DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2017/20

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1. Introduction

This report has been prepared by GEUS for Energinet.dk with the objective to evaluate the possibility of establishing an injection well in the vicinity of the gas storage facility at Lille Torup, Northern Jutland. The study was commissioned as a feasibility study.

The gas storage facility is situated on top of a salt structure and comprises 7 caverns washed out in the salt dome. During recent years, the facility has been subjected to, a still ongoing, comprehensive renovation including emptying the caverns from intrusive brine. Previously, brine produced from the salt caverns has been discharged into Lovns Bredning, but the authorization to do so has been cancelled.

Cavern no 6 still contains c. 520.000 m^3 of brine that must be disposed of. Several options regarding the disposal of the brine are presently being considered by Energinet.dk. One of these options is establishing an injection well if a target formation with appropriate storage properties can be identified. Environmental considerations should be taken into account, e.g. the increased formation pressure caused by injection should not "push" the pore fluid of overlying formations into freshwater reservoirs. Preferably, the injection well should be located close to the gas storage facility and target depth kept as shallow as possible, however, a maximum distance of 50 km from the gas storage facility and a total well depth of 2 km are acceptable if the cavern can be emptied in c. 1 year.

Five formations have been screened in order to identify potential brine storage intervals and evaluate their properties – These formations are (from deep to shallow):

- The Bunter Sandstone/Skagerrak Formation
- The Gassum Formation
- The Haldager Sand Formation
- The Frederikshavn Formation
- The Chalk Group

In the four deepest formations, the potential reservoirs are comprised by sandstone intervals. The Chalk Group consists almost exclusively of chalk and limestone.

The screening procedure includes the following steps:

1) Identification of formations or layers evaluated as reservoirs suitable for brine storage
2) Identification of low permeability formations or layers hindering pore water from propagating to the surface.
3) Evaluation of reservoir properties based on interpretation of well logs from selected deep wells.
4) Appointment of areas in the larger Lille Torup area evaluated as suitable for further studies for establishing an injection well.
5) Rough assessment of injection rate in potential reservoirs based on permeability and reservoir thickness assessments.
6) Rough assessment of the pore pressure in the potential reservoirs.

7) Rough assessment of uncertainties of the parameters listed in bullets 3–6.
8) Recommendations for detailed studies in the larger Lille Torup area and possible acquisition of new additional data with the purpose of documenting the presence and capacity of the proposed storage reservoirs.

2. Geological background

The Lille Torup area is located centrally in the Danish Basin in an area, where the Upper Permian–Mesozoic succession is approx. 5–5.5 km thick. The basin was formed by Late Carboniferous–Early Permian stretching of the crust and after deposition of syn-rift prisms of Rotliegendes coarse-grained clastic sediments followed by a phase with thermal contraction, which lead to deposition of thick Zechstein salts overlain by Triassic sandstones, mudstones, carbonates and salts (Nielsen 2003). These are overlain by Lower Jurassic mudstones, Middle Jurassic sandstones, Upper Jurassic–Lower Cretaceous mudstones and siltstones with few sandstones. The Mesozoic succession is terminated by approx. 1200 m thick carbonates and chalks.

The salt structure at Lille Torup is situated in the deep part of the Danish Basin and consists of mobilised Zechstein salt penetrating the Mesozoic succession above (Figure 1). The structure has its top point relatively close to the present day surface, typically c. 250 m below the surface.

Regionally, the Bunter Sandstone/Skagerrak Formation is present in most of the Danish Basin with thicknesses mostly in the range 50–250 m, but locally more than 700 m. Sandstone layers occur frequent.

The Gassum Formation is present in the entire basin and is approx. 30 m to more than 200 m thick. The lithology of the formation varies from dominating sandstones with few thin mudstones to siltstones, and mudstones with relatively few sandstone beds.

The Haldager Sand Formation is present in the northern part of the basin and disappears in the southernmost and easternmost parts. Generally, the formation thickness varies from 10 m to c. 100 m, but locally the thickness increases to more than 500 m. Frequently, sandstones dominate the lithology.

The Frederikshavn Formation is primarily present in the northern part of the basin and disappears in the southernmost and westernmost parts. The thickness varies from 150 m down to a few metres with sandstones as the dominating lithology.

The Chalk Group is more than 1000 m thick and constitutes the topmost pre-Quaternary formation in large parts of the Danish Basin. The lithology consists almost exclusively of chalk and limestone.

3. Well and seismic data

The evaluation of the reservoir quality in the study area is based on available well-logs, cuttings samples, conventional cores and seismic data that have been acquired over a long time span during hydrocarbon exploration, geothermal energy and gas storage activities.

Potential storage formations in the Lille Torup area are primarily considered to be sandstones of the Gassum and Bunter Sandstone/Skagerrak Formations as the reservoir properties of these formations are well-known from geothermal research. The Haldager Sand and Frederikshavn Formations are likely to constitute alternative storage formations. The distribution and reservoir properties of these formations is less known compared to the Gassum Formation, since they are known only from the northern Jutland area; the assessment of the geothermal potential is therefore more uncertain. The possibility of using the Chalk Group for storage is considered as well.

Within a radius of 50 km of Lille Torup storage facility, the local database comprises eleven deep wells and an open grid of 2D regional seismic profiles of variable quality and resolution acquired during earlier hydrocarbon exploration campaigns (Figure 1).

The wells used for interpretation of petrophysical properties of the formations mentioned above comprise Kvols-1, Hobro-1, Gassum-1, Rødding-1, Farsø-1 and Hyllebjerg-1 (highlighted in Figure 1). The Erslev-1–2 and Skive-1–2 wells were excluded from this database as their data is of very local character due to their location on top of a salt diapir. The Aars-1 well was excluded due to uncertainties regarding data-collecting and the Mors-1 well was excluded as it is separated from the Lille Torup storage facility by c. 20 km of fiord water. The reservoir evaluation is primarily based on petrophysical evaluation of available well log data from the selected wells using a standard approach for interpreting the wireline log data.

Reservoir properties include:

- Depth of formation top and base
- Formation thickness
- Gross sand thickness (i.e. cumulated thickness of all sandstone layers)
- Potential reservoir sand thickness (i.e. cumulated thickness of sandstone layers with a shale content<30% and a porosity>15%)
- Average porosity of the potential reservoir sandstone
- Average permeability of the potential reservoir sandstone
- Average transmissivity of the potential reservoir sandstone

In 2016, a comprehensive nation-wide geothermal subsurface mapping project (WebGIS) was finished based on interpretation of the vast pool of data available from deep wells and 2D seismic surveys (Vosgerau et al. 2016). As implied by the project name, the mapping results are accessible from a WebGIS-based application (http://dybgeotermi.geus.dk/).

Local results from the WebGIS project as well as GEUS´ general and regional geological models serve as starting point for the screening of the subsurface in the larger Lille Torup area with respect to identification and characterization of potential reservoirs for storage. Maps of formation depth, thickness and potential reservoir sand thickness were generated from the WebGIS application.

It is important to note, that the WebGIS maps showing potential reservoir sand thickness were developed for assessment of geothermal potential and should not be used directly as an analogue for injectivity. However, in this study, potential reservoir sand thickness is used as indicator of injection performance of the formation.

Further, the accuracy of reservoir properties and maps generated by the WebGIS application is dependent on quality and density of well and seismic data. In areas with no or poor data coverage, the resulting interpretations are less certain. As a consequence, the maps display trends on a regional scale. Assessing reservoir properties on a local scale involves a more complex integration of available data. For more information, see Vosgerau et al. (2016) and http://dybgeotermi.geus.dk/.

4. Formations containing potential reservoirs for brine storage

Based on geothermal research performed during the last decade on a national scale (e.g. Mathiesen et al. 2009; Vosgerau et al. 2016), a number of sandy formations are considered potential reservoirs (Figure 2). In the larger Lille Torup area, these formations comprise the Bunter Sandstone/Skagerrak, Gassum, Haldager Sand and Frederikshavn Formations. In addition, the Chalk Group is of major importance as a hydrocarbon reservoir in the North Sea and is included in this study.

As a rule of thumb, a geothermal reservoir should not be situated at a depth exceeding 3000 m (e.g. Mathiesen et al. 2009). The depth limit is selected due to the risk of insufficient porosity and permeability in reservoirs at greater depths. This rule is applied to the potential storage reservoir at Lille Torup as the requirements in terms of accommodation space (porosity) and permeability (injection rate) are assumed to be similar.

4.1 The Bunter Sandstone Formation

A depth map of the Bunter Sandstone Formation (Figure 3) shows burial depths of more than 3000 m in the larger Lille Torup area, which implies that porosity and permeability most likely are too insignificant for brine storage.

Consequently, the Bunter Sandstone Formation is discarded as storage formation.

4.2 The Gassum Formation

A depth map of the Gassum Formation (Figure 4) shows burial depths of more than 3000 m in large parts of the larger Lille Torup area. Most other occurrences of the formation are buried at depths between 2000 and 3000 m with thicknesses up to 500 m. Comparing the depth map to the formation thickness map (Figure 5) and the potential reservoir sand thickness map (Figure 6), reservoir properties seem to be excellent. However, potential reservoirs buried shallower than 2000 m are located more than 20 km away from Lille Torup and their number is limited.

Consequently, the Gassum Formation is discarded as storage formation.

4.3 The Haldager Sand Formation

The Haldager Sand Formation shows burial depths of more than 2000 m (Figure 7) in large parts of the larger Lille Torup area. More shallow occurrences of the formation are irregularly distributed. Generally, the formation is relatively thin (0–150 m) as seen from the thickness map (Figure 8), but it is seen to reach thicknesses of more than 400 m in local areas

NW and NE of Lille Torup. These local thicknesses are subject to interpretational challenges and may be down-adjusted to 100–200 m. The formation is sand-dominated and the potential reservoir sand thickness (Figure 9) is significant compared to formation thickness. From petrographic analysis, the formation is known to be highly quartz-dominated, which points to good reservoir properties.

In areas of relatively shallow burial (<2000 m) the Haldager Sand Formation may constitute a storage formation. As the formation is only slightly deeper buried than the Frederikshavn Formation, these two formations may be combined in one storage option.

4.4 The Frederikshavn Formation

The Frederikshavn Formation is the shallowest of the sandy formations with burial depths down to 2 km (Figure 10). In most areas within the 50 km range of Lille Torup, the burial depth is less than 2 km and the formation is generally more than 100 m thick (Figure 11). The highest thickness of potential reservoir sandstones is found east of Lille Torup (Figure 12). When burial depth, formation thickness and potential reservoir sand thickness are compared, several potential storage reservoirs with sufficient lateral extent can be identified.

The Frederikshavn Formation is evaluated as providing adequate reservoir properties for brine storage.

4.5 The Chalk Group

In the Lille Torup area, the Chalk Group is buried at depths ranging from 100 m to 400 m (Figure 13), the depth variations largely being controlled by the presence of mobilised salt bodies. However, toward the northeast, burial depth of the Chalk Group gradually decreases and locally reaches the surface. Oppositely, the burial depth increases toward southwest to more than 700 m. As mentioned above, the thickness amounts to more than 1 km (Figure 14).

