Changing the game – Case study of state of the art exploration of an aquifer storage site in Germany and impact of high resolution data on the initial development plan based on vintage data

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Background

Europe relies on natural gas for about a half of its primary energy needs (BP, 2011; BGR, 2011). In 2011, about one third of Germany's import of natural gas was of Russian origin. For enhancing the transport capacity from the gas fields in Siberia towards the main areas of consumption in Western and Central Europe, the Nord Stream pipeline, having a total length of approx. 1200 km, is being constructed across the Baltic Sea. The first of two planned strings went operational in late 2011, having a maximum transport capacity of 27.5 bcm/a. The second string adding another 27.5 bcm/a will be in operation in 2012. After reaching the German shoreline the pipeline will split into two branches: The NEL heading westwards and the OPAL heading southwards. At present there is no storage dedicated to this pipeline system adjacent to its route within North-Eastern Germany, a situation which would severely threaten necessary back up supply in times of need. Therefore, suitable geologic structures for underground storage located in the North-Eastern part of Germany were evaluated accordingly to add flexibility and safety to the system.

Aims

The project's task was to find a suitable geologic structure for underground storage (UGS) of natural gas to serve for the transmission system for mainly seasonal balancing and back-up reserve in case of technical interruptions. With reference to the enormous capacity of the pipeline the working gas capacity of the UGS should exceed 1 bcm and the gross performance of the facility should be in the range of 20 – 30 mmscm/d.

For the storage identification and selection procedure a large number of potential storage structures were evaluated using available vintage data sets, which were gathered mainly during the 1970s as part of the strategic mapping of the German Democratic Republic. A final ranking was developed using a set of decisive parameter, such as the petrophysical quality of reservoir and seal, depth of top reservoir, maximum permissible pressure, the capacity, possible performance and necessary number of wells, the distance to the main pipelines as well as regulatory issues.

Located in the Northern German Permian Basin, the structure of Hinrichshagen was named after a small village on top. The site is situated in an hilly, rural area with mainly agricultural and touristic use, about 100 km off the Baltic Sea and 26 km off the planned NEL-pipeline. Wide parts of the area are environmentally protected zones. The structure was chosen due to its most favourable conditions in terms of its size, depth, lithology and the available extensive vintage data set so that only a few open issues for the proof of its suitability as a UGS were identified. To close these identified gaps in the data pool a second phase of exploration was developed to provide the needed reliable and detailed results for all planning and permitting procedures. Due to time constraints related to the construction of the Nord Stream pipeline all necessary exploration work had to be performed simultaneously.

Methods

<u>Site selection on vintage data</u>

Close to or within the structure a total of 13 wells were drilled, tested and partially cored in the 1960s and 1970s. In addition several 2D seismic profiles were recorded during the 1970s strategic mapping campaign. This first phase of exploration in the 1970s confirmed the suitability of the structure as a UGS and led to a recommendation for its further development as a storage site.

The initial geological interpretation showed an undisturbed (unfaulted) E-W extended anticline above a Zechstein salt cushion with some minor erosional unconformities at the top of the Mesozoic succession, completely covered by more or less constant series of the Cenozoic sedimentary strata. The top of the Lower Jurassic reservoir sandstone (Hettangian) was identified at approx. 585 m below sea level (bsl) with a spill point at approx. 1100 m bsl.

