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The Geology of the CO_2SINK Site: From Regional Scale to Laboratory Scale

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Abstract

Here we report on the framework of geological site exploration, which encompassed investigations at different scales prior to and after the drilling of the three CO_2SINK boreholes. Past and new exploration data are integrated to delineate at regional scale (1) the geological structure of CO_2 storage formation and its overburden, including fault systems as potential fluid pathways and (2) the shallow hydrogeology and the groundwater flow directions for an assessment of effects in case of CO_2 leakage and migration. The poro-perm facies and mineralogical composition of the CO_2 reservoir rock and the top seal formation were studied by routine and special core analyses, including the measurement of porosity, gas and brine permeability, and by XRD analysis.

geological exploration, geological structure, lithology, 3D seismics, reservoir properties, caprock properties

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1. Introduction

The CO_2SINK project at the German town of Ketzin is aimed at a pilot CO_2 storage in a gentle anticline in the North German Basin. Since summer 2008, CO_2 is injected as a supercritical fluid in the CO2 Ktzi 201/2007 injection well. The total amount of injected CO_2 will at least be on the order of 60,000 t. Two observation wells (CO2 Ktzi 200/2007 and CO2 Ktzi 202/2007) were drilled to support the geological exploration of the site and later on observe the break through of the CO_2 in the storage formation. The three CO_2SINK wells provided a wealth of information and will be the used for downhole geophysical and geochemical monitoring in conjunction with surface geophysical surveys to observe and understand the complex processes at multiple scales involved in the injection and dissipation of the CO_2. Experience gained with the Ketzin storage will guide the development of the best

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practice in planning, performing and abandoning of geological storage projects and to advance the science on subsurface processes.

2. Regional geological structure

The CO_2SINK storage site is located at the southern flank of a gently dipping anticline, which formed above a salt pillow situated at a depth of 1500−2000 m. The target formation for CO_2 injection is the Stuttgart Formation of Triassic age, located at a depth of about 650 m (Fig. 1). The overburden of the storage formation contains several aquifers and aquitards. The top seal of the Stuttgart Formation is the Triassic Weser Formation.