Onshore porosities and permeabilities from Rørdal, Nye Kløv and Stevns (unpublished data) indicate good porosities in the 30–45% range, but poor permeabilities in the 1–10 mD range. Similar por–perm values should be expected in the Lille Torup area away from the salt structures. On top of the salt structure below Lille Torup, the Chalk Group may be fractured due to tensions generated by the salt movements and thus possess higher permeabilities. However, the Quaternary deposits between the Chalk Group and the surface are not expected to be of sufficient low effective permeability and potential brine storage would lead to environmental issues.

The Chalk Group is discarded as storage formation due to large risk of insufficient permeability away from salt structures and lack of low permeability layers on top of salt structures.

The vertical distribution of reservoirs and low permeability layers are shown in Figure 2.

5. Potential low permeability layers

Low permeability layers hinder the increased pressure from the target reservoir from propagating and pushing pore water to more shallow reservoirs. The vertical distribution of reservoirs and low permeability layers are shown in Figure 2.

The Chalk Group is expected to constitute a thick and effective low permeability layer hindering the propagation of pore pressure and pore water from the sandy formations beneath it. This is due to low permeability combined with thicknesses greater than 1000 m. The thickness remains constant throughout the larger Lille Thorup area except near or on top of salt structures.

The c. 250 m of chalk on top of the salt structure beneath Lille Torup is expectably fractured due to the salt movements and assumed to have too high effective permeabilities.

In addition, the Lower Cretaceous unit is mostly clay-composed and assumed to be of low permeability.

Regarding pressure and pore water propagation from the Bunter Sandstone and Gassum Formations, the clayey Fjerritslev Formation is considered a low permeability layer.

It should be noted that the pore pressure and permeability-hindering qualities of most of the above mentioned formations have not been investigated and verified.

6. Reservoir parameters of the selected formations

Reservoir parameters for the Bunter Sandstone, Gassum, Haldager Sand and Frederikshavn Formations in relevant wells within a radius of 50 km of the Lille Torup storage facility (Figure 1) are shown in Table 1.

6.1 The Bunter Sandstone and Gassum Formations

The Bunter Sandstone and Gassum Formations were discarded due to burial depths mostly exceeding 3000 m in the vicinity of Lille Torup (Figure 4). However, these two formations, especially the Gassum Fm, seemingly include the most prolific sandstone reservoirs as evidenced from potential reservoir sand thickness and average porosities and permeabilities (Table 1). As all wells indicate highly suitable storage properties of the Gassum Fm (Table 1) and as the wells are distributed around the Lille Torup area (Figure 1), there is reason to assume equally suitable reservoir properties of the Gassum Fm in the Lille Torup area.

6.2 The Haldager Sand Formation

Also, the Haldager Sand Formation was discarded due to burial depth. This formation mainly comprises sandstone layers with porosities in the 18–22% range and permeabilities in the 140–360 mD range (Table 1). Disregarding burial depth, the Haldager Sand Formation is assumed to provide suitable storage properties.

6.3 The Frederikshavn Formation

The Frederikshavn Formation is the shallowest of the sandy formations. For most wells, the porosity varies from 17% to 30%, the permeability from 110 mD to 1500 mD and the thickness of potential reservoir sand from 6 m to 66 m (Table 1). In the Kvols-1 well, however, the formation seems to have very little or no storage potential at all. This is most likely due to clay minerals (chlorite) reducing pore space and permeability significantly, a characteristic observed in the Frederikshavn Formation in other Danish wells (Weibel, pers.com.). Chlorite precipitation may thus inflict on reservoir performance in the Lille Torup area, but as indicated by porosity and permeability values in the Farsø-1, Gassum-1, Hobro-1 and Hyllebjerg-1 wells (Table 1), the formation performs well in most areas.

When combining the well data of Table 1 with the map showing the distribution of potential reservoir sand (Figure 12), an East–West trend is indicated with the higher thicknesses to the East, culminating with 65 m in the Gassum-1 well. West of the Lille Torup area, the thicknesses are low.

Well	Formation	Formation Top B.MSL (m)	Formation Base B.MSL (m)	Formation Thick-ness (m)	Gross Sand (m)	Pot. res. sand (m)	Avg. por. (%)	Res. perm. (mD)	Reservoir trans-missivity (Dm)
Gassum-1	Bunter Sandstone	2722	3416	694	308	84	18	188	16
Farsø-1	Gassum	2717	2915	198	61	35	17	100	3
Gassum-1	Gassum	1493	1623	130	46	44	25	938	41
Hobro-1	Gassum	2344	2489	145	143	63	21	275	17
Hyllebjerg-1	Gassum	2554	2723	169	77	42	19	219	9
Kvols-1	Gassum	2405	2513	108	55	38	21	300	11
Rødding-1	Gassum	1916	2012	96	36	34	24	500	17
Farsø-1	Haldager Sand	1934	1952	18	16	11	18	138	2
Gassum-1	Haldager Sand	1176	1179	2	2	2	19	188	0
Hobro-1	Haldager Sand	1852	1891	39	24	18	19	175	3
Hyllebjerg-1	Haldager Sand	1885	1894	9	9	9	22	344	3
Kvols-1	Haldager Sand	1940	1955	15	15	9	21	363	3
Farsø-1	Frederikshavn	1689	1839	150	25	9	17	106	1
Gassum-1	Frederikshavn	1053	1154	101	66	65	30	1500	97
Hobro-1	Frederikshavn	1741	1806	65	12	6	19	238	1
Hyllebjerg-1	Frederikshavn	1664	1810	146	37	15	19	188	3
Kvols-1	Frederikshavn	1856	1912	56	56	0	5	0	0

Table 1. *Reservoir parameters estimated from well logs for the selected sandy formations of relevant wells in the larger Lille Torup area. B.MSL = Below mean sea level; Pot. res. sand = Potential reservoir sand; Avg. por. = Average porosity; Res. perm. = Reservoir permeability. For detailed descriptions of the parameters, see* http://dybgeotermi.geus.dk/.

6.4 Parameter uncertainties

Uncertainties were assessed for each reservoir parameter during construction of the geothermal WebGIS portal. For *gross sand* and *potential reservoir sand*, the uncertainty is 5% (relative). For *porosity*, the uncertainty varies between 5 and 7% (relative). For *reservoir permeability* and *reservoir transmissivity*, the uncertainty is calculated by dividing or multiplying the given value with a factor of 5. For detailed descriptions of the uncertainty considerations, see http://dybgeotermi.geus.dk/. Reservoir parameters and uncertainty ranges are presented for five appointed areas in Table 2 (see also Section 7).

Appointed area	Wells in appointed area	Formation	Formation			Gross sand thickness			Potential reservoir sand thickness			Average net porosity			Reservoir permeability			Reservoir transmissivity		
			Top B.MSL (m)	Base B.MSL (m)	Thick-ness (m)	Fm av. (m)	Uncer–tainty (rel. %)	Range (m)	Fm av. (m)	Uncer–tainty (rel. %)	Range (m)	Fm av. (%)	Uncer–tainty (rel. %)	Range (%)	Fm av. (mD)	Uncer–tainty (factor)	Range (mD)	Fm av. (Dm)	Uncer-tainty (factor)	Range (Dm)
1	Farsø-1	Gassum	2717	2915	198	61	5	58 - 64	35	5	33 - 36	17	6	16 - 18	100	5	20 - 500	3	5	1 - 15
	Hyllebjerg-1	Gassum	2554	2723	169	77	5	73 - 80	42	5	40 - 44	19	5	18 - 20	219	5	44 - 1095	9	5	2 - 45
	Average	Gassum	2636	2819	184	69	5	65 - 72	38	5	36 - 40	18		18 - 18	160	5	32 - 798	6	5	1 - 30
	Farsø-1	Haldager Sand	1934	1952	18	16	5	15 - 17	11	5	10 - 12	18	5	17 - 19	138	5	28 - 690	2	5	0 - 10
	Hyllebjerg-1	Haldager Sand	1885	1894	9	9	5	9 - 9	9	5	8 - 9	22	5	21 - 23	344	5	69 - 1720	3	5	1 - 15
	Average	Haldager Sand	1909	1923	14	12	5	12 - 13	10	5	9 - 10	20		20 - 20	241	5	48 - 1205	3	5	1 - 13
	Farsø-1	Frederikshavn	1689	1839	150	25	5	24 - 27	9	5	9 - 10	17	5	16 - 18	106	5	21 - 530	1	5	0 - 5
	Hyllebjerg-1	Frederikshavn	1664	1810	146	37	5	35 - 39	15	5	14 - 16	19	5	18 - 20	188	5	38 - 940	3	5	1 - 15
	Average	Frederikshavn	1676	1824	148	31	5	30 - 33	12	5	12 - 13	18	5	17 - 19	147	5	29 - 735	2	5	0 - 10
2	*Average*	Gassum	2800	2955	155	84	10	76 - 92	45	10	41 - 50	20	10	18 - 22	224	10	22 - 2240	10	10	1 - 100
	Average	Haldager Sand	1900	1920	20	16	10	14 - 18	12	10	11 - 13	20	10	18 - 22	255	10	26 - 2550	3	10	0 - 30
	Average	Frederikshavn	1700	1756	56	33	10	30 - 36	8	10	7 - 9	15	10	14 - 17	133	10	13 - 1330	1	10	0 - 10
3	Hobro-1	Gassum	2344	2489	145	143	5	136 - 150	63	5	59 - 66	21	6	19 - 22	275	5	55 - 1375	17	5	3 - 85
	Hobro-1	Haldager Sand	1852	1891	39	24	5	23 - 26	18	5	17 - 18	19	5	18 - 20	175	5	35 - 875	3	5	1 - 15
	Hobro-1	Frederikshavn	1741	1806	65	12	5	11 - 12	6	5	6 - 6	19	5	18 - 20	238	5	48 - 1190	1	5	0 - 5
4	Gassum-1	Gassum	1493	1623	130	46	5	44 - 49	44	5	41 - 46	25	6	24 - 27	938	5	188 - 4690	41	5	8 - 205
	Gassum-1	Haldager Sand	1176	1179	2	2	5	2 - 2	2	5	2 - 2	19	7	18 - 20	188	5	38 - 940	0	5	0 - 0
	Gassum-1	Frederikshavn	1053	1154	101	66	5	63 - 70	65	5	61 - 68	30	7	28 - 32	1500	5	300 - 7500	97	5	19 - 485
5	Kvols-1	Gassum	2405	2513	108	55	5	52 - 58	38	5	36 - 40	21	5	20 - 22	300	5	60 - 1500	11	5	2 - 55
	Kvols-1	Haldager Sand	1940	1955	15	15	5	14 - 16	9	5	9 - 10	21	5	20 - 22	363	5	73 - 1815	3	5	1 - 15
	Kvols-1	Frederikshavn	1856	1912	56	56	5	53 - 59	0	5	0 - 0	5	5	5 - 5	0	5	0 - 0	0	5	0 - 0

Table 2. *Reservoir parameters of the Gassum, Haldager Sand and Frederikshavn Formations at the five areas appointed to be suitable for establishing an injection well. The reservoir parameters of appointed areas, 1, 3, 4 and 5, are based on the wells situated within the area (see* **Table 1***). The reservoir parameters of appointed area 2 is based on average values of the nearby wells, Hyllebjerg-1, Farsø-1, Hobro-1 and Kvols-1 wells situated within the Lille Torup area (see* **Table 1***). For detailed descriptions of the parameters and uncertainties, see* http://dybgeotermi.geus.dk/.