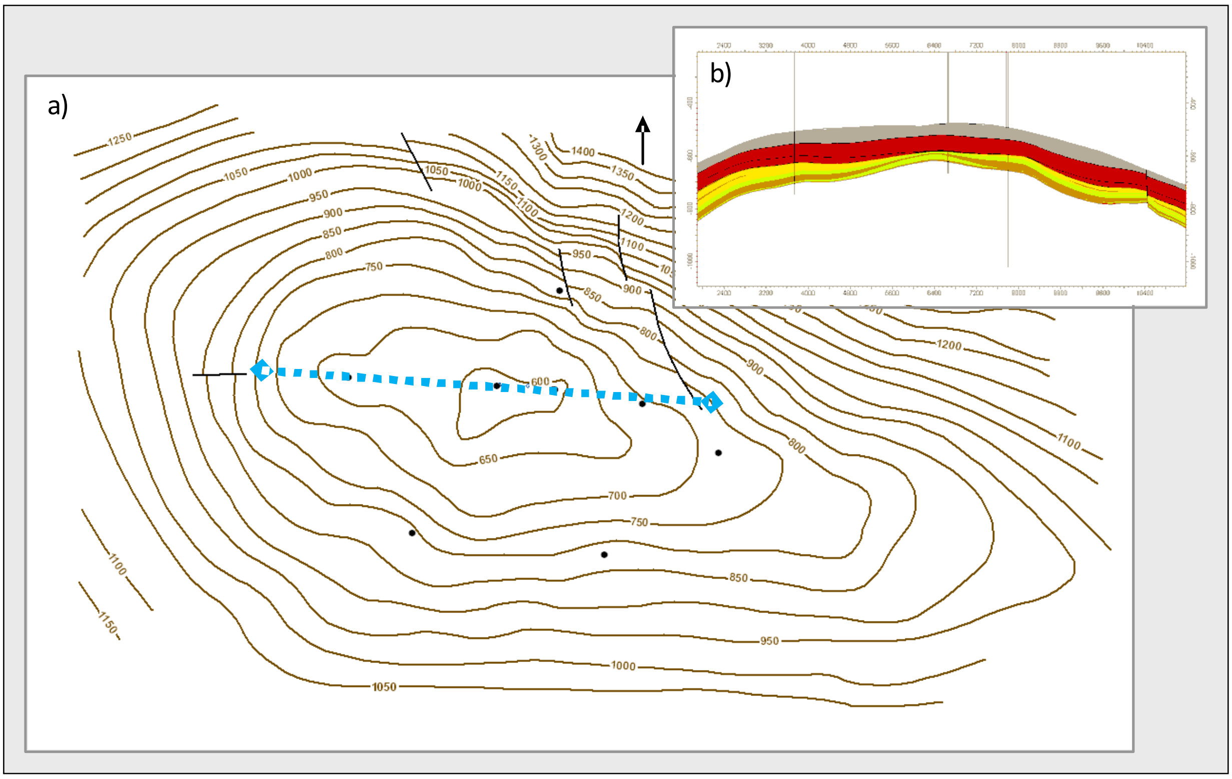


Figure 1. Initial geological interpretation of Hinrichshagen anticline. a) Map view of isobaths at top reservoir, Black points – old wells, black lines - faults. b) Vertical section of 3 main layers (monitor horizon, seal, reservoir). Grey – monitor horizon, red – seal, brown – interbedded strata, yellow - mainly sandstone, light green – pure sandstone.

The available core data were sparse but indicated an effective seal and a weakly consolidated but nevertheless excellent sandstone reservoir suitable for gas storage.

Based on these data an initial estimated storage capacity was calculated using the following assumptions:

- Gas water contact (GWC) at 700 m bsl (surface area of gas zone approx. 24 sqkm),
- mean effective sandstone porosity of 30 %,
- mean effective reservoir thickness of 50 m.

With reference to the predicted permissible pressure gradient and an adjusted pressure regime within operation realistic working gas volumina of > 2.5 bcm were modelled for an average gas saturation of 50 %.

After evaluating the vintage data the remaining open questions were related to:
- the capillary entrance pressure,
- the detailed lithology of the seal,
- the two phase permeability of the sandstone reservoir,
- the precise location and depth of the top
- and the practicable GWC of the reservoir.

From the technical point of view the challenge of an appropriate completion scheme for the weakly consolidated sandstone was still unsolved.

Site exploration methods

A concept for a second phase of exploration using state of the art technologies was developed which contained following activities:

- drilling, coring and testing of three additional wells (thereof two vertical and one S-shape) for filling the recognized data gaps and to ensure a reliable evaluation of the anticline,
- recording of a 3D-seismic survey for clarification of the structural build-up and verification of possible discontinuities as well as for analysis of areal coverage of sealing layers and proof of lateral continuity of lithology respectively reservoir properties.

