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Results of borehole logging in CO2 wells,
Dh1-CO2-07 and Dh2-CO2-07,
Longyearbyen, Svalbard

NGU
Norges geologiske undersøkelse
Geological Survey of Norway

Geological Survey of Norway
NO-7441 Trondheim, Norway
Tel.: 47 73 90 40 00
Telefax 47 73 92 16 20

REPORT

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Title:
Results of borehole logging in CO2 wells, Dh1-CO2-07 and Dh2-CO2-07, Longyearbyen, Svalbard

Authors: Harald Elvebakk	Client: UNIS
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Summary:

NGU has carried out borehole logging in two wells just outside Longyearbyen. The wells were drilled to locate deep reservoir sandstone formations which may store CO_2 from the local coal combusting power plant. Logging parameters were temperature, fluid conductivity, natural gamma, rock resistivity, seismic velocity, caliper, relative density and borehole deviation. Both wells were logged to a depth of 440 m. Deeper parts were blocked. Blocking is related to cut drill string in a 25 m thick fault zone of highly fractured shale that collapsed. Therefore there was no logging performed in the deepest part of the wells (820m). The well did not reach the main reservoir that was planned to be in Late Triassic sandstone.

The various logging results show good correlation between the geophysical logs and the lithological units. Sandstones are indicated with low gamma radiation, and increasing seismic velocity and apparent resistivity. However, more on actual results the prosperities of the most suitable formation for CO_2 storage could not be mapped in these wells. This will be done in a new well in Adventdalen which is to be drilled August 2008.

Coordinates:

Well	UTM-East 33X	UTM-North 33X
Dh1-CO2-07	512445	8684766
Dh2-CO2-07	512417	8684774

Keywords: Geophysics	Borehole logging	Resistivity
Seismic velocity	Temperature	Fluid conductivity
Natural Gamma	Deviation	Density

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1. INTRODUCTION

In Longyearbyen, Svalbard, all electrical energy is produced by a coal combusting power plant. The power plant is emitting about 25 000 tons of CO_2 a year. A research programme initiated by the University Centre in Svalbard (UNIS) has a vision to make Longyearbyen free of man-made CO_2. This will be done by capturing and storing the CO_2 in deep sandstone formations below the surface near Longyearbyen. Two wells were drilled in 2007 to locate suitable reservoirs (sandstones) for CO_2 injection. Significant problems caused by a 25 m thick fault zone of highly fractured shale at 450 m depth caused stability problems, and in the end stopped the drilling at 850 m depth in well Dh2-CO2-07. The well failed to reach the main reservoir that is prognosed to be in Late Triassic sandstone. Previous to this well, a well Dh1-CO2-07 was drilled to 518 m depth. Also this well failed for the same reason.

Borehole logging has been carried out by NGU in both wells down to 440 m depth. The risk for losing the logging tools was deemed too high by logging through the fault zone, especially since both wells have cut drill string located at this level. The logging parameters were temperature, fluid conductivity, natural gamma, rock resistivity, seismic velocity, caliper, relative density and borehole deviation.

The logging was carried out 04.12.07 – 07.12.07 by Harald Elvebakk, NGU, assisted by Malte Jochmann, SNSK.

Figure 1. Borehole location close to Longyearbyen. The blue tower hosts the drill rig.

2. BOREHOLE LOCATION

The CO2 wells are located just outside Longyearbyen close to the main road to Longyearbyen Airport, see figure 1. Both wells were drilled close to the shore in order to find water for drill bit lubrication and cooling. With respect to aquifer quality saline groundwater was found in both wells. Further the groundwater level coincides with the tide water level variation. Well data are shown in table 1. Borehole UTM-coordinates come from handhold GPS (WGS-84).

Tabel 1. Well data

Well	Drilled depth(m)	Logging depth (m)	Drilling finished	Logging date	UTM-East 33X	UTM-North 33X
Dh1-CO2-07	517.8	440	05.10.07	06/07.12.07	512445	8684766
Dh2-CO2-07	856.3	440	03.12.07	04/05.12.07	512417	8684774

The well diameter of Dh1-CO2-07 was 56 mm. Because of the problems encountered in the fault zone the second well was performed as a telescope drilling. Hence the first 550 m of Dh2-CO2-07 was drilled with a diameter of 66 mm. In deeper parts the diameter was 56 mm using the 66 mm drill string as casing through the fault zone. There were no problems with permafrost and frozen water in the boreholes.

3. LOGGING PARAMETERS

The logging parameters monitored by various tools were temperature, fluid conductivity, natural gamma, rock resistivity, seismic velocity, caliper, relative density and borehole deviation. The logging equipment is produced by Robertson Geologging Ltd. (http://www.geologging.com/).
The caliper and density probe belonged to SNSK. A description of the other probes (NGU) can be found on NGU's web site:
http://www.ngu.no/no/hm/Norges-geologi/Geofysikk/Borehullsgeofysikk/

3.1 Temperature

Temperature measurements should ideally be performed a long time after the drilling stops, since the energy from the drilling process (drilling water, rock crushing, and friction) will increase the temperature in the borehole. Stabilizing the temperature may take several weeks depending on the drilling method and borehole diameter. Commonly the upper 25-30 m of a borehole will be influenced by season variations in the surface temperature. From the temperature log the temperature gradient (^{o}C/km) can be calculated. Local changes in the gradient may indicate fractures and related inflow of water.

3.2 Conductivity

The fluid conductivity (µS/cm) depends on the fluid salinity. The conductivity measurements can identify zones of water in-flow/out-flow and locate zones of different water quality. The measured values are temperature compensated to a reference temperature of 25 ^{o}C. In the CO2 boreholes the conductivity is very high, caused both by the saline drilling water and by saline groundwater.

3.3 Natural Gamma

The natural gamma log (cps) is useful for geological mapping along walls of a borehole. All rocks contain small quantities of radioactive material, in that certain minerals contain trace amounts of Uranium and Thorium. Potassium-bearing minerals (most common) will include traces of a radioactive isotope of Potassium (K_{40}). Natural gamma measurements are useful because the radioactive elements are concentrated in certain rock types, e.g. clay, shale and granite, and depleted in others, e.g. sandstone and coal.

3.4 Resistivity

Resistivity logging in boreholes is extensively used in hydrocarbon exploration of sedimentary rocks both to identify lithological boundaries and to estimate the rock porosity. The resistivity depends on porosity and fractures (water content), content of sulphide minerals and clay. Saline pore water will influence on the apparent resistivity. The resistivity data are processed by using a program that corrects borehole resistivity logging data for the influence of the borehole liquid (Thunehed & Olsson 2004).

3.5 Seismic velocity

The sonic probe has one transmitter and two receivers that records the full sonic wave-train at both receivers simultaneously and also the velocity of the first arrival. Both P-velocity (compression) and S-velocity (shear wave) are calculated every 20 cm. Data are filtered using a running average filter over 0.8 m.The first arrival of the P-wave is quite easy to pick while the arrival of the S-wave is more indistinct. P-velocity (formation velocity) is used for lithological identification and fracture mapping. The quality of the P-wave data in the CO2 wells was good. Data processing is done by using software from ALT (ALT 2006).

3.6 Caliper

The three-arm caliper probe (from SNSK) provides a single continuous log of borehole diameter. The applications of the caliper measurements are location of cracks, fissures, caving, faulting and casing breaks. It is also used for correction of other logs affected by borehole diameter.

3.7 Density (qualitative measurements)

The trisonde density probe (from SNSK) is a convenient alternative to the standard RG sidewall density probe whenever borehole diameter is restricted and qualitative density measurements are sufficient. The trisonde log can be used for lithological identification, bed thickness and boundary location based on relative changes in the density.

3.8 Deviation

The RG verticality probe provides accurate, continuous measurements of borehole inclination and direction. The probe includes a triaxial magnetometer for measuring the borehole orientation and three accelerometers to measure inclination. From this the East and North deviation components are calculated.

4. RESULTS

The logs are presented as continuous plots including several parameters. Four plots are made for each well:

- P-velocity, S-velocity, Natural Gamma, Resistivity, Porosity, Caliper and Density
- Temperature, temperature gradients (20 m and 100 m depth intervals)
- Temperature, fluid conductivity, pH, Eh and O2
- Deviation, North- and East projection and horizontal projection (direction)

The sonic data were processed using the WellCad software from ALT (ALT 2006). The resistivity data were processed by using a program that corrects borehole resistivity logging data for the influence of the borehole liquid conductivity (Thunehed & Olsson 2004). This program also calculates an apparent porosity with the help of a slightly modified version of Archie's law (Thunehed & Olsson 2004), (Archie 1942).