7. Potential areas for establishing an injection well

As mentioned earlier, the maps showing formation depth, formation thickness and potential reservoir sand thickness (Figure 3–Figure 14) are suitable for extracting trends on a regional, but not local scale. This should be born in mind when areas containing reservoirs suitable for gas storage are appointed in the following. Selecting areas of limited extent, e.g. 1 km^2, is not advisable as uncertainties will be significant. Appointed areas (AA) thus cover several square kilometres as seen in Figure 15.

7.1 Appointed area – suggestion 1

AA1 is situated c. 10–20 km north of Lille Torup and includes the Hyllebjerg-1 and Farsø-1 wells (Figure 15). The reservoir parameters and burial depth (Table 1 and Table 2) are thus well documented. In the wells, the potential reservoir sand thickness of the Frederikshavn Formation is assessed to 15 m and 9 m (Figure 12), respectively, with corresponding porosities of 19% and 17% and permeabilities of 190 mD and 110 mD (Table 1, refer to Table 2 for uncertainty ranges).

The Haldager Sand Formation is evaluated to constitute an even better storage reservoir with higher porosities and permeabilities (Table 1). It is buried c. 100 m deeper and is separated from the Frederikshavn Formation by the Flyvbjerg and Børglum Formations (Figure 2). Together, the Frederikshavn and Haldager Sand Formations offer two storage options within a depth interval of a few hundred meters.

7.2 Appointed area – suggestion 2

AA2 is of limited extent and is situated immediately north and west of the salt structure beneath Lille Torup (Figure 15). The WebGIS-generated maps suggest the thicknesses up to 300–400 m for the Frederikshavn and Haldager Sand Formations (Figure 11 and Figure 8) and potential reservoir sand thicknesses of more than 15 m at depths shallower than 1400 m. However, interpretation of seismic data next to well-developed salt structures is complicated and uncertainties high. Existing seismic data are insufficient to confirm these thickness estimates and, as a possible consequence, the formation depths may be closer to 2000 m. Thus, the estimated reservoir parameters of the appointed area 2 is based on average values of the nearby wells, Hyllebjerg-1, Farsø-1, Hobro-1 and Kvols-1 wells situated within the area (see Table 2).

It is expected, that the Haldager Sand Formation is buried relatively close to the Frederikshavn Formation and that these two formations offer two storage options within a depth interval of a few hundred meters.

7.3 Appointed area – suggestion 3

AA3 is situated c. 10–15 km east of Lille Torup and includes the Hobro-1 well (Figure 15). The reservoir parameters and burial depth (Table 1 and Table 2) are thus well documented. In the Hobro-1 well, the potential reservoir sand thickness of the Frederikshavn Formation is assessed to 6 m in the Frederikshavn Formation and 18 m in the Haldager Sand Formation with corresponding porosities of 19% and 19% and permeabilities of 240 mD and 180 mD, respectively (Table 1, refer to Table 2 for uncertainty ranges).

In the Hobro-1 well, the Haldager Sand Formation is separated from the Frederikshavn Formation by the Flyvbjerg and Børglum Formations (Figure 2), c. 85 m deeper. Together, the Frederikshavn and Haldager Sand Formations offer two storage options within a depth interval of a few hundred meters.

7.4 Appointed area – suggestion 4

AA4 is situated c. 20–40 km east of Lille Torup and includes the Gassum-1 well (Figure 15). This area is interesting because the Frederikshavn Member is more shallowly buried (<1000 m in the Gassum-1 well, Figure 10), the porosity is high (30%) and the permeability is extremely high (1500 mD) in the Gassum-1 well offering the most excellent storage properties in the larger Lille Torup area (Table 1 and Table 2). In general, the thickness of potential sandstone seems to increase in an easterly direction. In AA4, the Haldager Sand is not present (Figure 7).

7.5 Appointed area – suggestion 5

AA5 is situated c. 10–20 km south of Lille Torup and includes the Kvols-1 well (Figure 15). The reservoir parameters and burial depth (Table 1 and Table 2) are thus well documented. Well-log interpretation of the Kvols-1 well indicates good reservoir properties of the Haldager Sand Formation (porosity = 21%, permeability = 360 mD) at a burial depth of 1940–1955 m. In contrast, the Frederikshavn Formation constitute a poor reservoir (porosity = 5%, permeability = 0 mD) (Table 1, refer to Table 2 for uncertainty ranges).

8. Assessment of injection rate and pore pressure in the potential reservoirs

Rough assessments of injection rate and pore pressure are given for the larger Lille Torup area. Each reservoir parameter presented in Table 3 was calculated as an average of all wells based on values in Table 1. The resulting well injection index thus encompasses the larger Lille Torup.

8.1 Injection rate

A preliminary assessment of the injectivity for the three formations was performed with use of the ECLIPSE reservoir simulation software (Schlumberger 2016).

A simple 3D grid was constructed in the Petrel software (Schlumberger 2015) with the reservoir properties given in Table 3; *i.e.* formation depths, thickness, porosity, permeability gross sand and potential reservoir sand. Compressibility and thermal properties were values determined for the Gassum Formation and also used for the Haldager Sand and Frederikshavn Formations.

Grid dimensions were 5 km x 5 km x <formation thickness>, with an individual grid size of 25 m x 25 m x 2 m. The pore volume of the outermost grid cells in the horizontal plane was multiplied with a factor of 1000 to secure proper boundary conditions for the calculations, *i.e.* to model as if the injection well is situated in a large aquifer.

The simulation results are presented as a well injection index in Table 3. The index returns the volume of brine that can be injected pr. bar injection pressure pr. day. It is assumed that the well injection index corresponds to a well production index. It must be stressed that the injection pressure must be kept below the formation fracture pressure.

Regarding the fracture pressure; a rule of thumb often used in reservoir engineering, states, that the injection pressure should not exceed 85% of the lithostatic pressure. The lithostatic pressure gradient depends on the lithology and porosity of the overburden. A rough estimate of the lithostatic pressure gradient for the area is approx. 0.23 bar/m. With a hydrostatic pressure gradient of max. 0.11 bar/m this returns a pressure window for injection of 0.23x0.85 – 0.11 = 0.09 bar/m. This means that at the top most perforation in the well, *e.g.* 1500 m depth, the injection pressure should not be more than 128 bar higher than the hydrostatic pressure.

8.2 Pore pressure

There are no indications of overpressure in the larger Lille Torup area. The subsurface pressure is thus assumed to be hydrostatic in the Gassum, Haldager Sand and Frederikshavn formations.

	Formation								WII
Formation	**Top** B.MSL (m)	**Base** B.MSL (m)	**Thickness** (m)	**Gross sand** (m)	**Pot. res. sand** (m)	**Avg. por.** (%)	**Res. perm.** (mD)	**Reservoir transmissivity** (Dm)	**(Well injection index)** (m3/bar/day)
Gassum	2238	2379	141	70	43	21	389	17	42
Haldager Sand	1757	1774	17	13	10	20	242	2	9
Frederikshavn	1601	1704	104	39	19	18	406	8	27

Table 3. *Average reservoir parameters for the selected sandy formations in the larger Lille Torup area. B.MSL = Below mean sea level; Pot. res. sand = Potential reservoir sand; Avg. por. = Average porosity; Res. perm. = Reservoir permeability. For detailed descriptions of the parameters, see* http://dybgeotermi.geus.dk/.

9. Conclusions

The Frederikshavn and Haldager Sand Formations constitute potential brine storage reservoirs in the larger Lille Torup area. The reservoir properties of the Haldager Sand Formation are better than for the Frederikshavn Formation but at greater depth except at the Gassum well where the Haldager Sand Formation is absent.

In the vicinity of the storage facility, these formations are relatively deeply buried due to possible rim synclines (peripheral sinks) around the Lille Torup salt structure, but shallower burial depths may be found 10–20 km away from the storage facility. Thus, if an injection well is intended close to the storage facility, it has to be deeper.

Regarding the Frederikshavn Formation, the reservoir potential increases toward the east and culminates in the Gassum-1 well at relatively shallow depth, but relatively far from Lille Torup.

Five areas considered to have storage potential have been appointed based on integrating data concerning formation depth, formation thickness, reservoir potential and distance to Lille Torup. These appointments are preliminary and subject to revision if further, more detailed studies should be performed.

The quality and density of the seismic data in the larger Lille Torup area are insufficient in terms of establishing a detailed evaluation of the spatial distribution of reservoir-holding formations.

Rough estimates of injection pressures are given for the Gassum, Haldager Sand and Frederikshavn Formations as well as production index values.

The formation pressure of potential storage formations is assumed to be hydrostatic.

Finally, it should be noted that when brine produced from a salt cavern is injected into a sandstone formation, the chemical equilibrium between rock and formation water is likely to shift. The possible consequences involve alteration of porosity and permeability due to precipitation and/or dissolution of minerals, e.g. carbonates, sulphates and salt. The alteration impact is controlled by brine composition, how much the formation water chemistry is shifted, mineral composition of the rock and to what degree the injected brine is diluted with fresh water.

10. Recommendations

The accuracy of reservoir properties and maps generated by the WebGIS application depends on quality and density of well and seismic data. In areas with no or poor data coverage, WebGIS interpretations may be less certain and overlook potential reservoir-holding formations. Thus, a more thorough interpretation of seismic data in the larger Lille Torup area is advisable, also in order to validate the storage potential of the five appointed areas.

As existing seismic lines rarely provide sufficiently detailed data of the subsurface in the area of interest, acquisition of new seismic data is mandatory in most cases, i.e. optimizing the understanding of the subsurface by shooting carefully planned new seismic lines. The new seismic data allow more detailed investigations of the reservoir continuity, presence of faults and, if the data resolution allows it, mapping of possible lateral and vertical variations in lithology.

Further, the properties of the overlaying formations should be assessed with respect to effective permeability and fracture strength. When brine is injected into a formation the formation pressure will increase which will inflict on the flow rate of the formation water. In most Danish reservoir rocks, the permeability parallel to layering, i.e. horizontal permeability, is higher than vertical permeability and thus, the bulk of formation water will be displaced laterally by the injected water.

A number of alternative options are available:

- Perform a detailed core analysis to strengthen the determination of porosity and permeability of the rocks.