Drilling
Main tasks of the wells were
- to achieve new petrophysical data about seal and reservoir characteristics (lithology, porosity, permeability, etc.) by intensive core analyses and wireline measurements,
- to appraise the vertical and lateral permeability within the reservoir by hydraulic testing and
- to evaluate the performance of the preferred completion (single wire screen and epoxy coated gravel) in the reservoir section for handling the challenge of weakly/non consolidated fine grained sandstone.

The major challenge of the drilling phase was to stabilize the open-hole without damaging the formation. This was achieved by using oversaturated salt mud to precipitate in the near well bore which was later dissolved again during the gravel procedures. The success of this approach was proven by the caliper logs, showing a minimum of wash outs, and the hydraulic tests, showing a minimum of skin and an excellent reservoir connection.

Well tests using reservoir fluid (brine) were performed to characterise the hydrodynamic properties of the reservoir and to check the lateral and vertical interference between the wells. The produced fluid was stored under nitrogen atmosphere and reinjected later.

The wireline programme encompassed a full log suite including NMR and high resolution FMI logs, the latter being in result of high value for identifying the small scaled reservoir lithology (cross bedding in mm scale) and the fracture/fault zones.

In total approx. 310 m cores were gained from the monitor horizon, the seal and the reservoir section. The analytical programme with more than 300 analysed samples encompassed the measurements of two-phase permeability at different pressures, fines migration, compressibility and capillary entrance pressure.

The results of both the core analyses and the logging data (especially FMI) provided the base for the detailed interpretation of the 3D seismic data.

3D-seismic

The seismic survey covered an area of 59 km² to ensure 30fold coverage for the whole anticline (see figure 2). In total more than 11,000 source points were used. A bin size of 15 x 15 m and a vertical resolution of < 10 m were ensured at the target depth of 600 m below mean sea level.

