea and sulfate-reducing bacteria. Both metabolic groups are cultivated in a liquid anaerobic media and are inoculated inside an anaerobic chamber (glovebox). Growth is monitored by methane production and changing sulfate concentrations. Using different media compositions and temperatures, defined enrichment cultures have already been obtained and will be further characterized physiologically in detail. Pure cultures are a prerequisite for further laboratory experiments to gain deeper insights into the link to mineralogical processes such as mineral precipitation and alteration under varying conditions. Further on molecular biological analyses will be complemented by biomarker analyses at the Deutsches GeoForschungsZentrum GFZ (K. Mangelsdorf). Diversity of soil fungal communities will be analyzed by P. Baldrian (Academy of Sciences of the Czech Republic).

The core shows many features that might result from the flow of mantle-derived CO_2 e.g., deformation structures and alteration features, which are the subject of upcoming petrographic and geochemical studies. Further pending questions are to distinguish between Mesozoic–Cenozoic deep chemical weathering of Palaeozoic mica schists and alteration due to CO_2 flow or hydrothermal influence, the contribution of pyroclastics to the basin fill, and the palaeoenvironmental information contained in the Cenozoic lake sediments, in particular in the finely laminated (varved) interval of the Cypris Fm.

Ongoing geophysical studies, notably seismic (TU Freiberg), geoelectric (University of Leipzig) and magnetotelluric surveys (GFZ Potsdam) focus on examining the subsurface structure beneath the Hartoušov degassing area. The drill core from well HJB-1 provides essential information on the basin's sediments for these studies whereas the geophysical surveys will help to better understand the findings of the drill.

Data availability. The data used in this paper that stems from pilot hole HJB-1 are in the process of being interpreted in detail for various research targets. When these analyses are finished, and the related publications are submitted, the data will be deposited in reliable public depositories for access. However, at the current state of the projects the raw data cannot be made accessible for public use. When available, details of the data depositories can be obtained by contacting the corresponding author.

Competing interests. The authors declare that they have no conflict of interest.

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References

Alawi, M.: Microbes in geo-engineered systems: geomicrobiological aspects of CCS and Geothermal Energy Generation, in: Microbial Life of the Deep Biosphere, (Life in Extreme Environments), edited by: Kallmeyer, J. and Wagner, D., De Gruyter, Berlin, 203–224, 2014.

Alawi, M., Lerm, S., Vetter, A., Wolfgramm, M., Seibt, A., and Würdemann, H.: Diversity of sulfate-reducing bacteria in a plant using deep geothermal energy, Grundwasser, 16, 105–112, 2011.

Alawi, M., Schneider, B., and Kallmeyer, J.: A procedure for separate recovery of extra- and intracellular DNA from a single marine sediment sample, J. Microbiol. Meth., 104, 36–42, 2014.

Alawi, M., Nickschick, T., and Kämpf, H.: Mikrobiologische Prozesse in CO_2-Aufstiegskanälen, System Erde, 5, 28–33, https://doi.org/10.2312/GFZ.syserde.05.01.5, 2015.

Bankwitz, P., Schneider, G., Kämpf, H., and Bankwitz, E.: Structural characteristics of epicentral areas in Central Europe: study case Cheb Basin (Czech Republic), J. Geodyn., 35, 5–32, 2003.

Beulig, F., Heuer, V. B., Akob, D. M., Viehweger, B., Elvert, M., Herrmann, M., Hinrichs, K. U., and Küsel, K.: Carbon flow from volcanic CO_2 into soil microbial communities of a wetland mofette, ISME J., 9, 746–759, 2015.

Beulig, F., Urich, T., Nowak, M., Trumbore, S. E., Gleixner, G., Gilfillan, G. D., Fjelland, K. E., and Küsel, K.: Altered carbon turnover processes and microbiomes in soils under long-term extremely high CO_2 exposure, Nature Microbiol., 1, 15025, https://doi.org/10.1038/nmicrobiol.2015.25, 2016.