- Check well tests (if any) in existing off-set wells.

- Setup a pressure prognosis for the overlying formations (pressure vs. depth chart) based on reasonable assumptions on porosity, formation and fluid density and conduct a very conservative estimate on the fracturing pressure.

- Perform a detailed rock mechanics study in order to obtain information on the fracture strength; but GEUS assess that the general rule of thumb of a 85% limit of the lithostatic pressure is valid for the present project.

11. References

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12. Figures

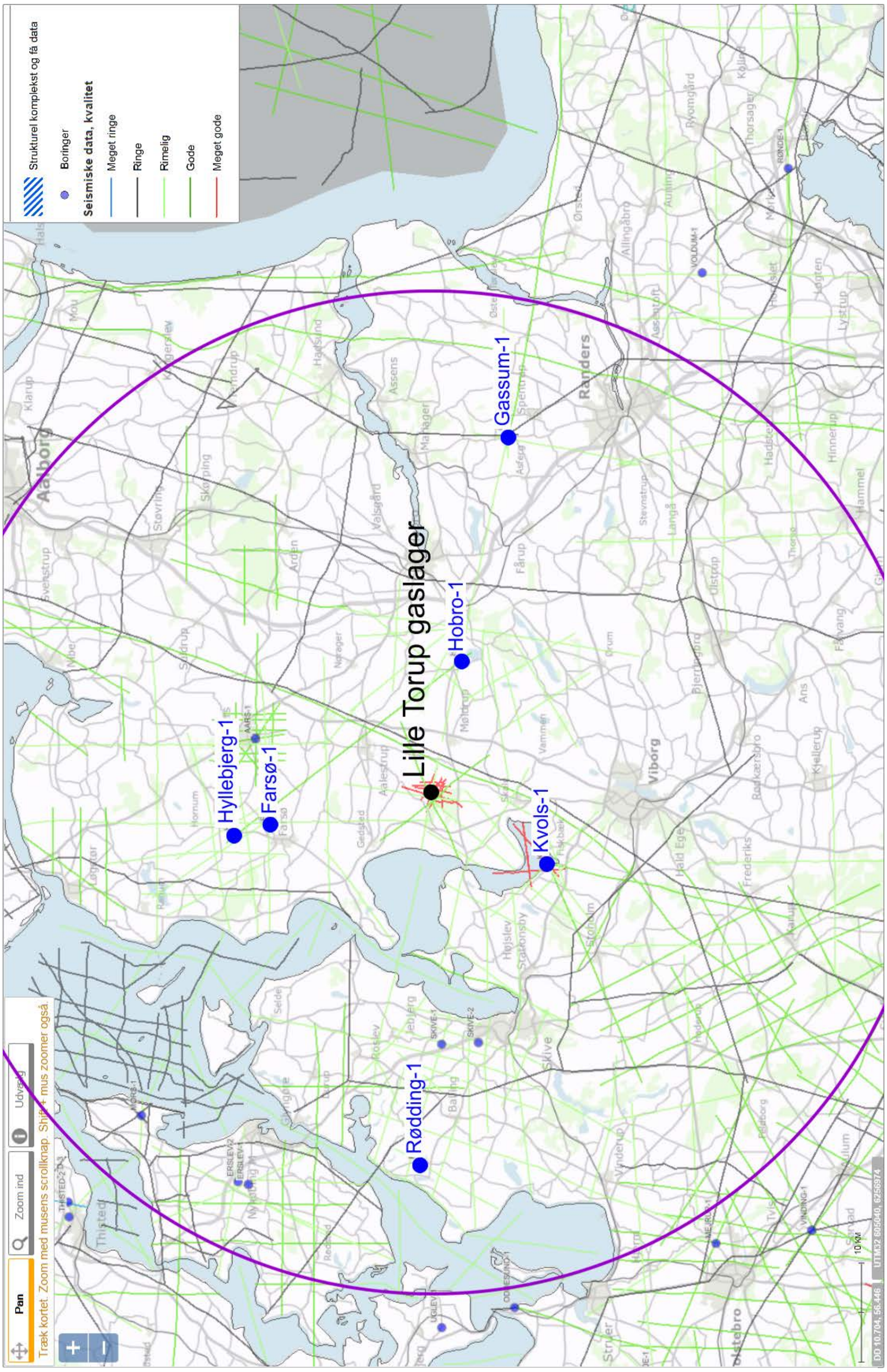

Figure 1. *Geographic map showing distribution of deep wells and 2D seismic lines in the Larger Lille Torup area. The location of the Lille Torup storage facility is shown and the area within 50 km of Lille Torup is marked (purple circle).*

system	Lithostratigraphic unit	
Quaternary	Post Chalk Group	
Cretaceous	Chalk Group	*Assumed low permeability layer*
	Lower Cretaceous unit	*Assumed low perm. layer*
Jurassic	Frederikshavn Fm	*Reservoir*
	Børglum Fm	
	Flyvbjerg Fm	
	Haldager Sand Fm	*Reservoir*
	Fjerritslev Fm	*Assumed low perm. layer*
Triassic	Gassum Fm	*Reservoir*
	Vinding Fm	
	Oddesund Fm	
	Tønder Fm	
	Falster Fm	
	Ørslev Fm	
	Bunter Sandstone Fm	*Reservoir*
Permian	Zechstein Group	

Figure 2. *Lithostratigraphic chart showing the vertical distribution of reservoirs and assumed low permeability layers.*

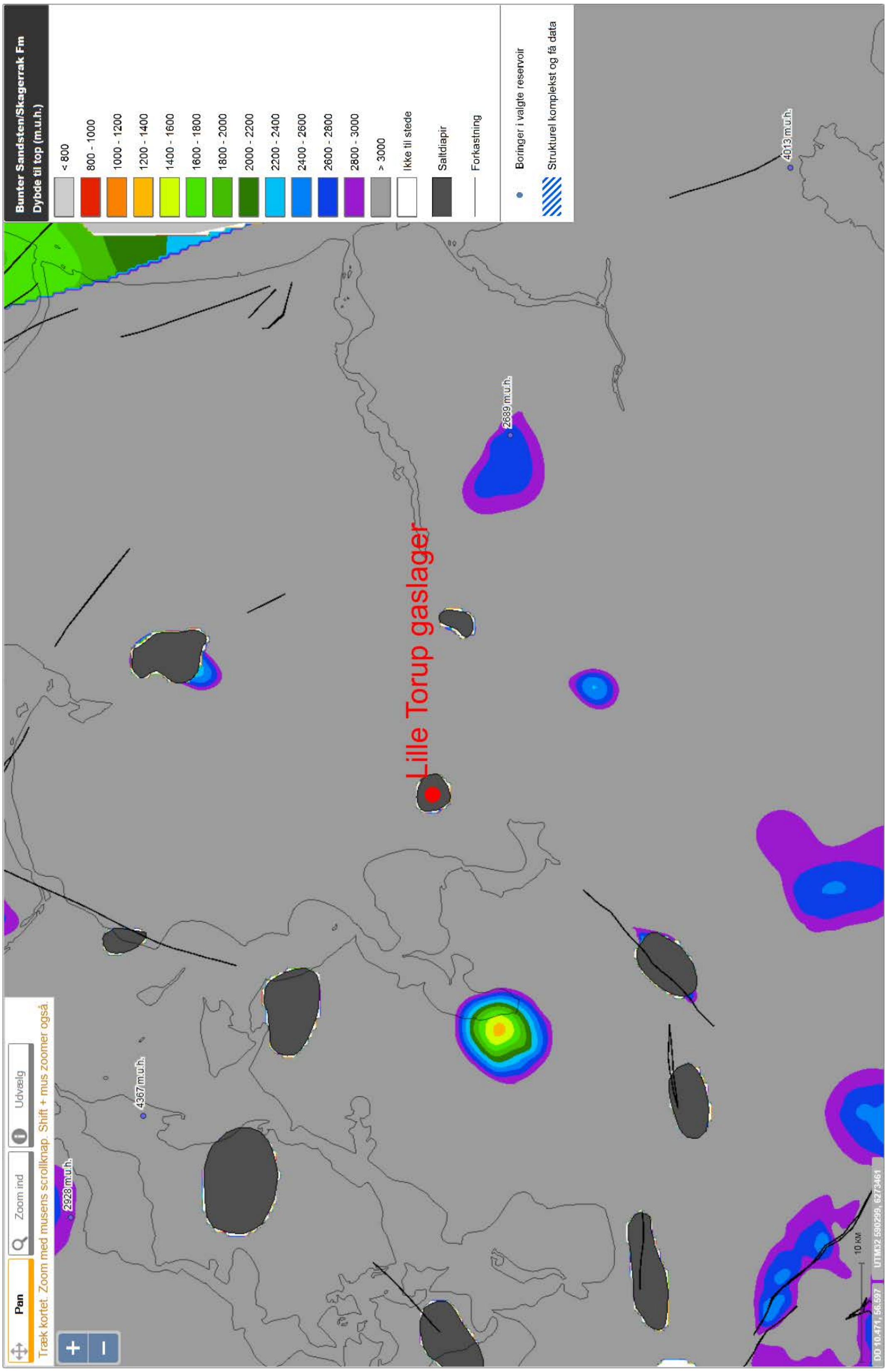

Figure 3. *Depth map of the Bunter Sandstone Formation in the larger Lille Torup area. Most of the formation is buried at depths exceeding 3000 m. Exact depth values are shown at the well sites. The location of the Lille Torup storage facility is shown.*