The temperature gradients are calculated using running least-squares gradients of a straight line with depth intervals of 20 m and 100 m. In such analysis the 20 m interval is more sensitive to local variations in the temperature.

This report presents all the logged and processed data from both wells. No detailed interpretation of the lithological units is performed. General comments regarding borehole logging interpretations are mentioned.

4.1 Dh2-CO2-07

Well Dh2-CO2-07 was the second bore hole, which was drilled to 856.3 m. The well did not reach the main reservoir (sandstone) because of well collapse in the mentioned fault zone (450 m -475 m). The well was logged to 440 m.

Figure 2 shows the logs of P-velocity, S-velocity, natural gamma, resistivity, porosity, caliper and qualitative density. Except for the upper 175 m of S-velocity data the data quality is god for all logs. Different geological units can be recognized on most of the logs. This is shown in figure 3 where some of the main rock types are indicated on the same logs as in figure 2. The sediment logs (Atle Mørk, pers. com.) are more detailed, but the most typical lithological units show up in figure 3.

The P-velocity log is indicating P-velocities of 3500 – 4500 m/s. Average velocities for the three main units are: sandstone – 4500 m /s, mud/sandstone – 4300 m /s and mud/claystone – 3700 m/s. This is in the range of normal velocities for sandstone, mud-and claystone.

The resistivity values seem to be less than normal values for this type of rocks with values of 2500 ohmm – 4500 ohmm. The resistivity data are corrected due to the borehole water conductivity, which is saline water. However, in this case the pore water is saline groundwater and this will also have an influence on the measured values. By using Archie's law the formation resistivity ρ_o can be calculated from the porosity, Φ, pore water resistivity, $\rho_{w.}$ and cementation exponent, m. (Archie 1942).

$$\rho_o / \rho_w = 1/ \Phi^m$$

If we assume a porosity of 10 %, pore water conductivity of 10 000 µS/cm and m equal to 2, the calculated formation resistivity will be 100 ohmm. This fits well with the logged values, 50 – 200 ohmm. The important issue here, however, is how the resistivity varies due to the changing lithology.

The gamma log clearly indicates the changes in lithology. The caliper log indicates fractures, but can also be related to small changes in the borehole diameter caused by variations in the rock hardness. In this way the formation thickness is indicated. For the density log, even if this gives a qualitative density measurement, the layer thicknesses are indicated.

In the following, some examples of log interpretations are described (units are marked with different colours in figure 3):

86 – 89 m : Indication of an open fracture. P- and S-velocity are very low, low resistivity and high porosity, increasing borehole diameter (caliper). Core logging indicates a thrust at 88.5 m.

150 – 220 m : Several layers of sandstones are indicated by low gamma radiation. Sandstone mixed up with mudstone will increase the gamma radiation and the resistivity, 220 – 227 m.

252 – 265 m : The P-velocity increase , gamma radiation decrease, apparent resistivity increase, porosity decrease, caliper decrease and there is a slight decrease in the HRD density. The rock in this case is described as muddy sandstone (Atle Mørk pers. com.). The combination of parameters indicates this type of unit.

265 – 281 m : Observations of decrease in P- and S-velocity, increase in gamma radiation, constant resistivity in a limited area, variations in caliper and constant density values. This signature is that of mud-claystone which is the rock at this depth.

362 – 388 m : Constant S-velocity and a slight increase in P-velocity, slight decrease in gamma radiation, slight decreasing resistivity. In drill cores, this unit is described as a debrisflow.

395 – 400 m : Remarkable decrease in gamma radiation and increase in relative density (cps). An increase in cps (count per second) using this probe, is caused by a decrease in the real density. This is sandstone with oil show.

427 – 440 m : At 427 m depth there is a boundary between sandstone and mud- claystone. There is a typical difference in the log parameters. P-velocity decrease, gamma radiation increase, resistivity decrease, porosity increase (?), borehole diameter (caliper) increase and there is a slight decrease in LSD density.

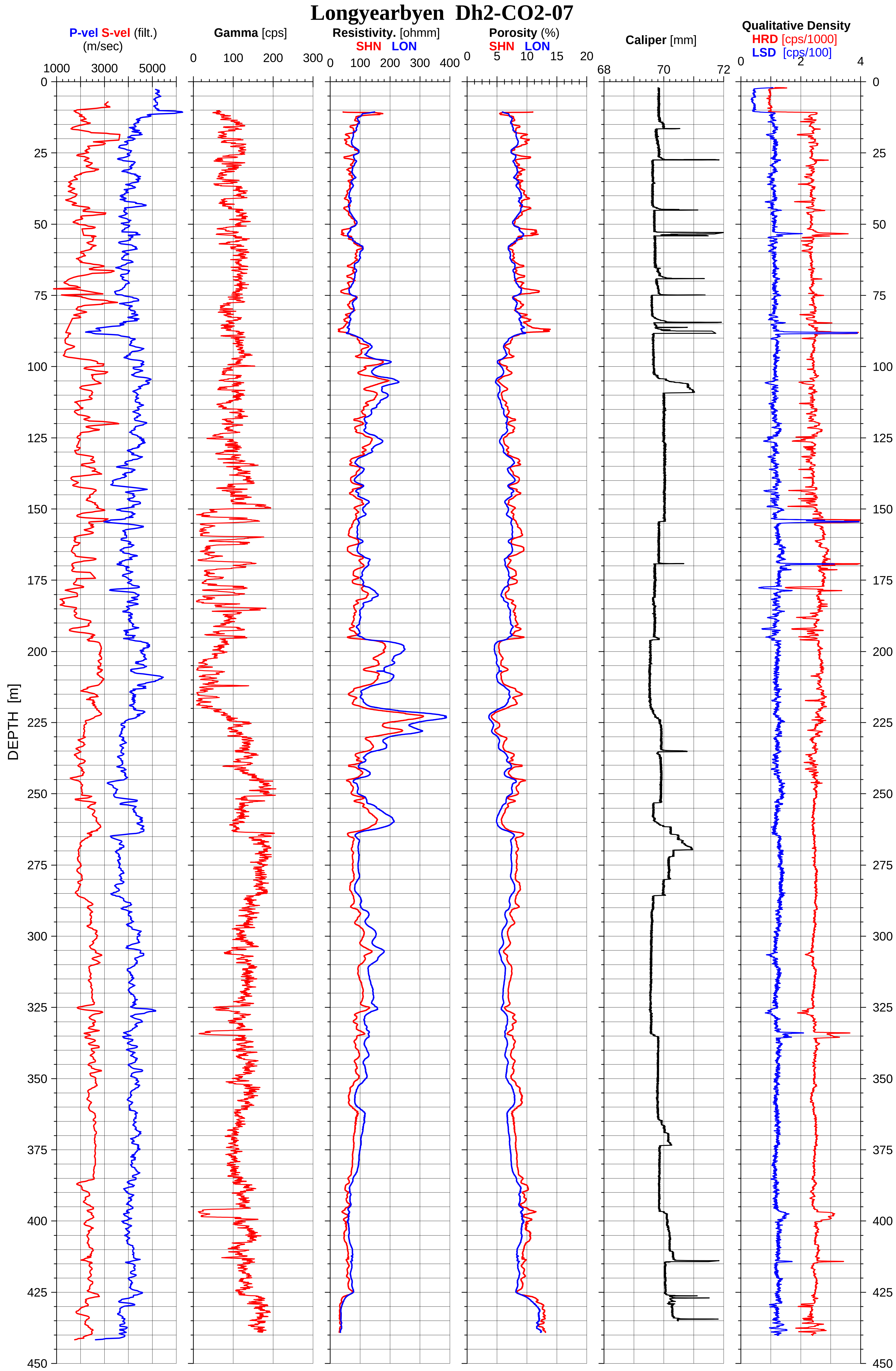


Figure 2. Dh2-CO2-07. P- and S-velocity, natural gamma, resistivity, porosity, caliper, qualitative density