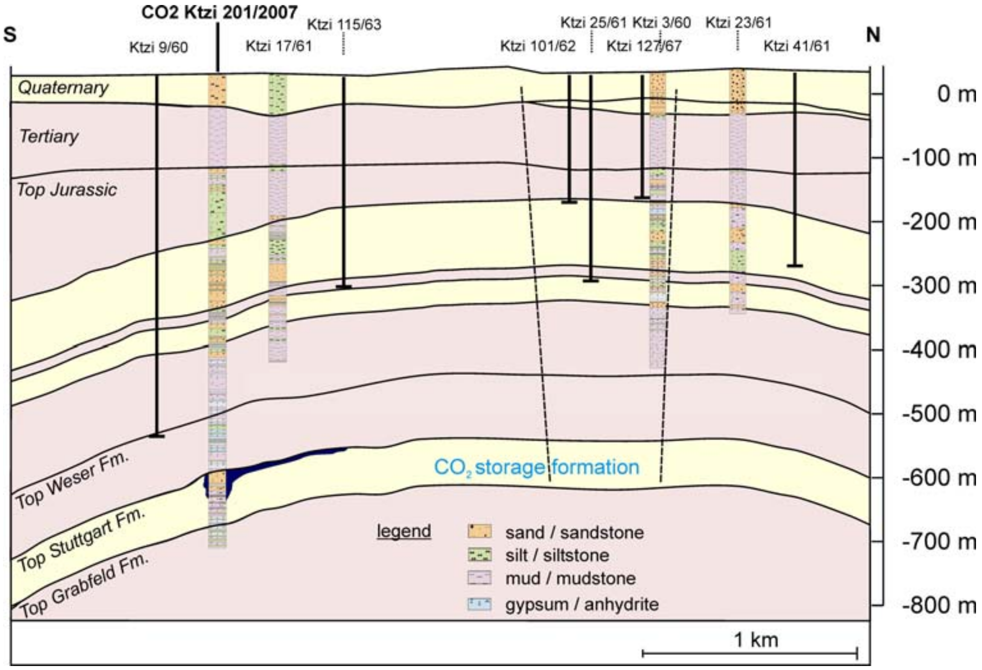

Fig. 1. Simplified geology of the Ketzin anticline with aquifer (light yellow) and aquitard (pink) units. Detailed lithology is shown for selected boreholes including the CO2 Ktzi 201/2007 injection well. The location of major faults (see also Fig. 3) is indicated by dashed lines. The predicted extension of 60, 000 t-injected CO_2 is shown in dark blue.

A 3D seismic survey over the Ketzin anticline (Fig. 2), performed as a baseline for future surveys of the CO_2 extension, provided new information on existing faults that was insufficiently known from previous reconnaissance 2-D seismic exploration. The 3D seismics clearly shows a fault system across the top of the anticline [1] that is termed the Central Graben Fault Zone (CGFZ). The fault zone consists of west-southwest−east-northeast- to east−west-trending normal faults bounding a 600−800 m wide graben (Fig. 3A). The discrete faults are well developed in the Jurassic section, where the main graben-bounding faults have throws of up to 30 m. The fault system seems to die out in the Tertiary Rupelian clay. The CGFZ, or at least its main bounding faults, can be recognized down to the top of the Weser Formation (K2 horizon, Fig. 3B) and possibly to the Stuttgart level.

With the aid of ECLIPSE 100 [*Schlumberger GeoQuest* 2000] a first reservoir-scale model of the medium-term CO_2 spatial distribution was developed for the Ketzin anticline [2] in order to mainly evaluate the supposed extension of the CO_2 plume with respect to existing faults. In the vertical dimension, the model extends over the

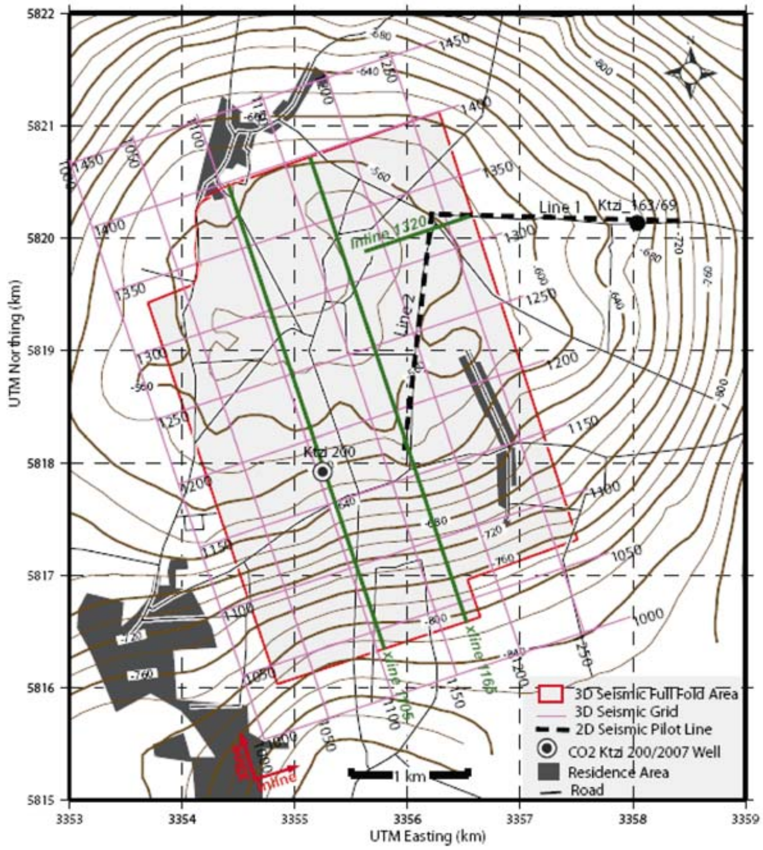

Fig. 2. Structure of the Ketzin anticline, indicated by the depth of the K2 (Top of Weser Fm.) seismic reflector, overlain by the 3D seismic survey area with the system of inlines and crosslines (from [3]). The locations of the CO2 Ktzi 200/2007 and the Ktzi 163/69 boreholes are marked.