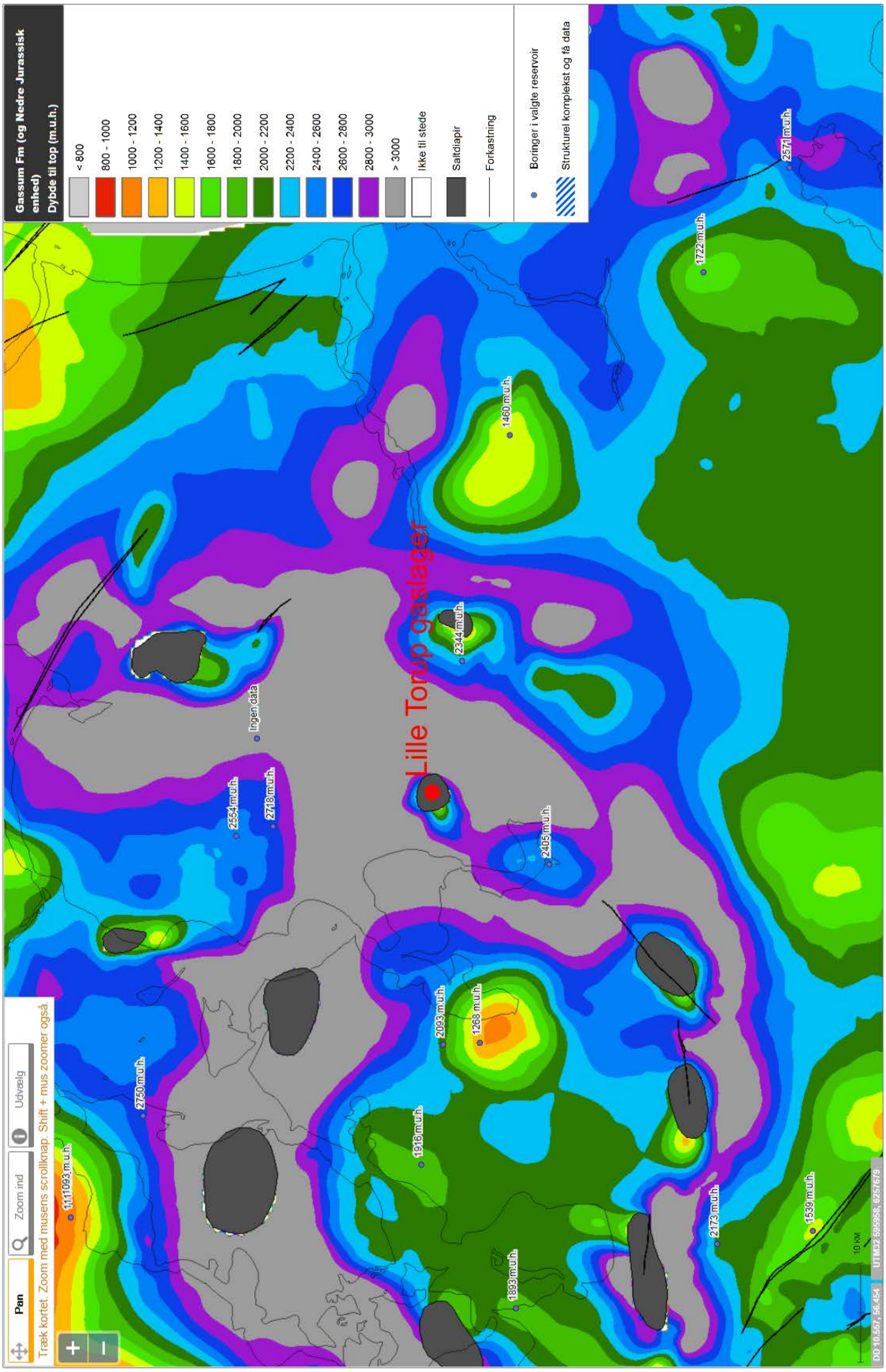

Figure 4. *Depth map of the Gassum Formation in the larger Lille Torup area. A Large part of the formation is buried at depths exceeding 3000 m. Exact depth values are shown at the well sites. The location of the Lille Torup storage facility is shown.*

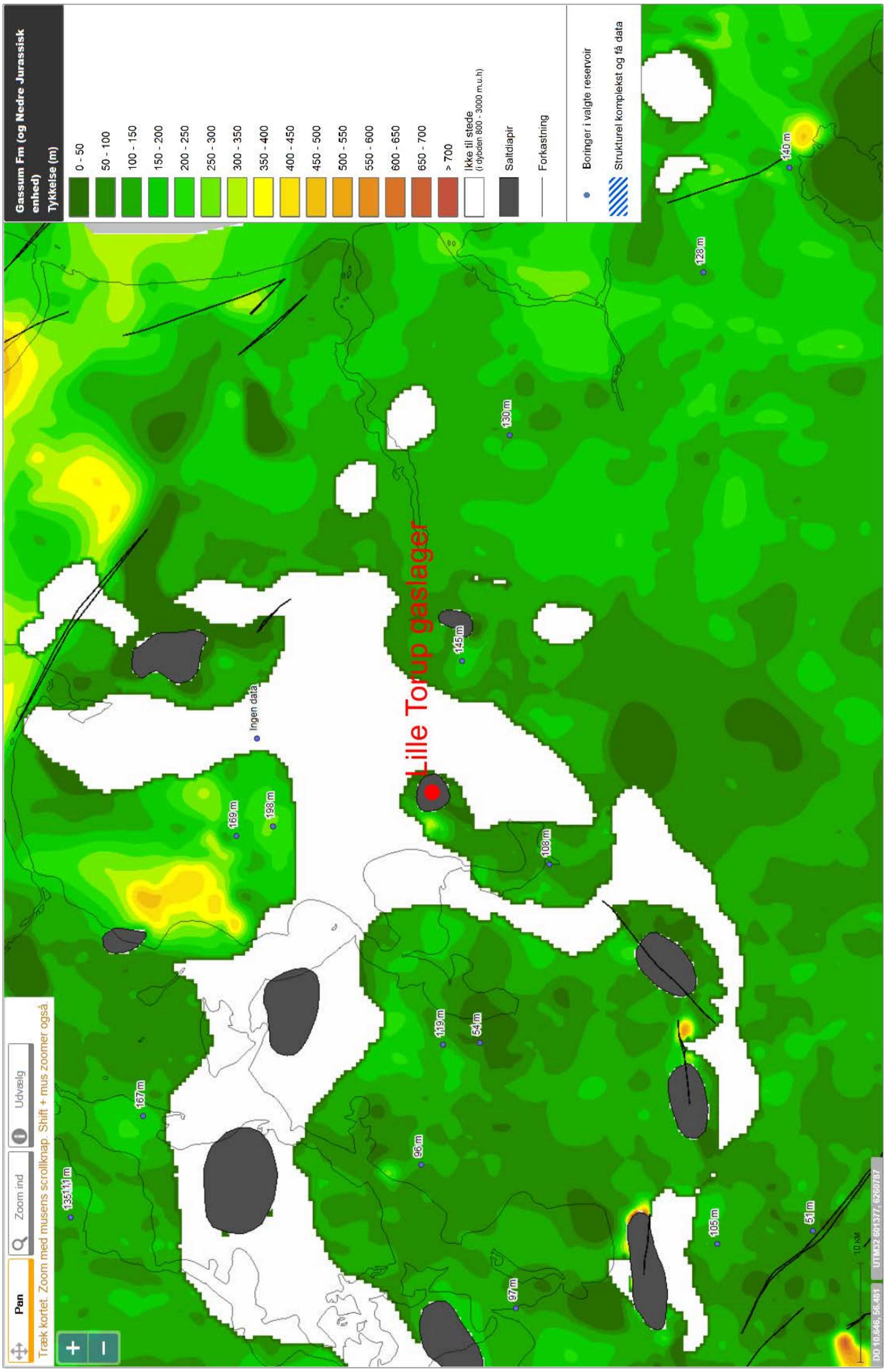

Figure 5. *Thickness map of the Gassum Formation in the larger Lille Torup area. Exact thickness values are shown at the well sites. The location of the Lille Torup storage facility is shown.*

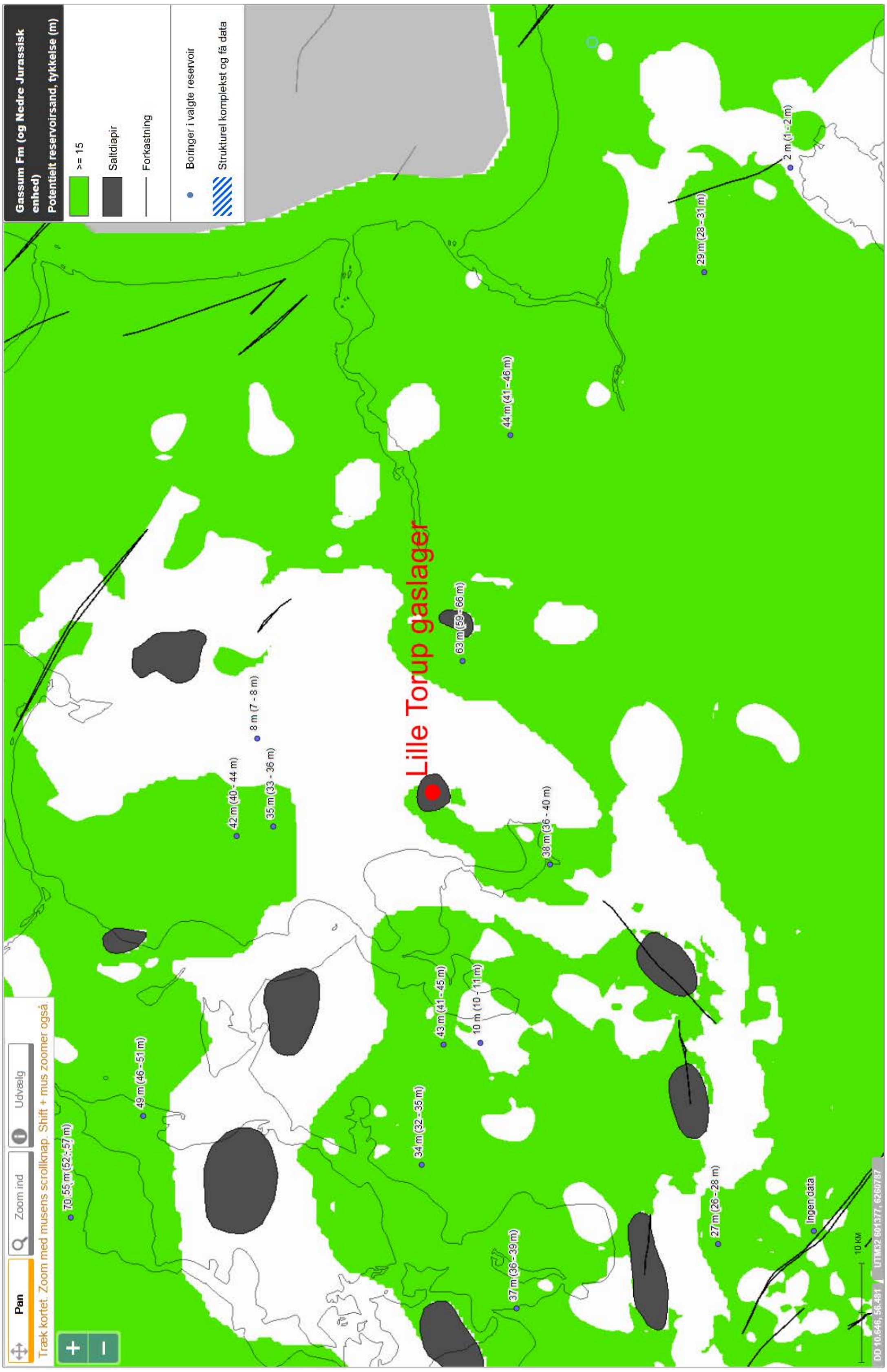

Figure 6. *Potential reservoir sand thickness map of the Gassum Formation in the larger Lille Torup area. In* c. *half of the shown area, the thickness exceeds 15 m. Exact thickness values with expected uncertainty range are shown at the well sites. The location of the Lille Torup storage facility is shown.*