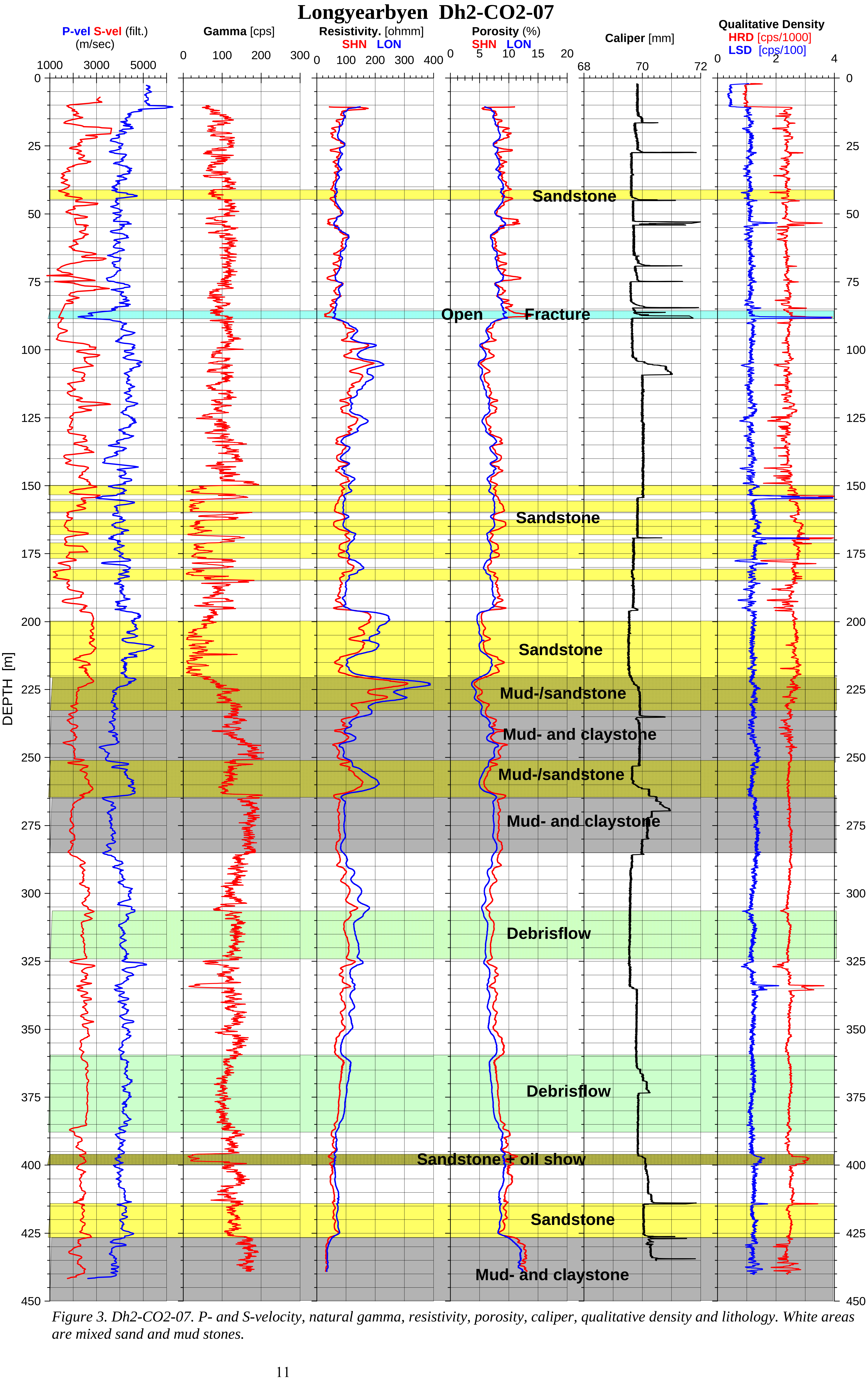


Figure 3. Dh2-CO2-07. P- and S-velocity, natural gamma, resistivity, porosity, caliper, qualitative density and lithology. White areas are mixed sand and mud stones.

4.1.1 Temperature

In the upper part of the boreholes the temperature is below zero. Because of the saline water the well is not frozen. Figure 4 shows the temperature in the upper 50 m in borehole Dh1-CO2-07 and Dh2-CO2-07. The difference in temperature is caused by the time the drilling was finished. The measurements in Dh2-CO2-07 were performed just after drilling, inside the heated cabin on the drilling rig. This is why temperatures above zero are measured. In Dh1-CO2-02, the first well drilled, the temperature conditions are stabilized and negative temperatures can be measured down to 40 m. The lowest measured temperature is -0.96 ^{o}C at 4.5 m depth.

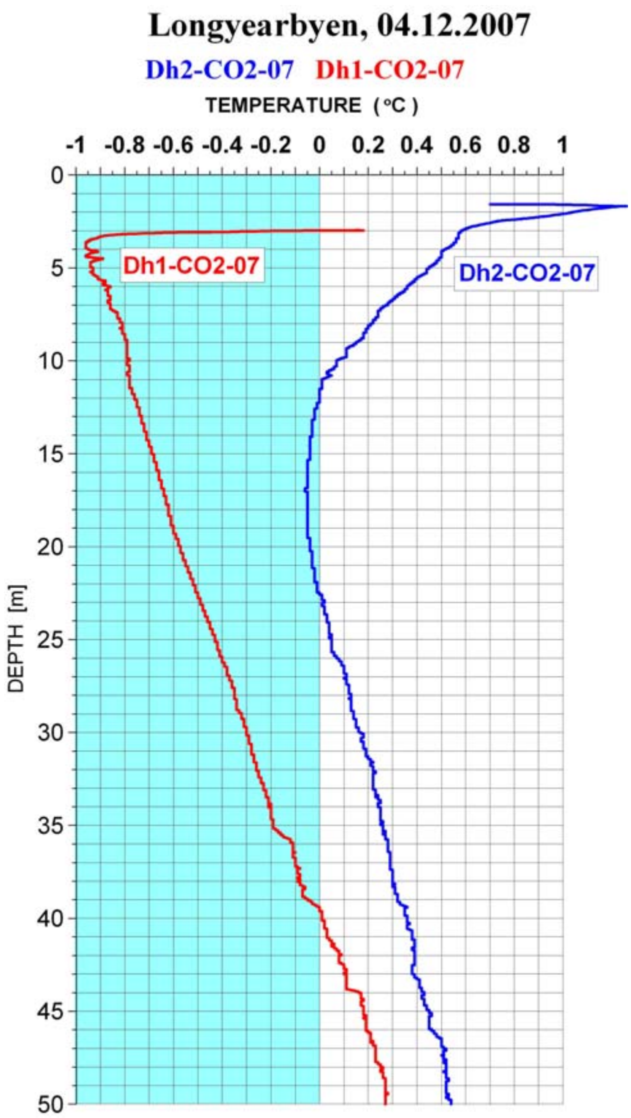


Figure 4. Temperature log of the upper 50m in Dh2-CO2-07(blue) and Dh1-CO2-07(red).

Figure 5 shows the temperature log and the temperature gradients for 20 m and 100 m depth intervals. The temperature gradient is high compared to gradients measured onshore in Norway. In the deepest part of the logged borehole the gradient is close to 40 ^{o}C/km.
Some local variations are observed on the 20 m interval gradient. Local variations in the temperature gradient are usually caused by open fractures with inflow of water or a change in the thermal conductivity. In this case it could be caused by porous sandstones that let groundwater flow. If the thermal conductivity decreases the heat flow decreases. But the temperature gradient will increase. At 80 m depth the local rise in the gradient is probably caused by water inflow from an indicated fracture. At about 250 m and 280 m depth the gradient might be changed by change in the thermal conductivity and the occurrence of permeable sandstones. It is expected that the thermal conductivity in the mud- claystone is less than in sandstone. The thermal conductivity depends strongly on the content of quartz.

Estimated temperature on 900 m depth.
The temperature on 900 m depth can be estimated by using the measured temperatures and the calculated gradients.

Gradient 30 ^{o}C/km or 0.03 ^{o}C/m.

Temperature on 440 m depth:	12.8 ^{o}C
Temperature increase 440-900 m: 460 x 0.03	13.8 ^{o}C
Temperature on 900 m depth:	26.6 ^{o}C

Gradient 40 ^{o}C/km or 0.04 ^{o}C/m.

Temperature on 440 m depth:	12.8 ^{o}C
Temperature increase 440-900 m: 460 x 0.04	18.4 ^{o}C
Temperature on 900 m depth:	31.2 ^{o}C

By using gradients 30 or 40 ^{o}C/km the temperature in a reservoir on 900 m depth is predicted to be at 26 -31 ^{o}C.