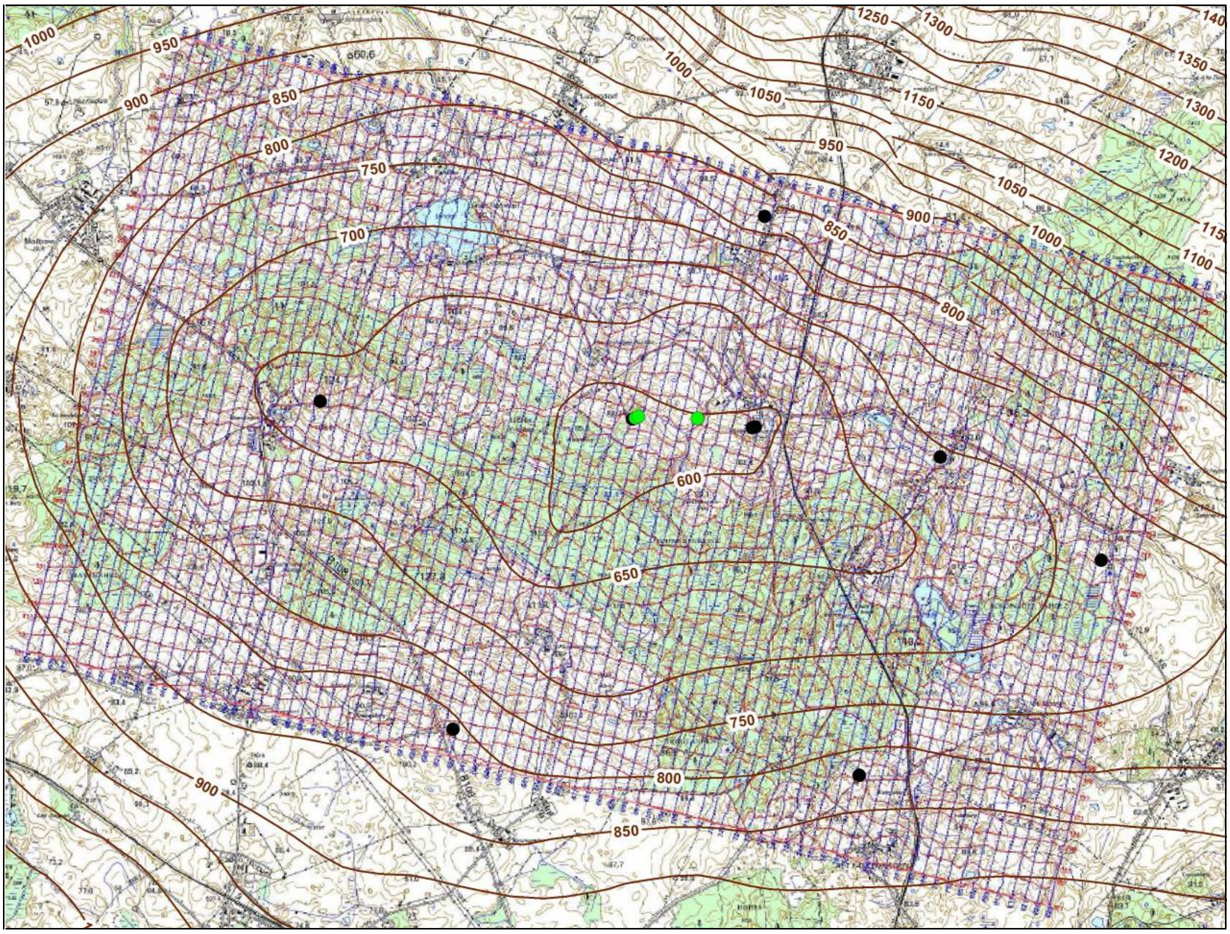


Figure 2. Topographical map with the surveyed seismic source and receiver points. Brown lines - initial isobaths of top reservoir, points: black – old wells, green - new wells.

The field work was performed in late autumn 2008 to prevent damage to the field crop and to fulfil the demands of nature protection. Consisting of 84 % vibroseis the field work was very effective with an average of more than 200 source points/day. The ecological footprint was kept low by permanent coordination with environmental agencies and NGOs.

<u>Interpretation methods</u>

Seismic interpretation

The workflow of the seismic interpretation project consisted of two stages, the initial structural interpretation in time (stage 1) followed by the depth domain (stage 2). After stage 1, horizon grids were delivered to the data processing centre, where they were used as input for the prestack depth conversion of the seismic. In stage 2, the depth converted cube was to be interpreted with the focus of the structural interpretation.

For time interpretation, a prestack zerophase time-volume was used. Six time grids were used as input to the depth conversion of the cube. To optimize the depth conversion, four additional horizons were interpreted and eleven wells were incorporated.
In depth domain, a prestack zerophase depth-volume was used for horizon interpretation (7 horizons) and detailed fault delineation. In addition, attribute cubes were calculated in time and depth domain and used for structural interpretation.
Furthermore an acoustic impedance inversion of pre-stack time migrated seismic was utilized to improve the vertical resolution within the potential storage compartments and estimate reservoir porosities. For this study, well log information from the recently acquired wells were available.

However no reliable lithology discrimination has been established from the well data. Despite the expected good relation between acoustic impedance and neutron porosity, the relation between acoustic impedance and effective porosity was less reliable.

Structural modeling
The static model of Hinrichshagen structure was limited due to the detected complex fault systems which vary in direction and abundance at different intervals. As a result of these limitations the strata model was reduced to four layers of interest: monitor horizon, seal, reservoir and footwall. As input data all known well data (including digitised old logging data) and four interpreted seismic horizon grids and their associated fault delineations were used. The final static model was subdivided into 16 layers (representing strata down to 4 m) with a grid size of 50 x 50 m and nearly 225,000 cells in total. Porosity and permeability distributions were derived from borehole measurements which were calibrated on core data.

Results

The excellent quality of the 3D seismic data was the key for understanding the structural build-up of the anticline and for constructing a reliable static model as well as simulating the 2 phase flow during injection and production of gas. Finally a new development plan was prepared.