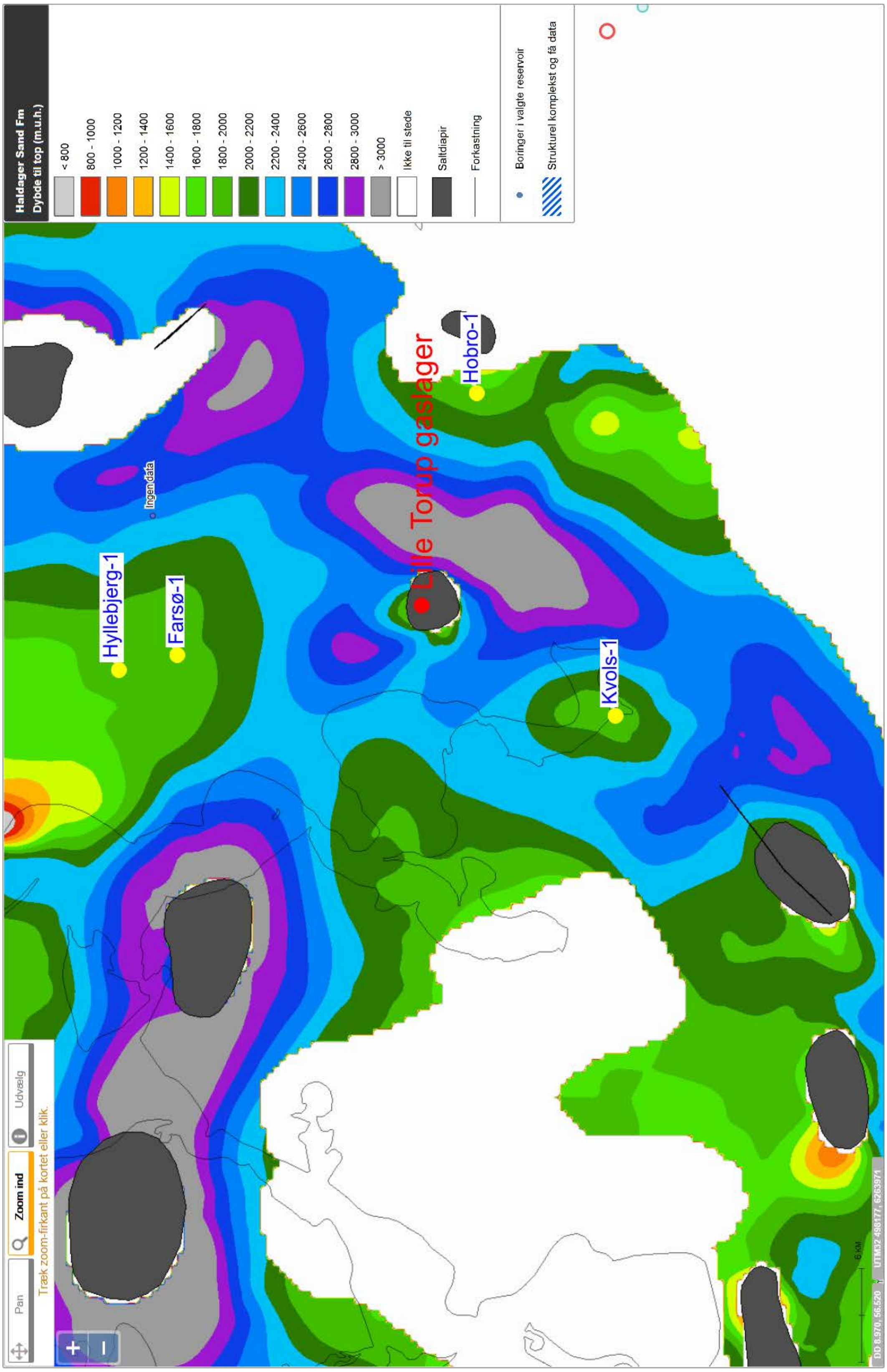

Figure 7. *Depth map of the Haldager Sand Formation in the larger Lille Torup area. The formation is missing in large parts or is buried at depths exceeding 2000 m. The location of the Lille Torup storage facility is shown.*

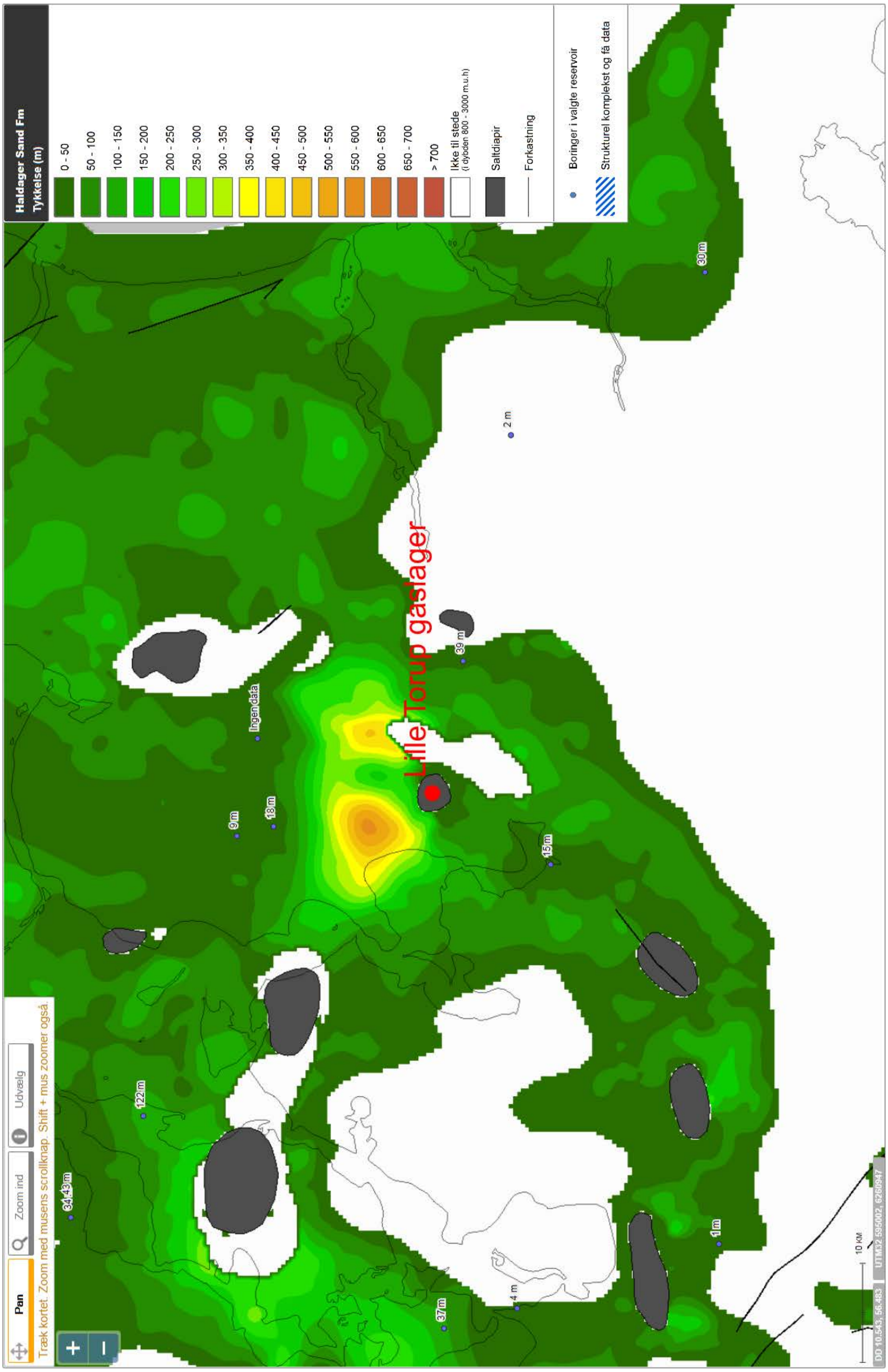

Figure 8. *Thickness map of the Haldager Sand Formation in the larger Lille Torup area. In general, the thickness varies between 0 m and 200 m. Exact thickness values are shown at the well sites. The location of the Lille Torup storage facility is shown.*

Figure 9. *Potential reservoir sand thickness map of the Haldager Sand Formation in the larger Lille Torup area. In* c. *half of the shown area, the thickness exceeds 15 m. Exact thickness values with expected uncertainty range are shown at the well sites. The location of the Lille Torup storage facility is shown.*

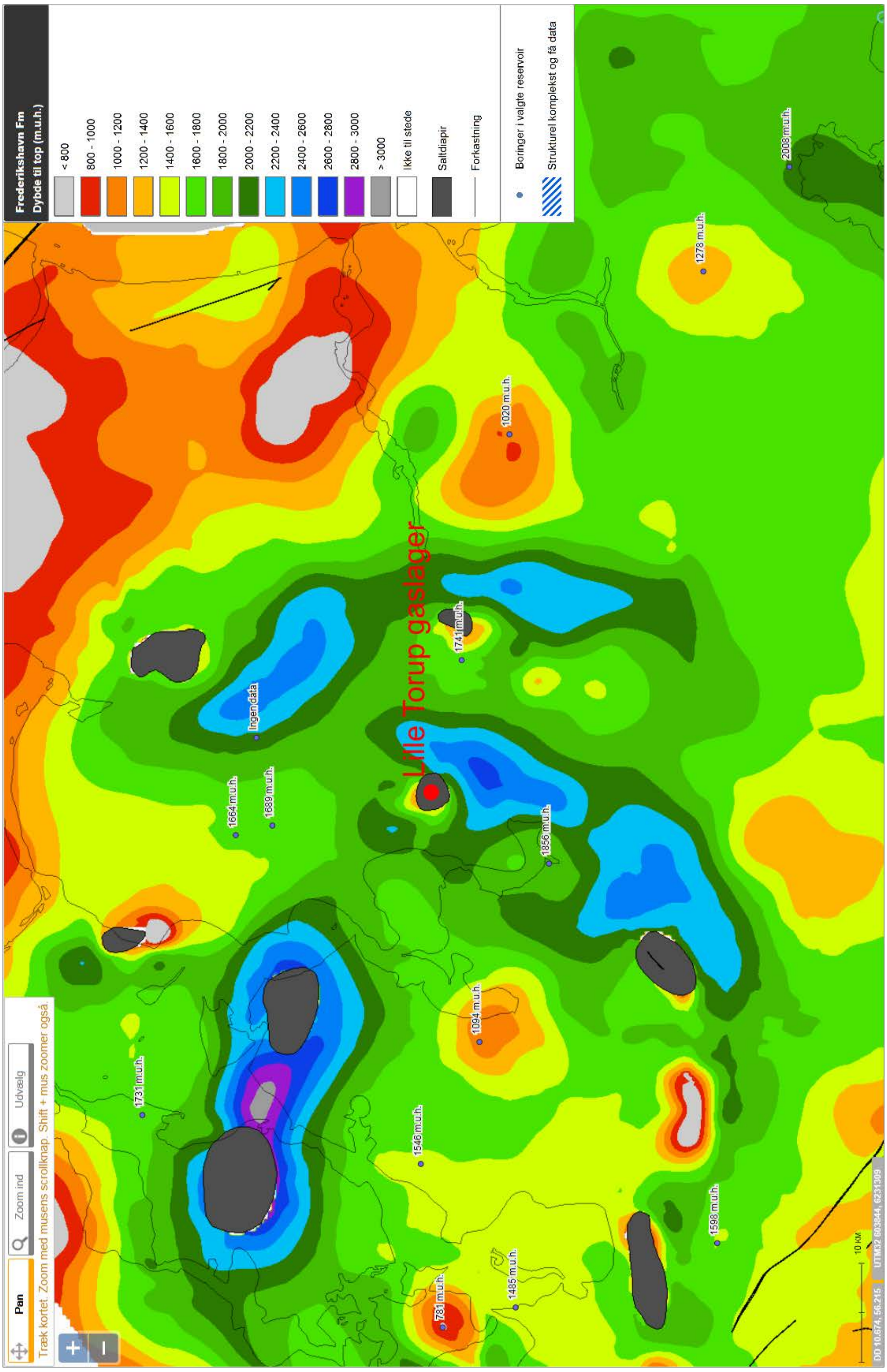

Figure 10. *Depth map of the Frederikshavn Formation in the larger Lille Torup area. Mostly, the formation is buried at depths ranging from 1400 m to 2000 m. Exact depth values are shown at the well sites. The location of the Lille Torup storage facility is shown.*