Figure 6 shows the temperature log and temperature gradients in both boreholes. The upper 95 m temperature is a bit higher in Dh2-CO2-07 due to the time after drilling influence. The temperature curve below 95 m is almost equal. From 395 m to 440 m it's a bit warmer in Dh1-CO2-07, probably caused by change in the thermal conductivity, see later.

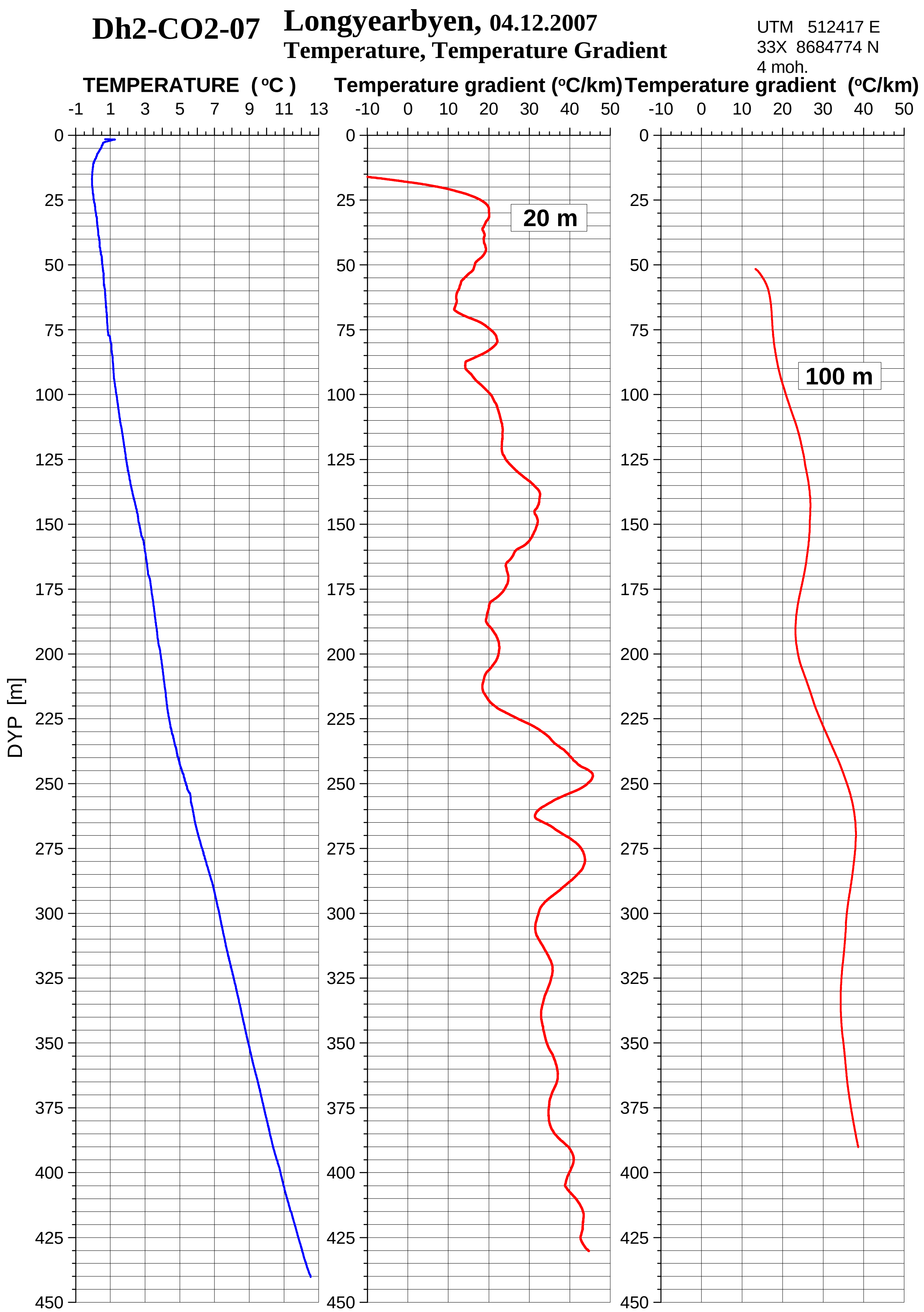


Figure 5. Temperature and temperature gradients in Dh2-CO2-07.

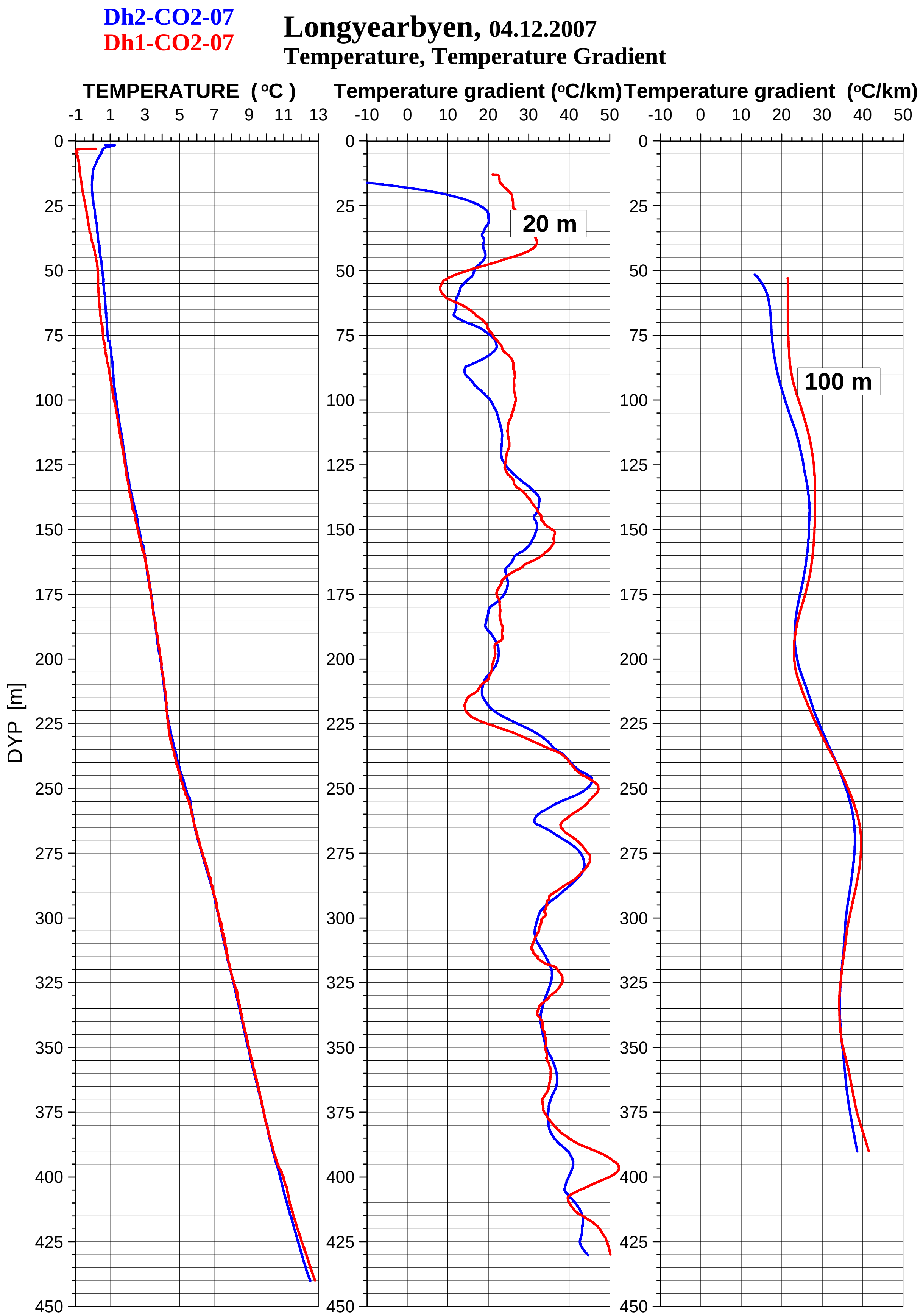


Figure 6. Temperature and temperature gradients in Dh2-CO2-07 and Dh1-CO2- 07.

Figure 7 shows the logs from the water quality sonde in Dh2-CO2-07. The temperature log is described above. The water conductivity decreases linearly from the top of borehole to the stop logging point at 440 m. This means that the salinity decreases. The conductivity is close to seawater values. Except in the upper 25 m pH, Eh and O2 is almost constant. There is no data from the NO3 sensor.