Bräuer, K., Kämpf, H., Strauch, G., and Weise, S. M.: Isotopic evidence ($^3He/^4He$, $^{13}C_{CO2}$) of fluid-triggered intraplate seismicity, J. Geophys. Res.-Sol. Ea., 108, 2070, https://doi.org/10.1029/2002JB002077, 2003.

Bräuer, K., Kämpf, H., Faber, E., Koch, U., Nitzsche, H.-M., and Strauch, G.: Seismically triggered microbial methane production relating to the Vogtland NW Bohemia earthquake swarm period 2000, Central Europe, Geochem. J., 39, 441–450, 2005.

Bräuer, K., Kämpf, H., Koch, U., Niedermann, S., and Strauch, G.: Seismically induced changes of the fluid signature detected by a multi-isotope approach (He, CO_2, CH_4, N_2) at the Wettinquelle, Bad Brambach (central Europe), J. Geophys. Res., 112, B04307, https://doi.org/10.1029/2006JB004404, 2007.

Bräuer, K., Kämpf, H., Niedermann, S., Strauch, G., and Tesař, J.: The natural laboratory NW Bohemia – comprehensive fluid studies between 1992 and 2005 used to trace geodynamic processes, Geochem. Geophys., 9, Q04018, https://doi.org/10.1029/2007GC001921, 2008.

Bräuer, K., Kämpf, H., Koch, U., and Strauch, G.: Monthly monitoring of gas and isotope compositions in the free gas phase at degassing locations close to the Nový Kostel focal zone in the western Eger Rift, Czech Republic, Chem. Geol., 290, 163–176, https://doi.org/10.1016/j.chemgeo.2011.09.012, 2011.

Bräuer, K., Kämpf, H., and Strauch, G.: Seismically triggered anomalies in the isotope signatures of mantle-derived gases detected at degassing sites along two neighbouring faults in NW Bohemia, central Europe, J. Geophys. Res.-Sol. Ea., 119, 5613–5632, 2014.

Chen, F., Turchyn, A., Kampman, N., Hodell, D., Gázquez, F., Maskell, A., and Bickle, M.: Isotopic analysis of sulfur cycling and gypsum vein formation in natural CO_2 reservoir, Chem. Geol., 436, 72–83, 2016.

Corciulo, M., Roux, P.-F., Campillo, M., Dubucq, D., and Kuperman, W. A.: Multiscale matched-field processing for noise-source localization in exploration geophysics, Geophysics, 77, 33–41, 2012.

Dahm, T., Fischer, T., and Hainzl, S.: Mechanical intrusion models and their implications for the possibility of magma-driven swarms in NW Bohemia Region, Stud. Geophys. Geod., 52, 529–548, 2008.

Dahm, T., Hrubcová, P., Fischer, T., Horálek, J., Korn, M., Buske, S., and Wagner, D.: Eger Rift ICDP: an observatory for study of non-volcanic, mid-crustal earthquake swarms and accompanying phenomena, Sci. Dril., 16, 93–99, https://doi.org/10.5194/sd-16-93-2013, 2013.

Deflaun, M. F., Fredrickson, J. K., Dong, H., Pfiffner, S. M., Onstott, T. C., Balkwill, D. L., Streger, S. H., Stackebrandt, E., Knoessen, S., and van Heerden, E.: Isolation and characterization of a *Geobacillus thermoleovorans* strain from an ultra-deep South African gold mine, Syst. Appl. Microbiol., 30, 152–164, 2007.

Dvořák, J.: Hydrogeology and the genesis of mineral waters of the Carlsbad type in western Bohemia, Münchner Geologische Hefte, B8, 63–69, 1998.

Egerter, H.-G., Plötner, G., Dvořák, J., and Jordan, H.: Geochemische Beziehungen in vogtländisch-westböhmischen Mineralwässern, Abhandlungen der Sächsischen Akademie der Wissenschaften zu Leipzig, mathematisch-naturwissenschaftliche Klasse, 56, 1–60, 1984.

Fiala, J. and Vejnar, Z.: The lithology, geochemistry, and metamorphic gradation of the crystalline basement of the Cheb (Eger) Tertiary Basin, Saxothuringian Unit, Bull. Geosci., 79, 41–52, 2004.