reservoir formation of 80 m thickness. The ECLIPSE 100 program, a black oil reservoir simulation program for oil and gas reservoir management, was employed by attributing brine and CO_2 properties to the simulator's oil and gas phases, respectively. The phase behavior is described by black-oil PVT (pressure-volume-temperature) tables that are interogated during the simulation run. The solubility of brine in CO_2 is considered negligible and was not taken into account. CO_2 is injected into the reservoir at a continuous rate of 0.76 kg/s during 2.5 yrs (total of 60,000 tons). Injection is then stopped and the spread of CO_2 is followed for up to 20 yrs after injection commenced. CO_2 migration is mapped by the saturation of CO_2. From this model it can be concluded that the maximum extension of injected CO_2 in the subsurface (Fig. 1) does not reach the major fault system of the CGFZ.

In the larger Ketzin area, two major erosional troughs are incised into the Tertiary clay aquitard and into the Jurassic [4] and are filled with Quaternary sediments (Fig. 4). The troughs cutting through the uppermost clay barrier allow saline water to ascend and mix with freshwater in shallow aquifers. To assess the impact on CO_2 leakage into shallow saline aquifers and further up into the freshwater system, a groundwater-flow model was generated, honoring the complexity in the geological structure of the Quaternary known from borehole data and regional studies. The layering of different lithotypes in the Cenozoic also is resolved in a 3D seismic tomography section. Comparison with repeated surveys after the end of the project could help to decipher whether CO_2 leakage has occurred at Ketzin up to the shallow subsurface.