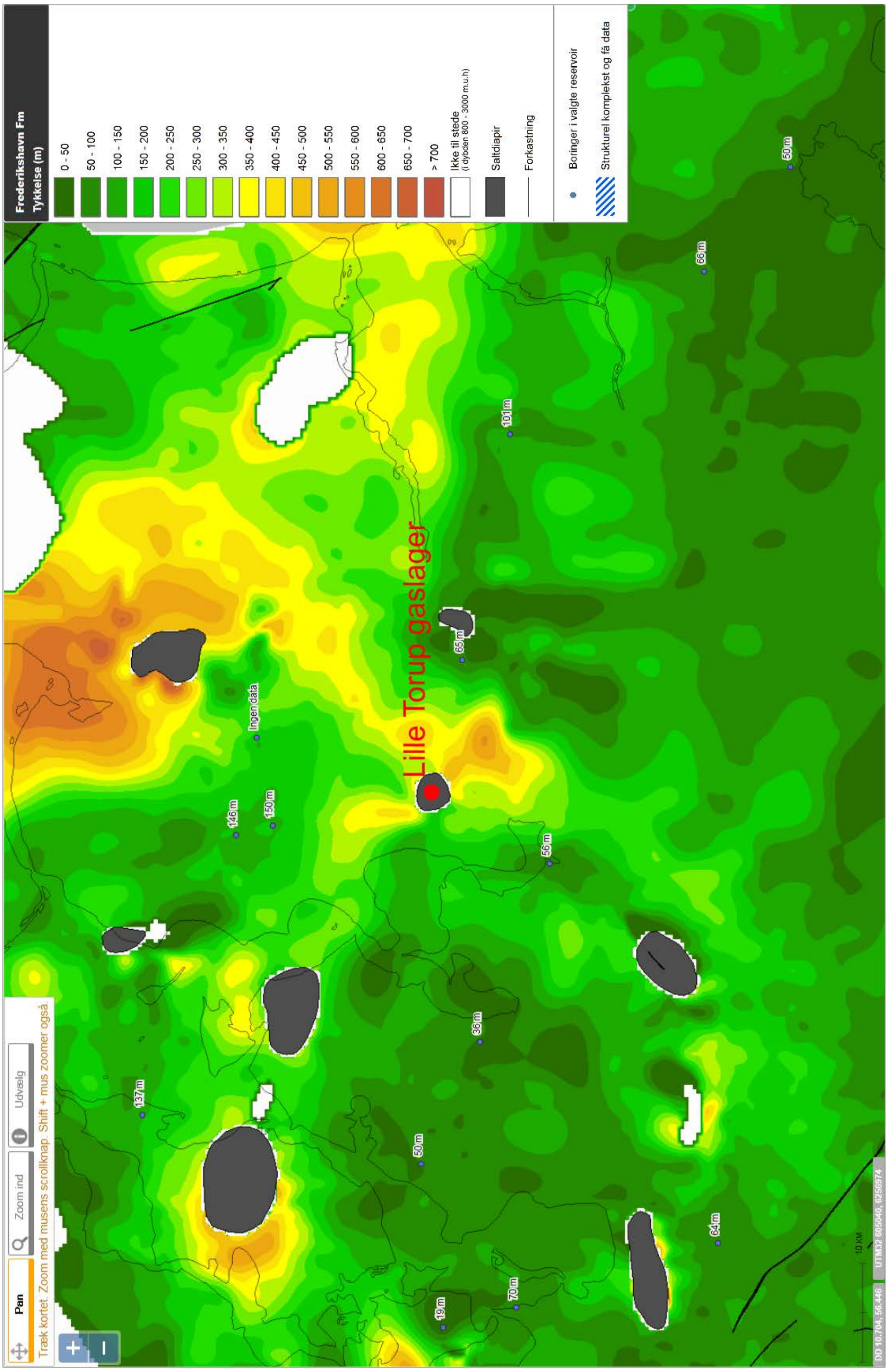

Figure 11. *Thickness map of the Frederikshavn Formation in the larger Lille Torup area. In general, the thickness varies between 50 m and 200 m. Exact thickness values are shown at the well sites. The location of the Lille Torup storage facility is shown.*

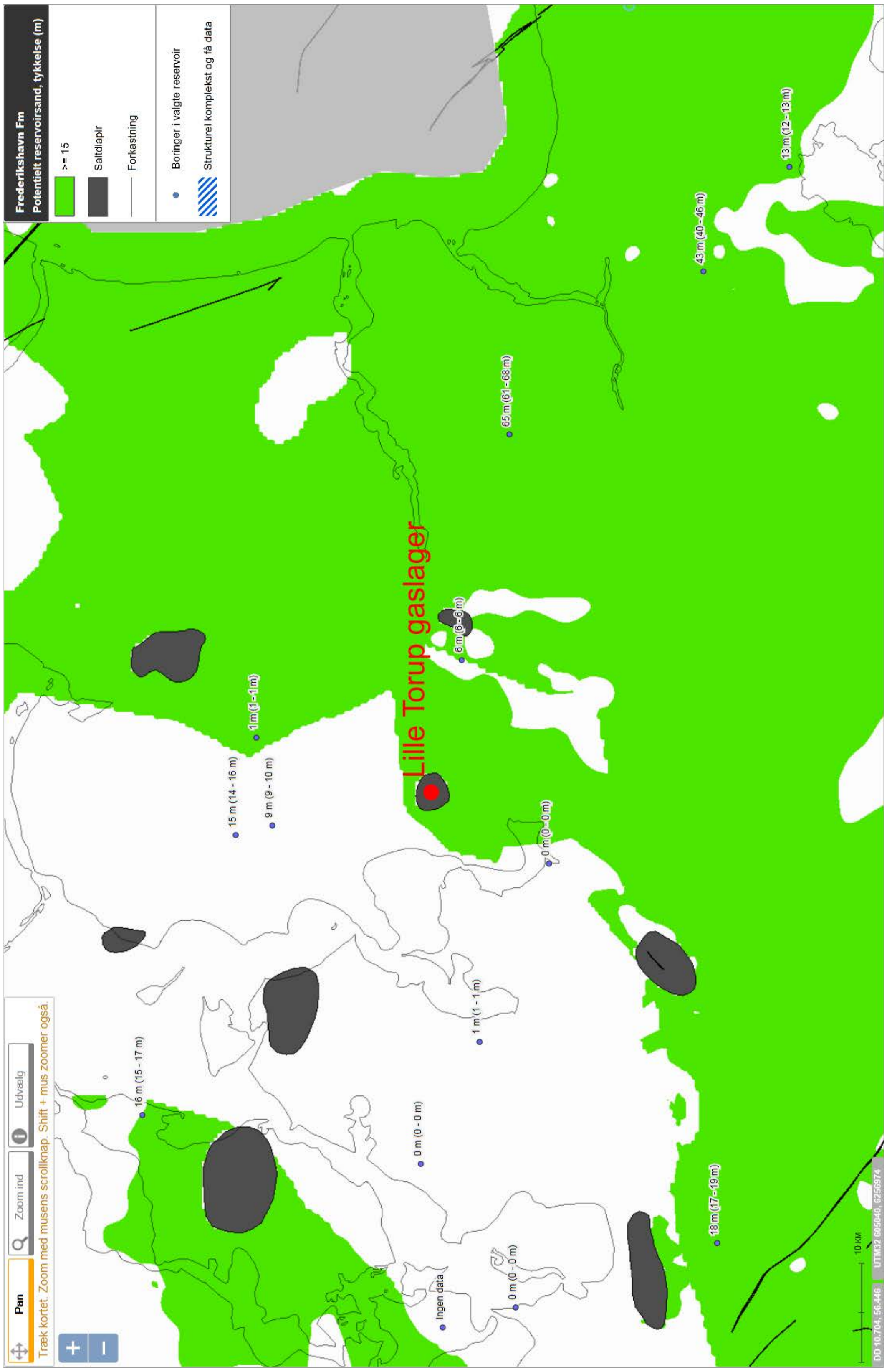

Figure 12. *Potential reservoir sand thickness map of the Frederikshavn Formation in the larger Lille Torup area. In most of the shown area, the thickness exceeds 15 m. Exact thickness values with expected uncertainty range are shown at the well sites. The location of the Lille Torup storage facility is shown.*