<u>Resulting geological interpretation</u>

The new seismic study substantially revised the structural concept of Hinrichshagen which previously was based on vintage 2D lines. The new model shows a tectonically strongly faulted and segmented anticline with parallel bedded strata series. The main difference compared to the vintage data was the identification of a NNE – SSW trending central fault zone with maximum displacements of approx. 100 m. This half graben system divided the anticline in a Western and Eastern part and has previously not been identifiable by the use of both old and new well data as well as of the 2D seismic (see figure 3). Further main fault directions were ESE – WNW and ENE – WSW trending extensional fault zones. The fault system has been reactivated several times and lasts up to the Palaeogene sediments. The top of the structure is located in the Western part and approx. 50 m above the previously interpreted top. The Eastern part of the structure is characterised by a central horst block and distinct downthrows in the northern slope of the anticline.

In contrast the lithological and petrophysical results of old data have been verified by the results of core investigations, logging analyses and test interpretations. High resolution core logs including sedimentary and micro structural FMI analyses show a reservoir composition of a fine grained, nearly unconsolidated sandstone with micro scale sedimentary patterns and partially argillaceous interbedded strata at the lower part of the reservoir (see figure 3). The total thickness of reservoir is 78 m in average. To avoid clogging of the gravel filter by fines migration, filters were installed only in the upper part of reservoir (35 – 45 m).