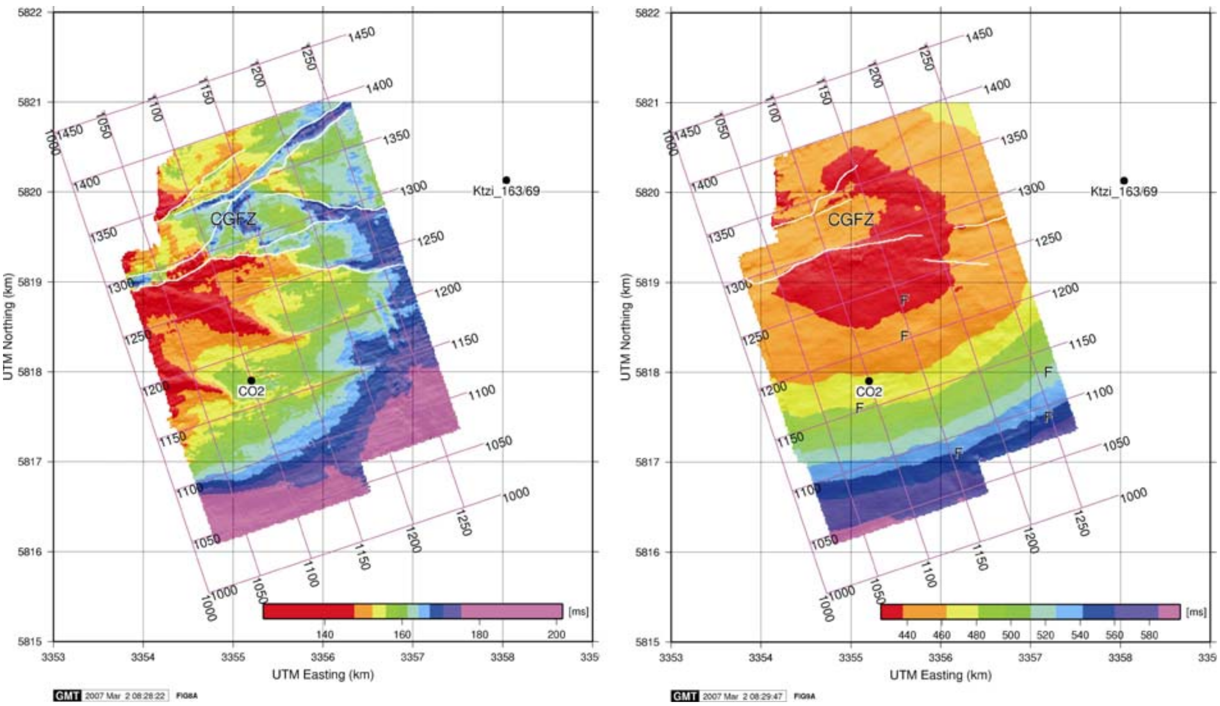

Fig. 3. Time horizon maps from the 3D seismic survey [1] with the CGFZ and the CO_2SINK drill site marked as CO_2. Left, map of the T1 reflector (near base Tertiary); right, map of the K2 reflector (top Weser Fm.), which is about 80 m above the top of the Stuttgart Formation.

3. Reservoir and top seal lithology

The Stuttgart Formation is of fluvial origin and exhibits a heterogeneous lithology. Sandy channel-(string)-facies as well as levee and crevasse-splay deposits alternate with muddy, flood-plain facies rocks [5], [6]. For a detailed lithological description of the formation at Ketzin, a total of 143 m core was drilled in the three CO_2SINK project wells. While the entire Stuttgart Formation was cored in the CO2 Ktzi 200/2007 and CO2 Ktzi 201/2007 wells, only the uppermost part (18.5 m) of the Stuttgart Formation was cored in the CO2 Ktzi 202/2007 well. The three wells, about 50–100 m apart, show a different lithostratification of the Stuttgart Formation, attesting lateral changes and cyclicity in fluvial sedimentation (Fig. 5). In the CO2 Ktzi 200/2007 borehole, for example, the bottom part of the Stuttgart Formation is composed of siltstone (698–699 m) overlain by a silty mudstone. A second fluvial cycle starts with sandstone, developed at 692–693 m, and is overlain by mudstones, which shows oxidized remnants of biogenic material and paleosoil according to observations by [7]. The upper part of the 2nd cycle contains a 0.5-m-thick coal. The basal part of the 3rd cycle is composed of mudstone interbedded by sandstone (668–673 m) and is overlain by a 14-m-thick mudstone. A 4th cycle contains at 652–654 m a fine-grained sandstone overlain by 2 m mudstone. The uppermost part of the Stuttgart Formation is composed of a 14-m-thick, fine-grained, cross-bedded channel sandstone (Fig. 6) underlain by a 2-m-thick siltstone and overlain by a thin mudstone (5th cycle). The fluvial sandstones are fine-grained to medium-grained and well-sorted.