Fischer, T., Horálek, J., Hrubcová, P., Vavryčuk, V., Bräuer, K., and Kämpf, H.: Intracontinental earthquake swarms in west-Bohemia and Vogtland: A review, Tectonophysics, 611, 1–27, 2014.

Fischer, T., Matyskac, C., and Heinicke, J.: Earthquake-enhanced permeability – evidence from carbon dioxide release following the ML3.5 earthquake in West Bohemia, Earth Planet. Sc. Lett., 460, 60–67, https://doi.org/10.1016/j.epsl.2016.12.001, 2017.

Flechsig, Ch., Bussert, R., Rechner, J., Schütze, C., and Kämpf, H.: The Hartoušov Mofette Field in the Cheb Basin, Western Eger Rift (Czech Republic): a comparative geoelectric, sedimentologic and soil gas study of a magmatic diffuse degassing structure, Zeitschr. Geol. Wiss., 36, 177–193, 2008.

Flechsig, C., Fabig, T., Rücker, C., and Schütze, C.: Geoelectrical investigations in the Cheb basin/W-Bohemia: An approach to evaluate the near-surface conductivity structure, Stud. Geophys. Geod., 54, 417–437, 2010.

Flechsig, C., Heinicke, J., Mrlina, J., Kämpf, H., Nickschick, T., Schmidt, A., Günther, T., Rücker, C., and Seidel, E.: Integrated geophysical and geological methods to investigate the inner and outer structures of the Quaternary maar Mýtina (W-Bohemia Czech Republic), Int. J. Earth Sci., 104, 2087–2105, 2015.

Flores Estrella, H., Umlauft, J., Schmidt, A., and Korn, M.: Locating mofettes using seismic noise records from small dense arrays and matched field processing analysis in the NW Bohemia/Vogtland Region, Czech Republic, Near Surf. Geophys, 14, 327–335, 2016.

Fredrickson, J. K., McKinley, J. P., Bjornstad, B. N., Long, P. E., Ringelberg, D. B., White, D. C., Krumholz, L. R., Suflita, J. M., Colwell, F. S., Lehman, R. M., Phelps, T. J., and Onstott, T. C.: Pore-size constraints on the activity and survival of subsurface bacteria in a Late Cretaceous shale-sandstone sequence, northwestern New Mexico, Geomicrobiol. J., 14, 183–202, 1997.

Glombitza, C., Mangelsdorf, K., and Horsfield, B.: A novel procedure to detect low molecular weight compounds released by alkaline ester cleavage from low maturity coals to assess its feedstock potential for deep microbial life, Organic Geochem., 40, 175–183, 2009.

Goldscheider, N., Hunkeler, D., and Rossi, P.: Review: Microbial biocenoses in pristine aquifers and an assessment of investigative methods, Hydrogeol. J., 14, 926–941, 2006.

Günther, T. and Rücker, C.: Advanced inversion strategies using a new geophysical inversion and modelling library. Paper presented at the 15th European Meeting of Environmental and Engineering Geophysics, Dublin, Ireland, 7–9 September 2009.

Günther, Th., Rücker, C., and Spitzer, K.: Threedimensional modelling and inversion of dc resistivity data incorporating topography – II. Inversion, Geophys. J. Int., 166, 506–517, https://doi.org/10.1111/j.1365-246X.2006.03011.x, 2006.

Gulliver, D. M., Lowry, G. V., and Gregory, K. B.: Comparative study of effects of CO2 concentration and pH on microbial communities from a saline aquifer, a depleted oil reservoir, and a freshwater aquifer, Environ. Enginer. Sci., 33, 806–816, 2016.

Hecht, L., Vigneresse, J. L., and Morteani, G.: Constraints on the origin of zonation of the granite complexes in the Fichtelgebirge (Germany and Czech Republic): Evidence from a gravity and geochemical study, Geol. Rundsch., 86, 93–109, https://doi.org/10.1007/pl00014669, 1997.