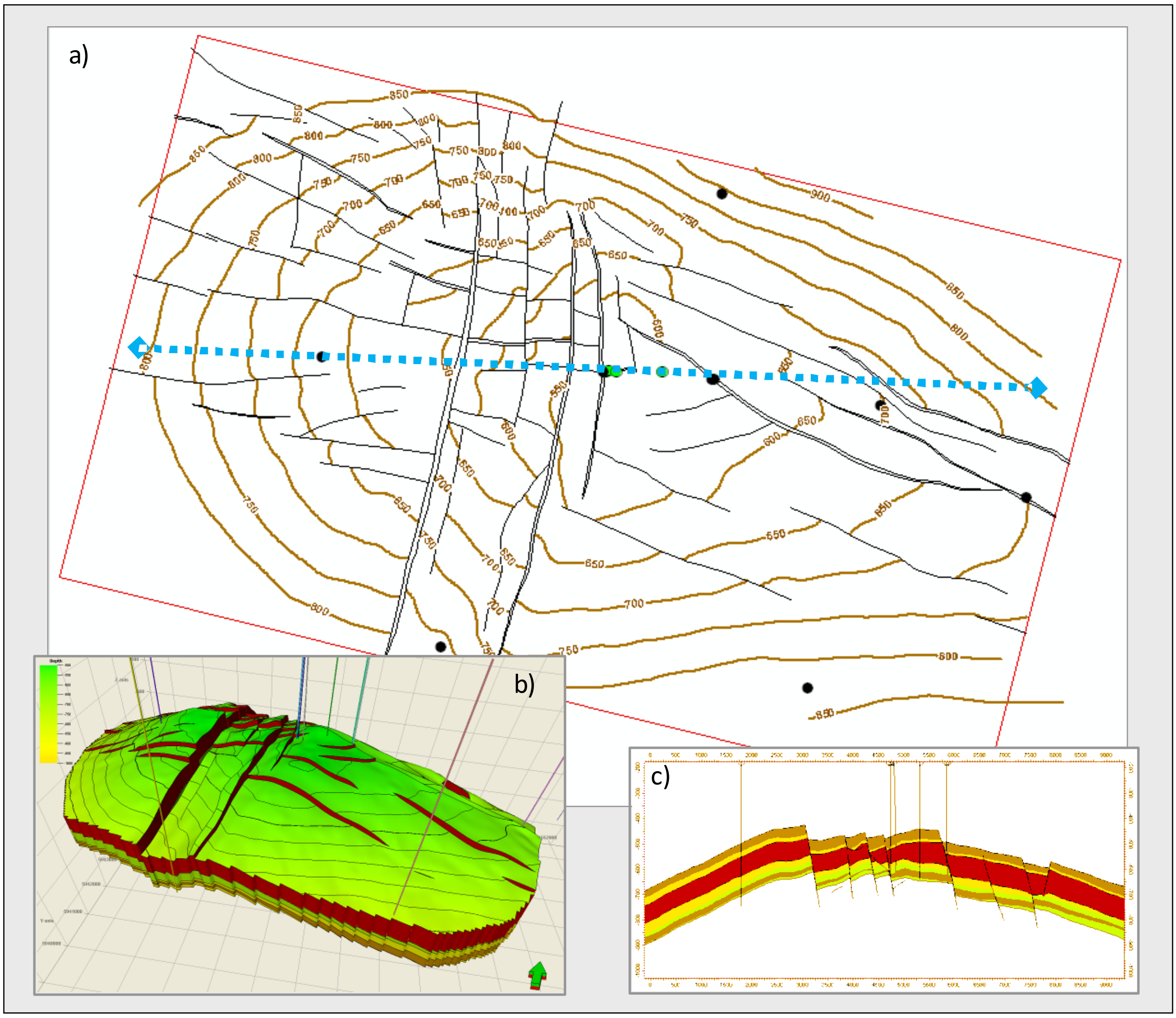


Figure 3. Resulting geological interpretation of Hinrichshagen anticline. a) Map view of isobaths at top reservoir. Points: green – new wells, black – old wells; rectangle – 3D seismic area, dotted line – vertical section. b) 3D structural model of 2 main layers (seal, reservoir). c) Vertical section of 3 main layers (monitor horizon, seal, reservoir). Red – seal, brown – interbedded strata, yellow - mainly sandstone, light green – pure sandstone.

With NMR and standard lithodensity/neutron logging analyses as well as with conventional and special core analyses the expected excellent reservoir properties were reconfirmed. The interpretation of logging data at the three new wells (filter installed interval) showed an arithmetic mean of effective porosity between 28 – 33 %. Corresponding core data varied between 30 – 32 % in average. Additionally arithmetic means of gas permeability between 470 – 790 mD (vertical direction) and 990 – 1790 mD (horizontal direction) were measured. Results of well tests showed a reservoir fluid permeability varying between 990 – 1650 mD which exceed the laboratory results (560 - 620 mD) of the tested intervals significantly.

The core investigations of sealing layers comprised a large amount of capillary pressure investigations supported by additional threshold pressure investigations. Five petrographic, lithological units with total thickness of approx. 80 m and decreasing seal potential in upward direction could be indentified.

Changed focus on interpretation methods

Based on the structural reinterpretation the focus was shifted on proofing the tightness of seal, therefore micro- and macro-scale investigations were applied:

- petrophysical characterisation of sealing strata,
- lithostratigraphic correlation,
- micro-scale seal fault analysis,
- macro-scale fault analysis.

In addition to standardised logging methods at the new drilled wells a high resolution seal fault analysis of micro structures (see figure 4) was performed using:

- FMI-analyses (vertical resolution in mm)
- NMR-analyses of T2-decay time distribution (vertical resolution in dm).