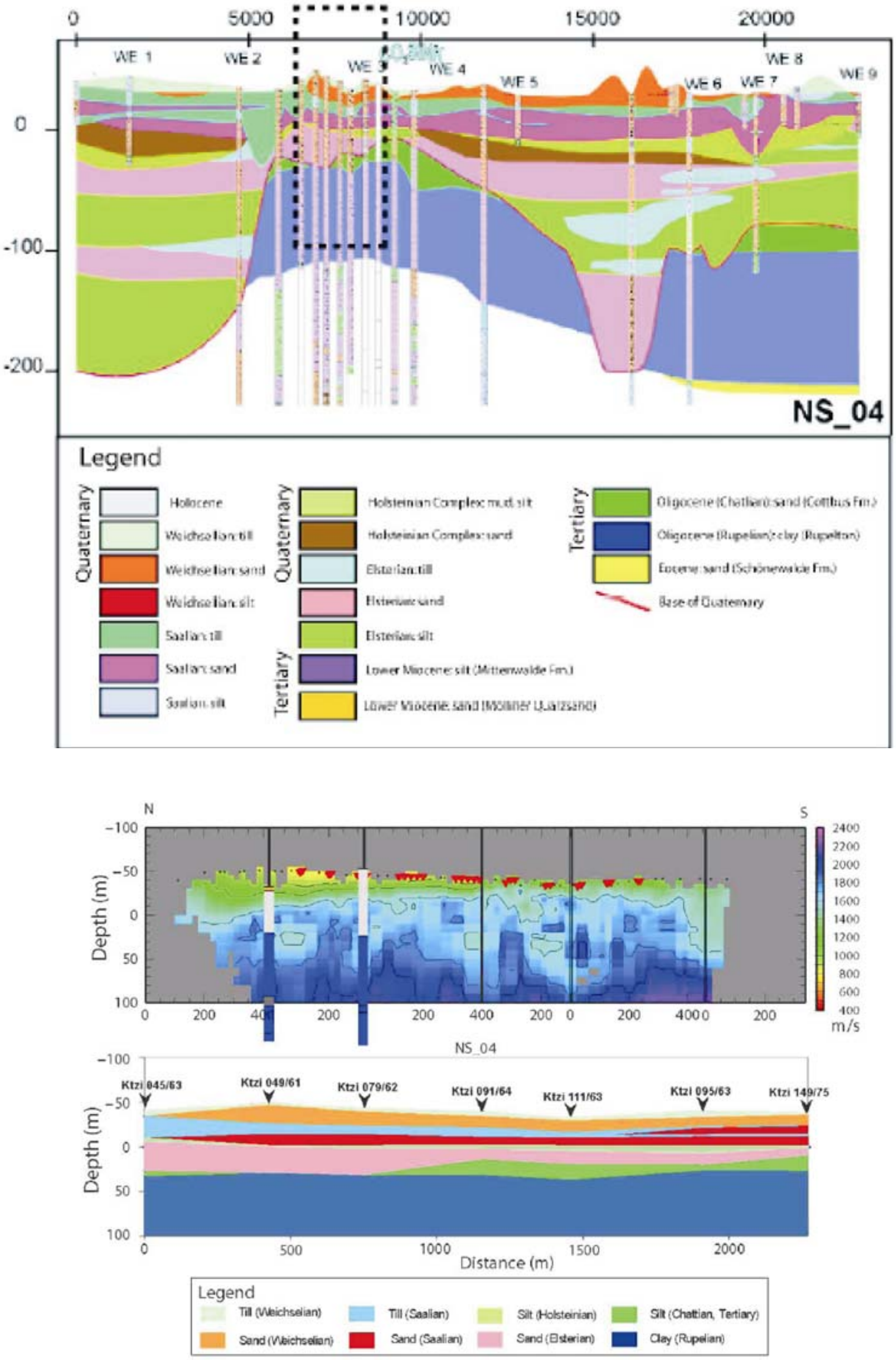

Fig. 4. Upper, schematic hydrogeological cross section through the shallow subsurface of the larger Ketzin area [8]. Dashed line window encloses that area of the 3D seismic survey and therewith the portion of the section shown at larger scale in lower figure. Lower, comparison of tomographic section with borehole section along NS_04 (upper figure) [8].