Hubert, C., Loy, A., Nickel, M., Arnosti, C., Baranyi, C., Brüchert, V., Ferdelman, T., Finster, K., Christensen, F. M., de Rezende, J. R., Vandieken, V., and Jorgensen, B. B.: A constant flux of diverse thermophilic bacteria into the cold Arctic seabed, Science, 325, 1541–1544, 2009.

Kämpf, H., Strauch, G., Vogler, P., and Michler, W.: Hydrologic and hydrochemic changes associated with the December 1985/January 1986 earthquake swarm activity in the Vogtland/NW Bohemia seismic area, Z. Geol. Wissenschaft., 17, 685–698, 1989.

Kämpf, H., Peterek, A., Rohrmüller, J., Kümpel, H. J., and Geissler, W. H.: The KTB deep crustal laboratory and the western Eger Graben, in: GeoErlangen 2005/Exkursionsführer, edited by: Koch, R. and Röhling, H. G., Schriftreihe der Deutschen Gesellschaft für Geowissenschaften, 40, 37–108, 2005.

Kämpf, H., Geissler, W. H., and Bräuer, K.: Combined gas-geochemical and receiver function studies, of the Vogtland/NW-Bohemia intraplate mantle degassing field Central Europe, in: Mantle Plumes – A Multidisciplinary Approach, edited by: Ritter, J. R. R. and Christiansen, U. R., Springer-Verlag, Berlin-Heidelberg-New York, 127–158, 2007.

Kämpf, H., Bräuer, K., Schumann, J., Hahne, K., and Strauch, G.: CO_2 discharge in an active, non-volcanic continental rift area (Czech Republic): Characterisation (delta C-13, He-3/He-4) and quantification of diffuse and vent CO_2 emissions, Chem. Geol., 339, 71–83, https://doi.org/10.1016/j.chemgeo.2012.08.005, 2013.

Kallmeyer, J. and Wagner, D. (Eds.): Microbial Life of the Deep Biosphere, (Life in Extreme Environments; 1), Berlin, De Gruyter, XVII, 325 pp., 2014.

Lerm, S., Westphal, A., Miethling-Graff, R., Alawi, M., Seibt, A., Wolfgramm, M., and Würdemann, H.: Thermal effects on microbial composition and microbiologically induced corrosion and mineral precipitation affecting operation of a geothermal plant in a deep saline aquifer, Extremophiles, 17, 311–327, 2013.

Lomstein, B. A., Langerhuus, A. T., D'Hondt, S., Jorgensen, B. B., and Spivack, A. J.: Endospore abundance, microbial growth and necromass turnover in deep sub-seafloor sediment, Nature, 484, 101–104, 2012.

Malkovský, M.: The Mesozoic and Tertiary basins of the Bohemian Massif and their evolution, Tectonophysics 137, 31–42, 1987.

McMahon, P. B. and Chapelle, F. H.: Microbial production of organic acids in aquitard sediments and its role in aquifer geochemistry, Nature, 349, 233–235, 1991.

Mitchell, A. C., Phillips, A. J., Hiebert, R., Gerlach, R., Spangler, L. H., and Cunningham, A. B.: Biofilm enhanced geologic sequestration of supercritical CO2, Int. J. Greenh. Gas Control, 3, 90–99, 2009.

Morozova, D., Wandrey, M., Alawi, M., Zimmer, M., Vieth, A., Zettlitzer, M., Wurdemann, H., & Grp, C. S.: Monitoring of the microbial community composition in saline aquifers during CO2 storage by fluorescence in situ hybridisation. Int. J. Greenh. Gas Control, 4, 981–989, 2010.

Mrlina, J., Kämpf, H., Geissler, W. H., and van den Bogaard, P.: Proposed Quaternary maar structure at the Czech/German boundary between Mýtina and Neualbentreuth (western Eger Rift, Central Europe): geophysical, petrochemical and geochronological indications, Zeitschr. Geol. Wissenschaft., 35, 213–230, 2007.