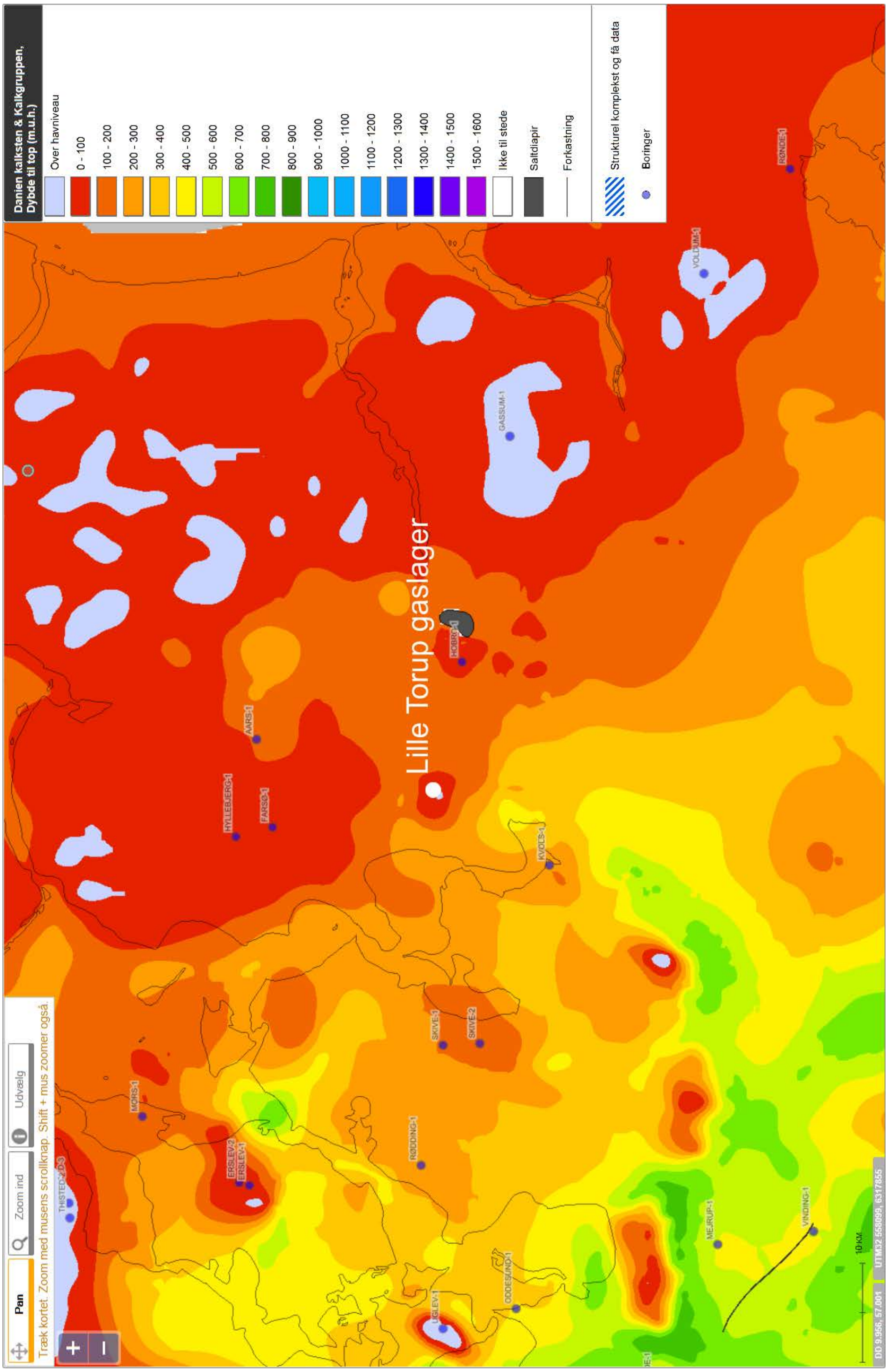

Figure 13. *Depth map of the Chalk group in the larger Lille Torup area. The depth ranges from 0m to more than 700 m. The location of the Lille Torup storage facility is shown.*

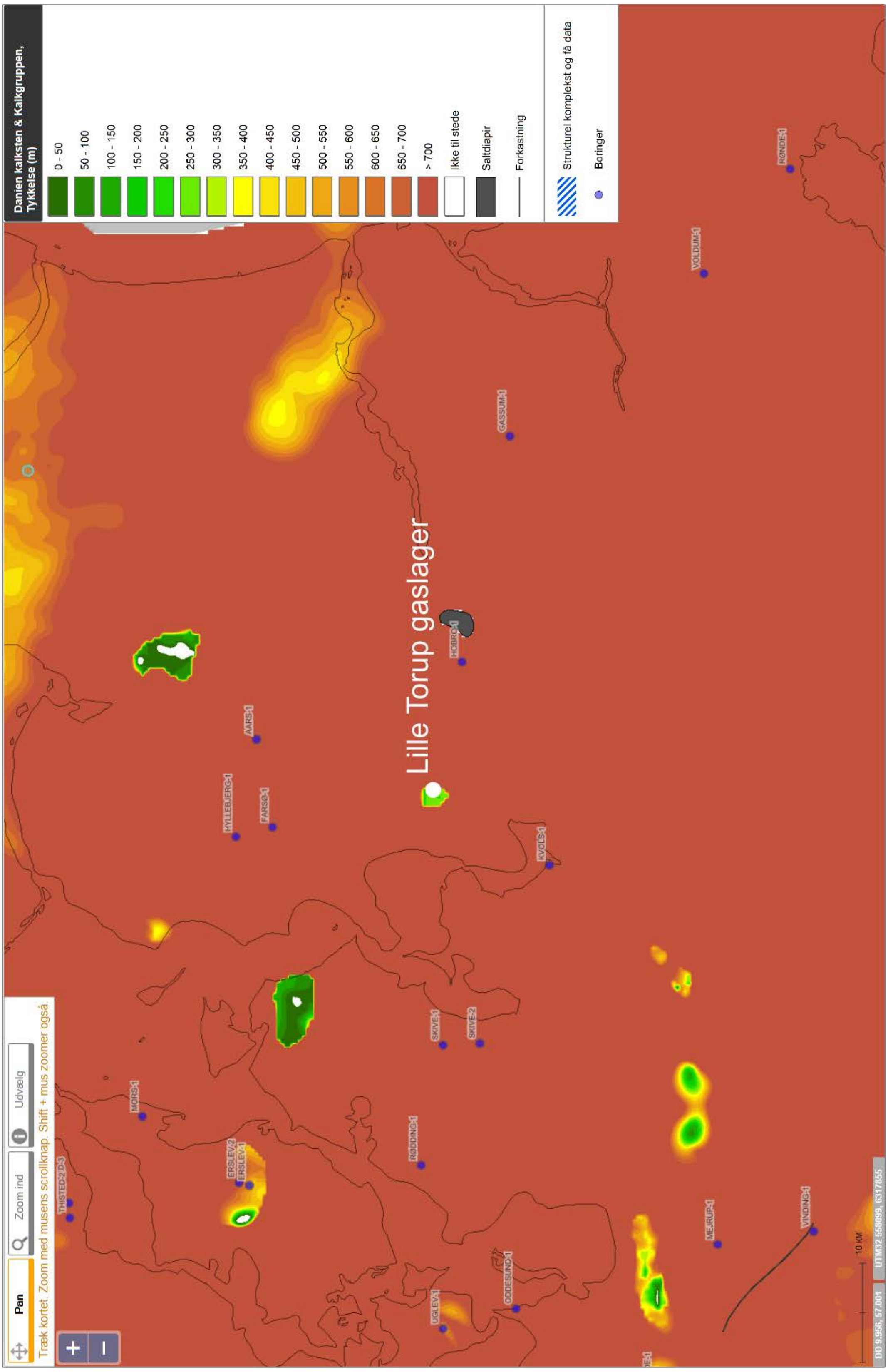

Figure 14. *Thickness map of the Chalk Group in the larger Lille Torup area. Thicknesses greater than 700 m are not differentiated but are known to exceed 1000 m in the shown area. The location of the Lille Torup storage facility is shown.*

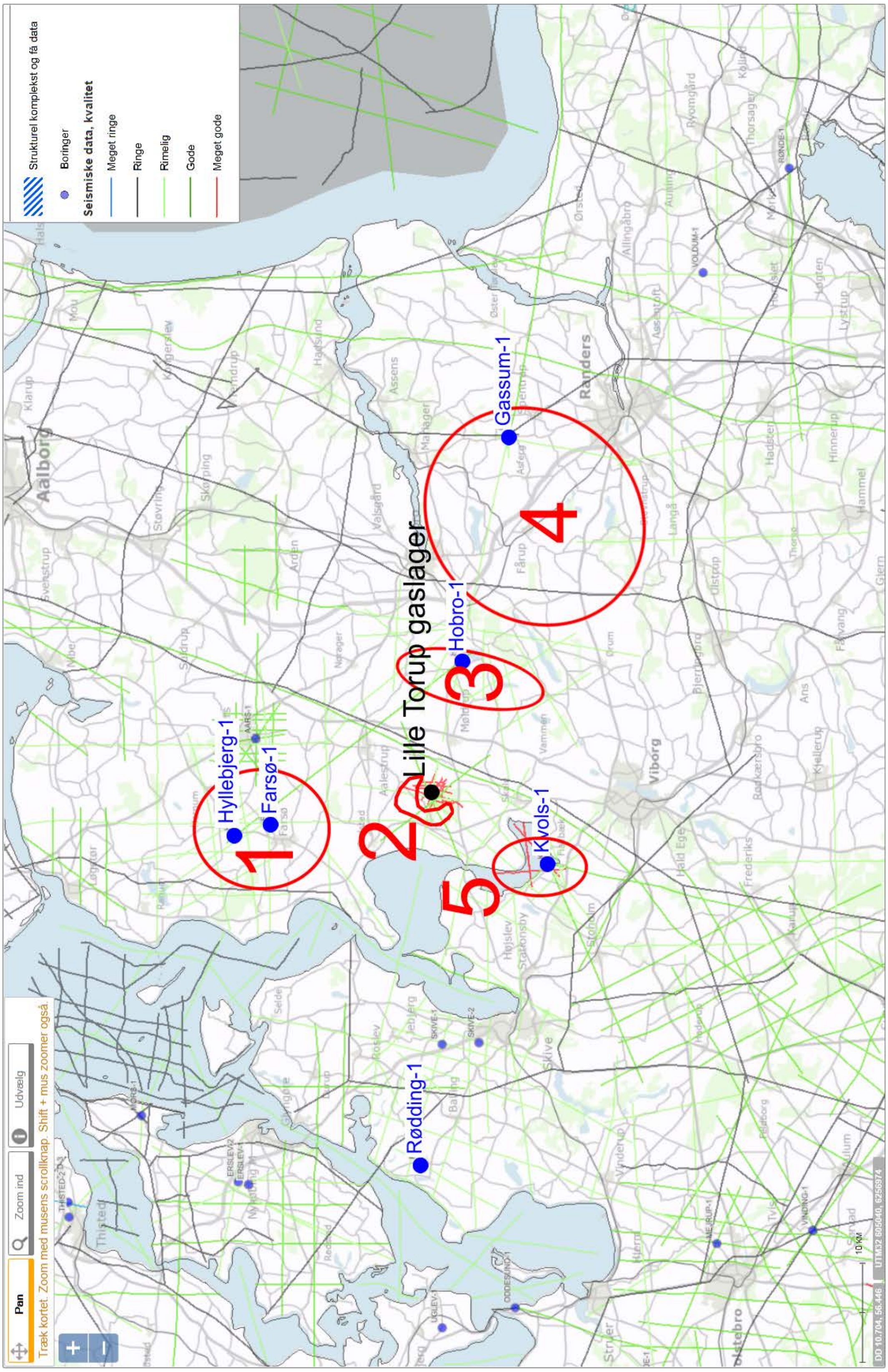

Figure 15. *Map of the larger Lille Torup area showing five areas (red circles) suggested for further research.*