Deviation components are shown in figure 8, confirming that the deviation from vertical is very small. At a depth of 440 m the East-component is 2.9 m and the North-component 3.7 m. The deviation from vertical of the borehole is towards the South-East.

Dh2-CO2-07

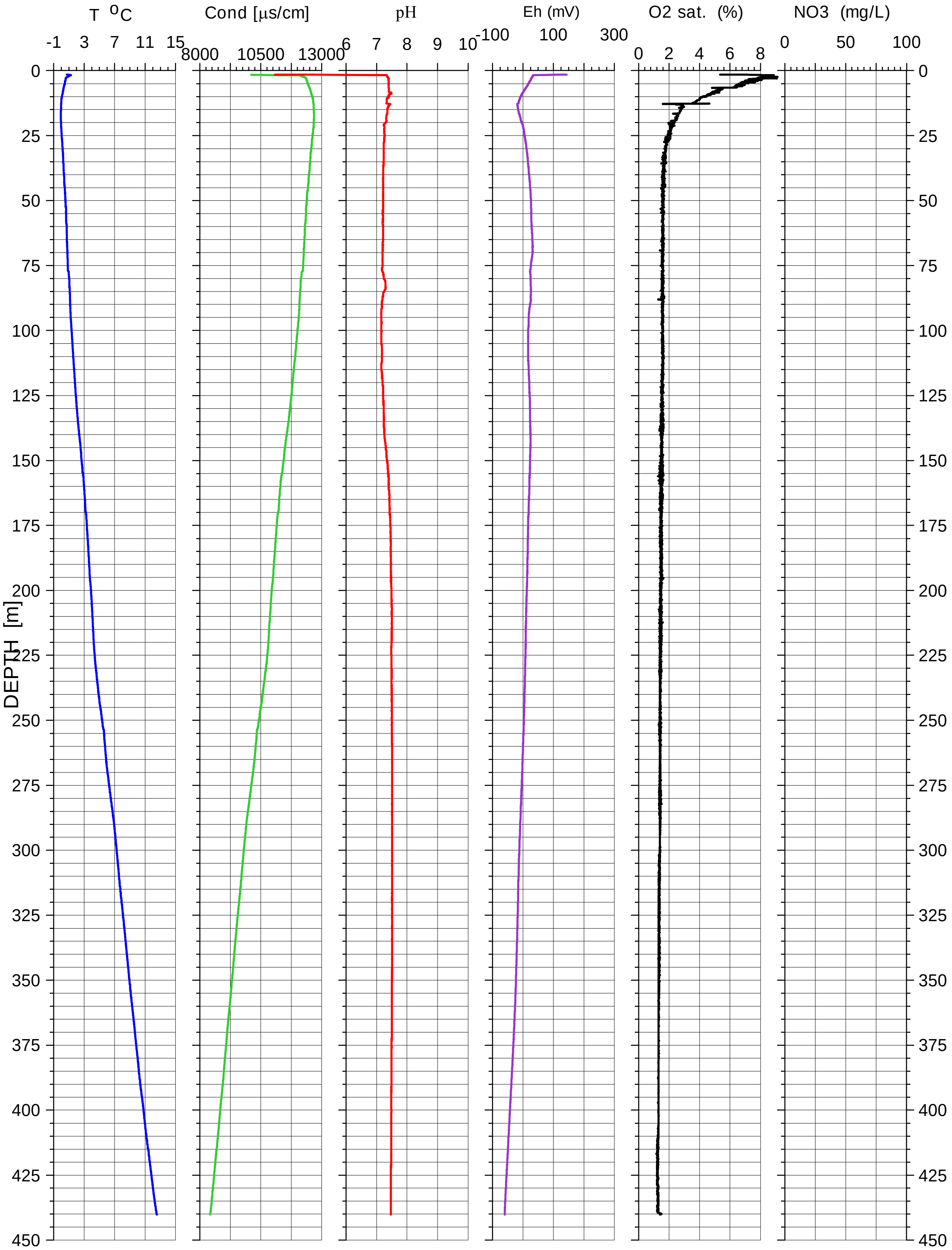
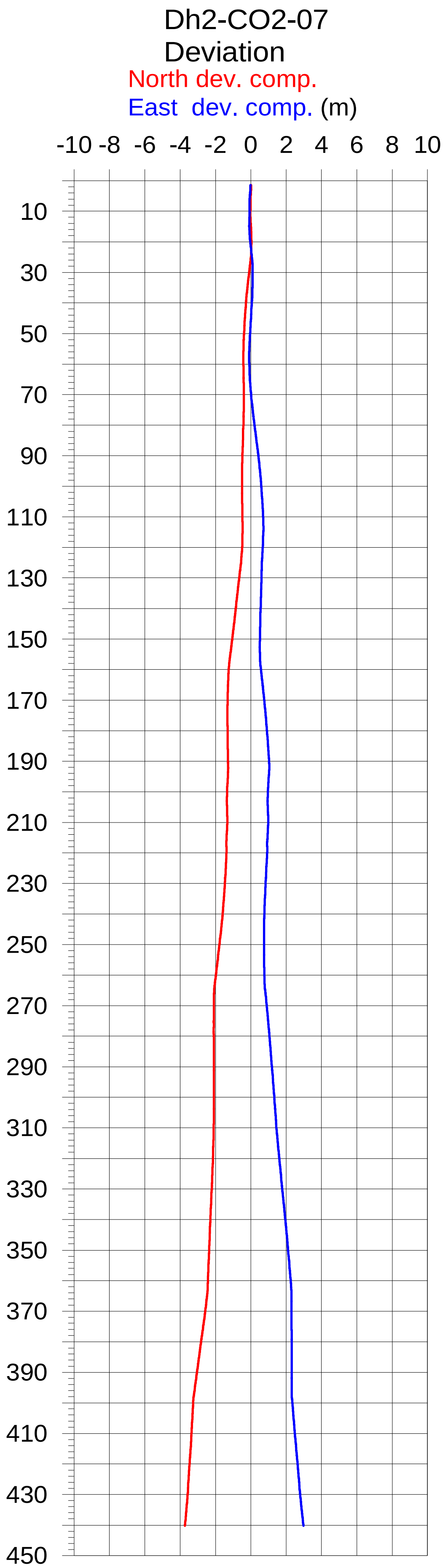


Figure 7. Water quality logs in Dh2-CO2-07.



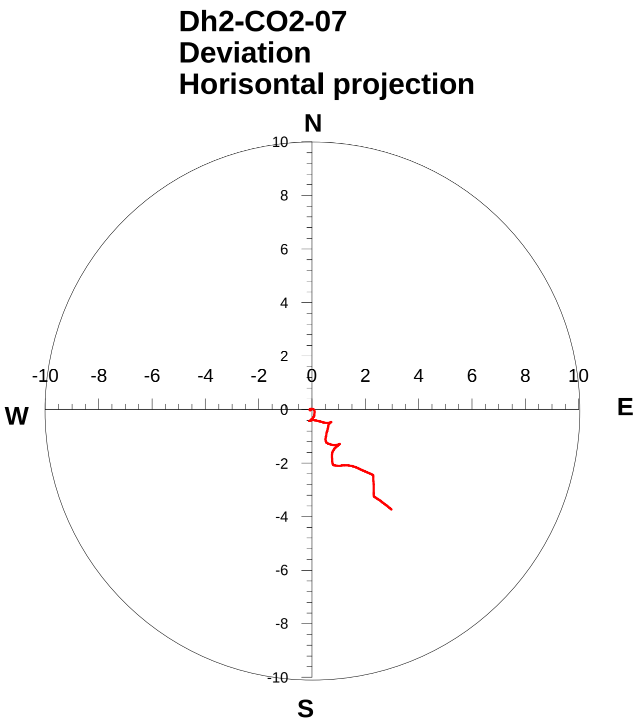


Figure 8. Deviation plots Dh2-CO2-07, E – N components (left) and direction (right).

4.2 Dh1-CO2-07

Bore hole Dh1-CO2-07 was the first well, which was drilled to 517 m. The distance between Dh1-CO2-07 and Dh2-CO2-07 is nearly 30 m, hence there should not be changes in the lithology. The geophysical logs confirm this, but there are some small changes.