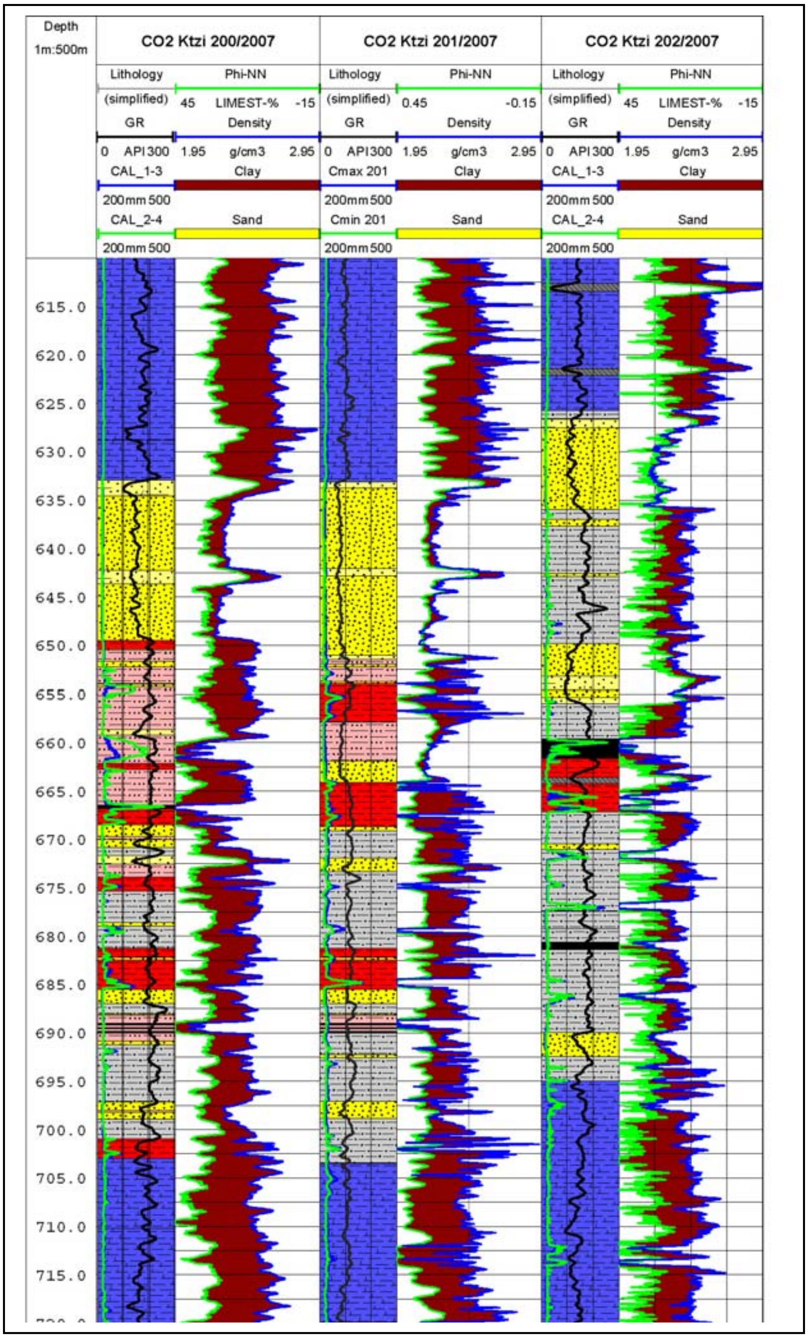

Fig. 5. Simplified litho-logs for Stuttgart Formation section and lowermost part of Weser Formation from core description and well-log response.

The top seal of the CO_2 storage formation, the Weser Formation, deposited in a clay/mud-sulfate playa environment [6], consists mostly of mudstone, clayey siltstone, and anhydrite as observed on well logs and on 30 m core obtained in the CO2 Ktzi 200/2007 and CO2 Ktzi 201/2007 wells (Fig. 5).