Mrlina, J., Kämpf, H., Kroner, C., Mingram, J., Stebich, M., Bräuer, A., Geissler W.H., Kallmeyer, J., Matthes, H., and Seidl, M.: Discovery of the first Quaternary maar in the Bohemian Massif, Central Europe, based on combined geophysical and geological surveys, J. Volc. Geoth. Res., 182, 97–112, 2009.

Nickschick, T., Kämpf, H., Flechsig, Ch., Mrlina, J., and Heinicke, J.: CO_2 degassing in the Hartousov mofette area, western Eger Rift, imaged by CO_2 mapping and geoelectrical and gravity surveys, Int. J. Earth Sci., 104, 2107–2129, https://doi.org/10.1007/s00531-014-1140-4, 2015.

Nickschick, T., Flechsig, Ch., Meinel, C., Mrlina, J., and Kämpf, H.: Architecture and temporal variations of a terrestric CO_2 degassing site using electrical resistivity tomography and CO_2 gas measurements, Int. J. Earth Sci., https://doi.org/10.1007/s00531-017-1470-0, 2017.

Onstott, T. C.: Impact of CO_2 injections on deep subsurface microbial ecosystems and potential ramifications for the surface biosphere, in: Carbon Dioxide Capture for Storage in Deep Geologic Formations – Results from the CO_2 Capture Project, v. 2: Geologic Storage of Carbon Dioxide with Monitoring and Verification, edited by: Benson, S. M., Elsevier Science, London, 1217–1250, 2005.

Onstott, T. C., Phelps, T. J., Colwell, F. S., Ringelberg, D., White, D. C., Boone, D. R., McKinley, J. P., Stevens, T. O., Long, P. E., Balkwill, D. L., Griffin, W. T., and Kieft, T.: Observations pertaining to the origin and ecology of microorganisms recovered from the deep subsurface of Taylorsville Basin, Virginia, Geomicrobiol. J., 15, 353–385, 1998.

Paces, T. and Smejkal, V.: Magmatic and fossil components of thermal and mineral waters in the Eger River continental rift (Bohemian massif, central Europe), in: Water-Rock Interaction, edited by: Wanty, R. B. and Seal II., R. R., Taylor and Francis Group, London, 167–172, 2004.

Pellizzari, L., Neumann, D., Alawi, M., Voigt, D., Norden, B., and Wurdemann, H.: The use of tracers to assess drill-mud penetration depth into sandstone cores during deep drilling: method development and application, Environ. Earth Sci., 70, 3727–3738, 2013.

Pellizzari, L., Morozova, D., Neumann, D., Klapperer, S., Kasina, M., Zettlitzer, M., and Würdemann, H.: Comparison of the microbial community composition of the well and saline aquifer fluids and of rock cores at the Ketzin CO_2 storage site – results of geochemical and molecular biological characterisation, Environ. Earth Sci., 75, 1323, https://doi.org/10.1007/s12665-016-6111-6, 2016.

Pešek, J., Brož, B., Brzobohatý, R., Dašková, J., Doláková, N., Elznic, A., Fejfar. O., Franců, J. Hladilová, Š., Holcová, K., Honěk, J., Hoňková, K., Kvaček, J., Kvaček, Z., Macůrek, V., Mikuláš, R., Opluštil, S., Rojík, P., Spudil, J., Svobodová, M., Sýkorová, I., Švábenická, L., Teodoridis, V., and Tomanová-Petrová, P.: Tertiary basins and lignite deposits of the Czech Republic, Czech Geological Survey, Prague, 260 pp., 2014.

Peterek, A., Reuther, C. D., and Schunk, R.: Neotectonic evolution of the Cheb Basin (Northwestern Bohemia, Czech Republic) and its implications for the late Pliocene to Recent crustal deformation in the western part of the Eger Rift, Zeitschr. Geol. Wissenschaft., 349, 335–365, 2011.

Rajchl, M., Uličný, D., Grygar, R., and Mach, K.: Evolution of basin architecture in an incipient continental rift: the Cenozoic Most Basin, Eger Graben (Central Europe), Basin Res., 21, 269–294, 2009.