Figure 9 shows the logs for P-velocity, S-velocity, natural gamma, resistivity, porosity, caliper and density in Dh1-CO2-07. The logs are quite similar to the Dh2-CO2-07 logs. However, there are some differences in layer thickness and depth. Above 200 m the layers seem to occur at the same depth. Below 200 m the depth for some units is less in Dh1-CO2-07. Some examples based in well Dh1-CO2-07:

253 m – 259 m: Mud- sandstone layer is thinner in 1-CO2.
295 m – 313 m: Debrisflow, about 10 m up
342 m – 376 m: Debrisflow, about 10 m up
387 m – 405 m: Sandstone with oil show. Thicker and 8 m up
413 m – start of mud- claystone unit, about 15 m up

Figure 10 shows a simple lithological interpretation of the geophysical logs in 1-CO2 based on a sedimentary log and geophysical logs in Dh2-CO2-07. The oil show layer is clearly indicated by the gamma and density log and is 13 m thick, while the same formation in Dh2-CO2-07 was 5 m.

Temperature
The temperature log and temperature gradients are shown in figure 11. The description (interpretation) in chapter 4.1 for the Dh2-CO2-07 temperature log can also be used for the Dh1-CO2-07.There is one difference in the 20 m interval gradient. At 390 – 405 m depth there is a significant increase in the gradient. This is probably caused by a change in the thermal conductivity. The geophysical logs indicate a 13 m thick sandstone layer with oil show at this level (see above).

The water quality logs are shown in figure 12 and the deviation plots in figure 13.
The deviation from vertical is very small. At a depth of 440 m the East-component is 1.5 m and the North-component 4.4 m. The direction of the borehole is North-West.

Figure 14 shows the horizontal deviation of both wells plotted in the UTM coordinate system. The two wells drift towards each other at depth. At a depth of 440 m they are 23 m apart.

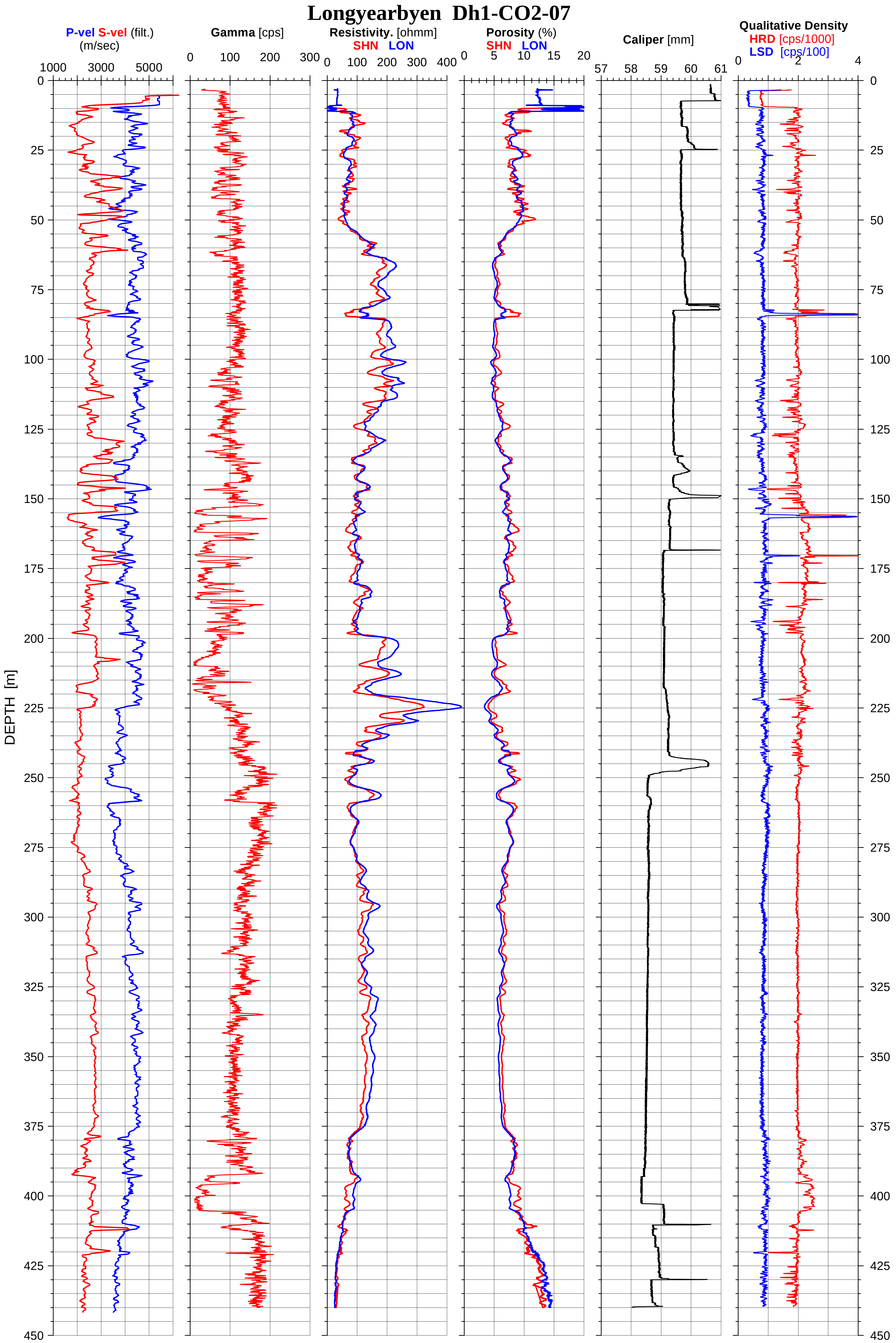


Figure 9. Dh1-CO2-07. P- and S-velocity, natural gamma, resistivity, porosity, caliper, qualitative density

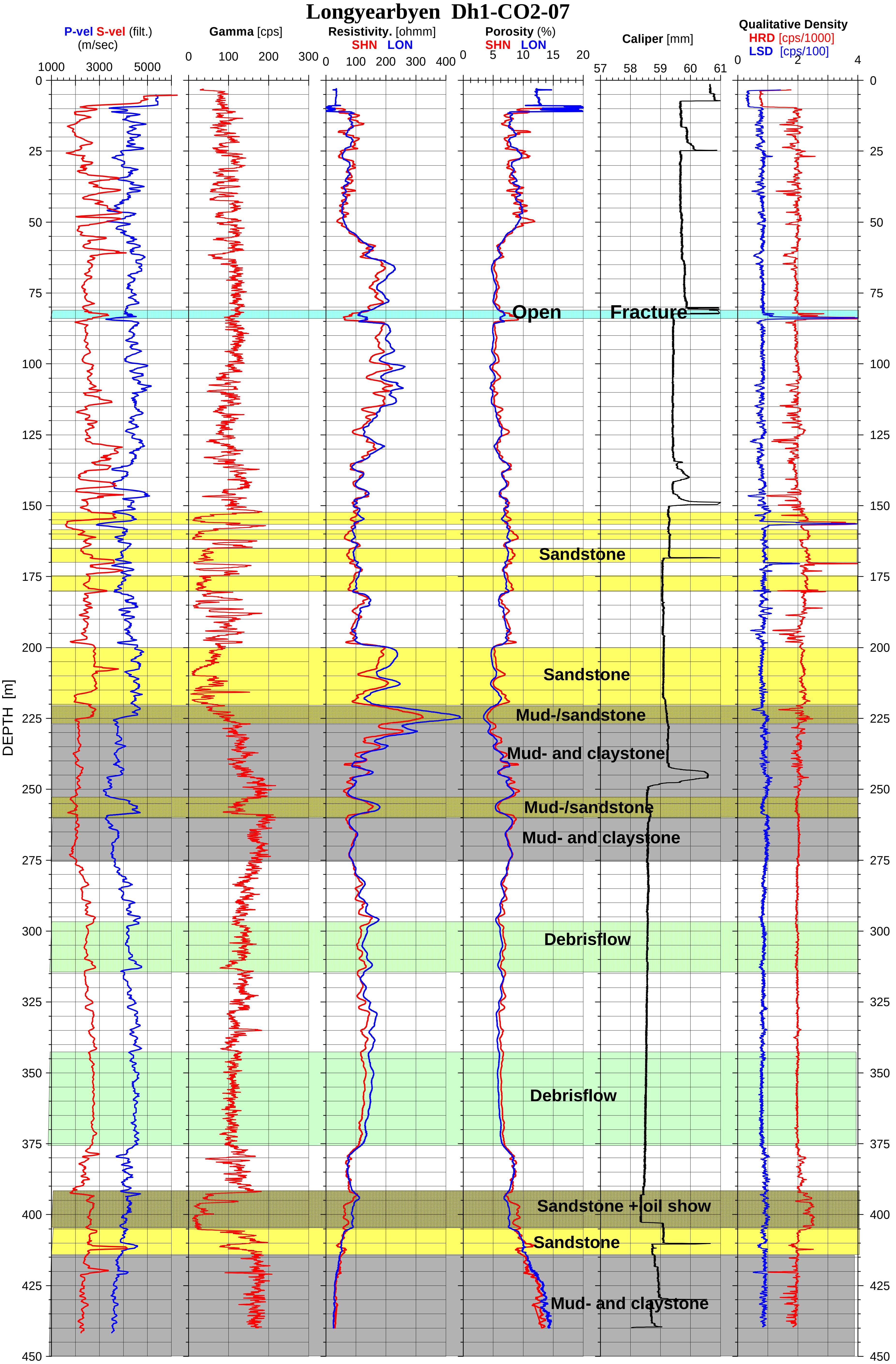


Figure 10. Dh1-CO2-07. P- and S-velocity, natural gamma, resistivity, porosity, caliper, qualitative density and lithology. White areas are mixed sand and mud stones.