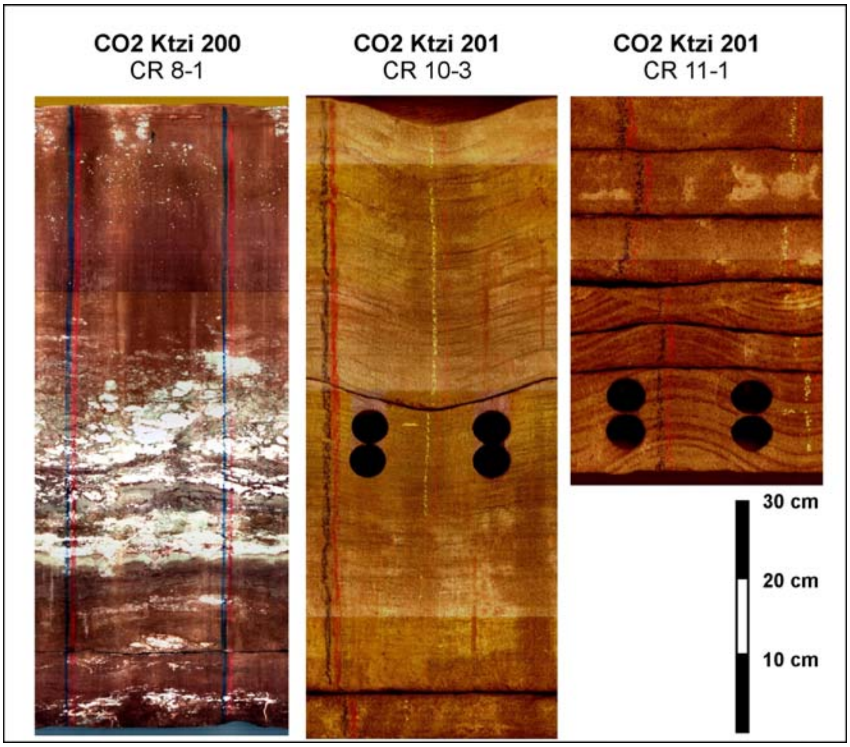

Fig. 6. Unrolled core scan images. Left: 623.10−623.90 m (anhydritic mudstone of the Weser Formation), center: 646.65−647.45 m (sandstone of the Stuttgart Formation), right: 647.80−648.30 m (sandstone of the Stuttgart Formation).

4. Mineralogy and poro-perm facies

The sandstones of the Stuttgart Formation are composed (in wt% ± 1σ stdw) of quartz (36.6 ± 6.1), plagioclase (17.2 ± 2.8), illite (16.0 ± 10.4), anhydrite (8.9 ± 12.8), amorphous phases (5.5 ± 4.1), orthoclase (4.6 ± 1.8), analcime (4.6 ± 3.2), chlorite (2.9 ± 1.4), halite (2.1 ± 1.6), hematite (0.8 ± 1.0), dolomite (0.4 ± 1.3), and pyrite (0.2 ± 0.8). Routine laboratory analysis of these sandstones shows variable He-porosity and brine-permeability ranging from 5 to >35% and from 0.02 mD to >5000 mD, respectively. Brine permeabilities were calculated using a correction function between gas-permeability and brine permeability values derived from measurements on a subset of core plugs.

The mudstones in the cored section consist (in wt% ± 1σ stdw) illite (46.7 ± 9.7), dolomite (19.3 ± 7.1), anhydrite (15.6 ± 17.7), quartz (13.5 ± 3.5), plagioclase (4.7 ± 2.2), chlorite (2.6 ± 0.3), hematite (1.0 ± 0.6), amorphous phases (1.6 ± 2.3), orthoclase (1.4 ±0.7), and halite (1.0 ± 0.3). Ambient He-porosity of the mudstones ranges from 5 to 15% and is on average 12 % ± 3 (1σ stdw). The higher values (>10 %) are observed in rocks exhibiting fine fractures. The average gas-permeability is 0.010 mD, no significant correlation is observed between gas permeability and porosity. Both porosity and permeability are mainly controlled by fractures and the dolomite/anhydrite cementation. Pore bodies and pore throats are small (<500 nm and 10−36 nm, respectively), and the pore space is usually unconnected. The high clay-mineral content and the observed pore-space geometry attest good sealing properties.

5. Summary and outlook

The three CO_2SINK boreholes with their extensive core recovery provided valuable information on the geology of the reservoir and seal and their hydraulic parameters. An integrated interpretation of the core data and the data from an extensive logging program is ahead, which forms the input for verification of the geological reservoir model for dynamic modeling of the CO_2 migration at Ketzin.

Acknowledgements

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