Rempel, K. U., Liebscher, A., Heinrich, W., and Schettler, G.: An experimental investigation of trace element dissolution in carbon dioxide: Applications to the geological storage of CO_2, Chem. Geol., 289, 224–234, 2011.

Rennert, T. and Pfanz, H.: Hypoxic and acidic soils on mofette fields, Geoderma, 280, 73–81, https://doi.org/10.1016/j.geoderma.2016.06.019, 2016.

Rojik, P.: New stratigraphic subdivision of the Tertiary in the Sokolov Basin in Northwestern Bohemia, J. Czech Geol. Survey, 49, 173–185, 2004.

Sauer, P., Glombitza, C., and Kallmeyer, J.: A system for incubations at high gas partial pressure, Front. Microbiol., 3, 1–9, 2012.

Schuessler, J. A., Kämpf, H., Koch, U., and Alawi, M.: Earthquake impact on iron isotope signatures recorded in mineral spring water, J. Geophys. Res., 121, 8548–8568, 2016.

Schütze, C., Sauer, U., Beyer, K., Lamert, H., Bräuer, K., Strauch, G., Flechsig, C., Kämpf, H., and Dietrich, P.: Natural analogues: a potential approach for developing reliable monitoring methods to understand subsurface CO_2 migration processes, Environ. Earth Sci., 67, 411–423, https://doi.org/10.1007/s12665-012-1701-4 2012.

Špičáková, A., Ulčny, D., and Kouldelková, G.: Tectonosedimentary evolution of the Cheb Basin (NW Bohemia, Czech Republic) between Oligocene and Pliocene: a preliminary note, Stud. Geophys. Geod., 44, 556–580, 2000.

Störr, M.: Zur Kenntnis der jungmesozoisch–tertiären Formation der Verwitterungskruste in der DDR, Schriftenreihe geologische Wissenschaften, 5, 231–241, 1976.

Takai, K., Moser, D. P., Onstott, T. C., Spoelstra, N., Pfiffner, S. M., Dohnalkova, A., and Fredrickson, J. K.: *Alkaliphilus transvaalensis* gen. nov., sp. nov., an extremely alkaliphilic bacterium isolated from a deep South African gold mine, Int. J. Syst. Evol. Microbiol., 51, 1245–1256, 2001.

Trimarco, E., Balkwill, D., Davidson, M., and Onstott, T. C.: In situ enrichment of a diverse community of bacteria from a 4–5 km deep fault zone in South Africa, Geomicrobiol. J., 23, 463–473, 2006.

Ulrych, J., Krmíček, L., Tomek, Č., Lloyd, F. E., Ladenberger A., Ackerman, L., and Balogh, K.: Petrogenesis of Miocene alkaline volcanic suites from western Bohemia: whole rock geochemistry and Sr–Nd–Pb isotopic signatures, Chem. Erde-Geochem., 76, 77–93, 2016.

Vandemeulebrouck, J., Roux, P., Gouédard, P., Legaz, A., Revil, A., Hurst, A. W., Boléve, A., and Jardani, A.: Application of acoustic noise and self-potential localization techniques to a buried hydrothermal vent (Waimangu Old Geyser site, New Zealand), Geophys. J. Int., 180, 883–890, 2010.

Wagner, C., Mau, M., Schloemann, M., Heinicke, J., and Koch, U.: Characterization of the bacterial flora in mineral waters in upstreaming fluids of deep igneous rock aquifers, J. Geophys. Res., 112, G01003, https://doi.org/10.1029/2005JG000105, 2007.

Youssef, N., Elshahed, M. S., and McInerney, M. J.: Chapter 6 Microbial processes in oil fields: culprits, problems, and opportunities, in: Advances in Applied Microbiology, edited by: Allen, S. S., Laskin, I., and Geoffrey, M. G., Academic Press, 141–251, 2009.

Zhang, G., Dong, H., Xu, Z., Zhao, D., and Zhang, C.: Microbial diversity in ultra-high-pressure rocks and fluids from the Chinese Continental Scientific Drilling Project in China, Appl. Environ. Microbiol., 71, 3213–3227, 2005.