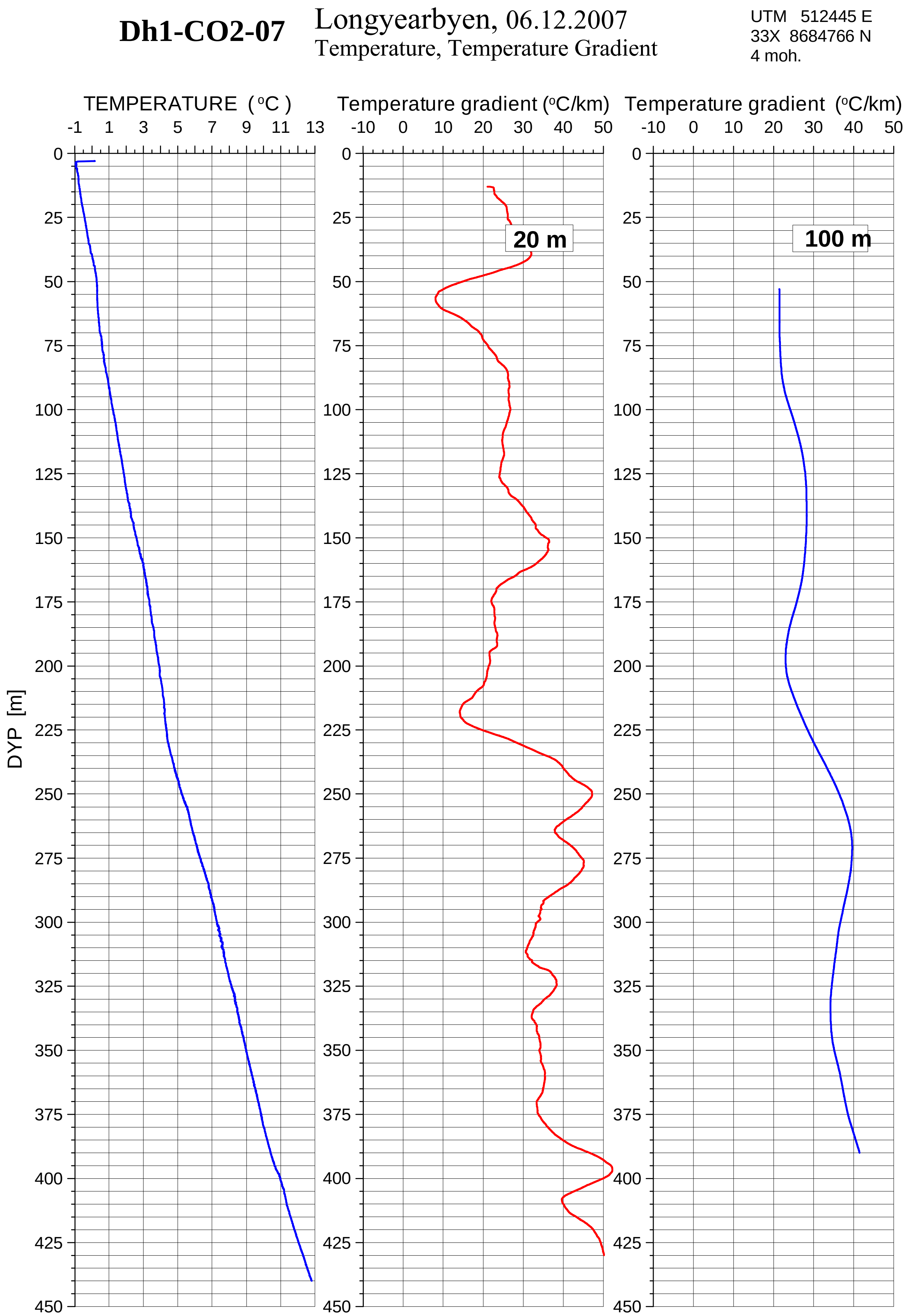


Figure 11. Temperature and temperature gradients in Dh1-CO2-07.

Dh1-CO2-07

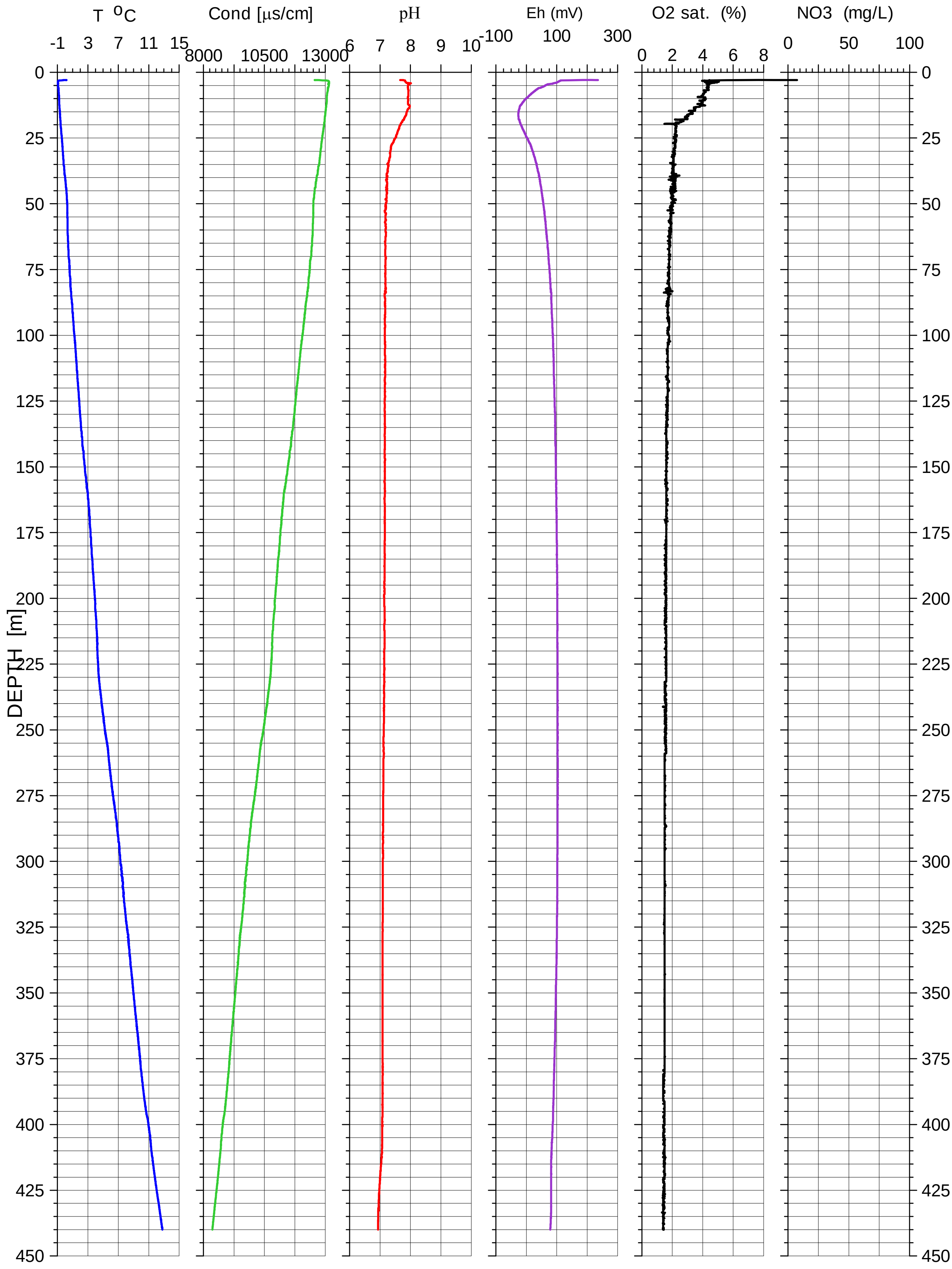
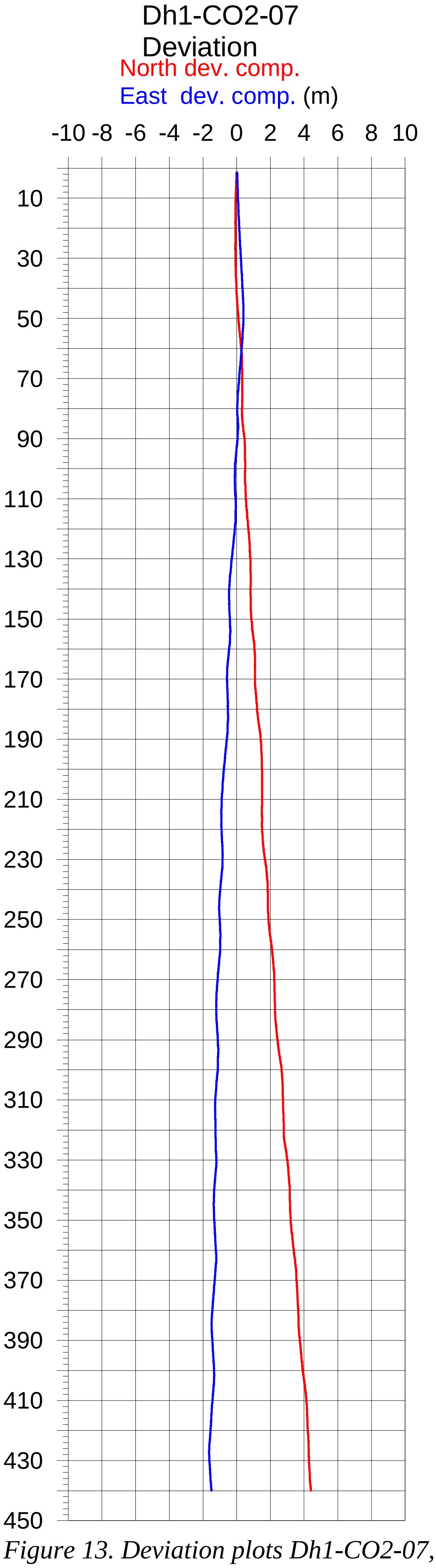


Figure 12. Water quality logs in Dh1-CO2-07.



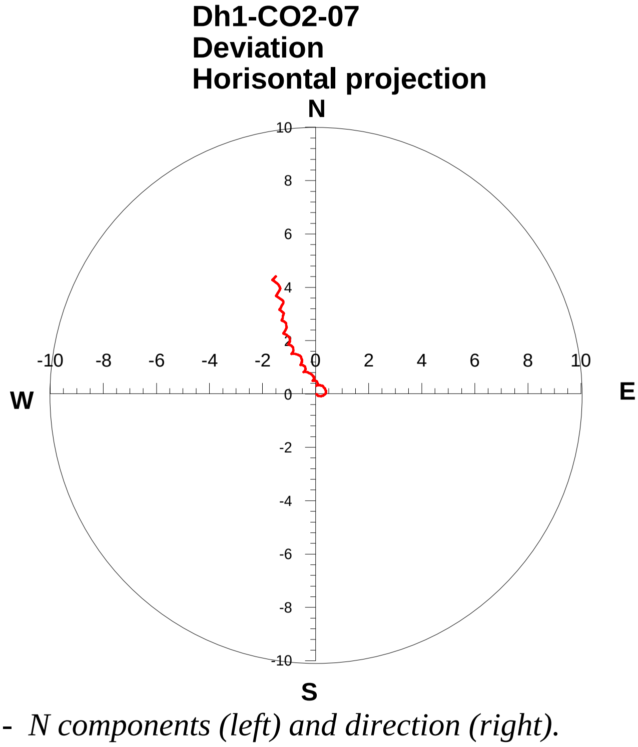


Figure 13. Deviation plots Dh1-CO2-07, E - N components (left) and direction (right).

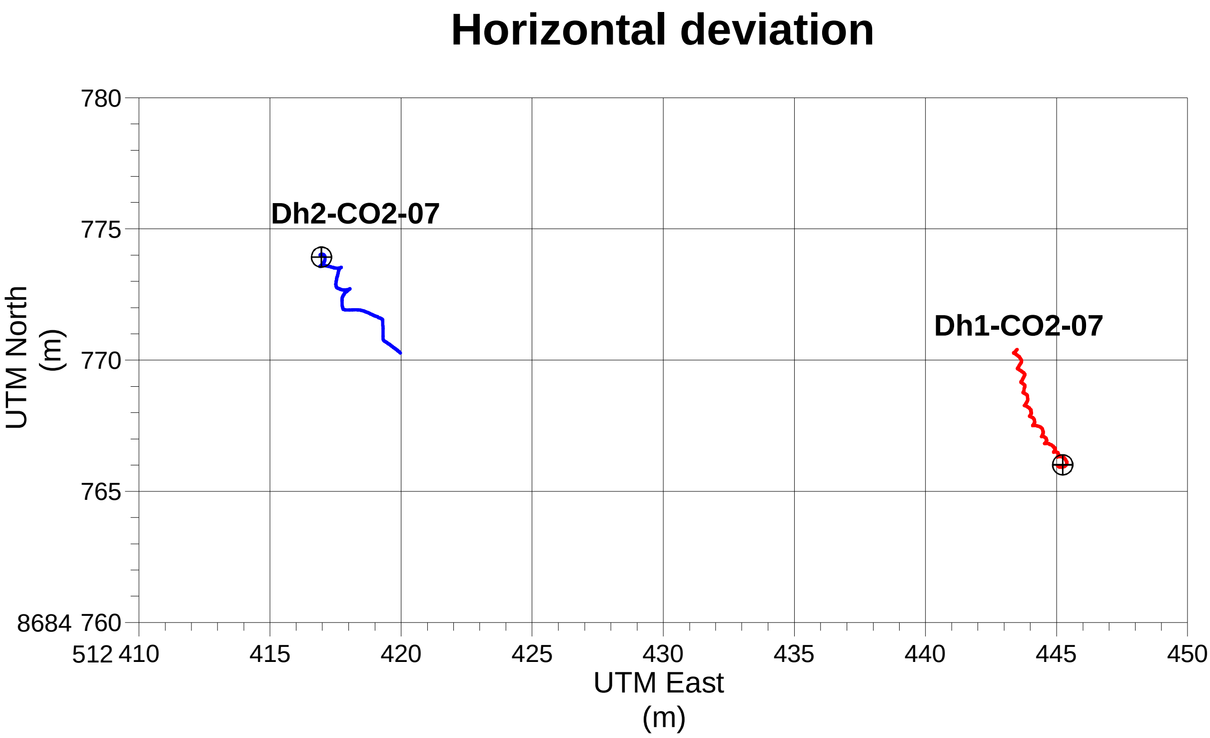


Figure 14. Horizontal deviation of the two wells, Dh1-CO2-07 and Dh2-CO2-07.

5. CONCLUSION

NGU has carried out borehole logging in two wells just outside Longyearbyen. The wells were drilled to locate deep sandstone formations that may be used to store CO_2 from the local coal combusting power plant. Logging parameters were temperature, fluid conductivity, natural gamma, rock resistivity, seismic velocity, caliper, relative density and borehole deviation. Both wells were logged to a depth of 440 m. Because of stability problems in a fault zone, logging could not be performed in the deepest part of the wells (820m). The well failed to reach the main reservoir that was planned to be in Late Triassic sandstone.

The results show good correlation between the geophysical logs and the lithological units. Sandstones are indicated with low gamma radiation and increasing seismic velocity and apparent resistivity. However, the properties of the most suitable unit for CO_2 storage could not be mapped in these wells. This will be done in a new well in Adventdalen, which is to be drilled August 2008.

6. REFERENCES

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