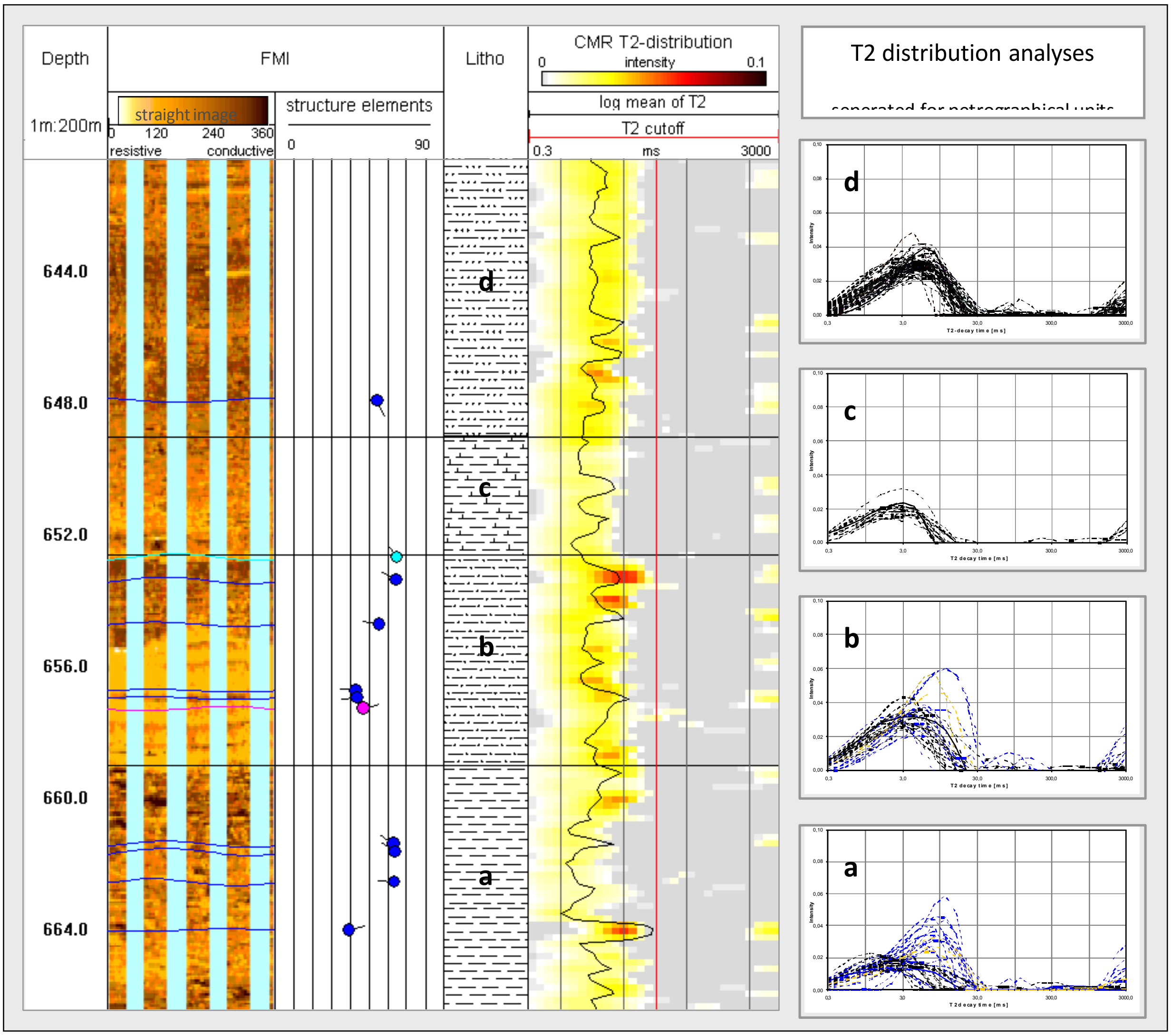


Figure 4. Results of micro-scale seal fault analysis including FMI and CMR-logging data at well Ug HirWa 8. FMI: dark blue – conductive fractures, light blue – resistive fracture, pink – micro fault; NMR diagrams: blue dotted – T2 distribution curves of fractured zones, black dotted – T2 distribution curves of unfractured zones, yellow dotted – T2 distribution curves of sedimentary interbeddings.

An adjustment with petrographical and petrophysical properties of sealing units was made. The results of these micro fault analysis show the occurrence of sporadic micro faults with corresponding predominantly conductive fractures. They significantly influence areas close to faults which causes a decrease of seal capacity in these zones.

By using the static structure model a fault analysis of macro structures and a spill point analysis were carried out. Because of the large fault displacements, the focus was on the characterisation of the fault zone juxtapositions and possible migration paths in relation to the varying gas-water contact (GWC).

A first result of these investigations was the detection of critical migration paths along the main normal fault where reservoir and monitor horizon are located in juxtaposition and enable an uncontrolled gas cross flow (see figure 5). This process can take place at a spill point below 609 m bsl (+/- 10 m resolution of seismic).

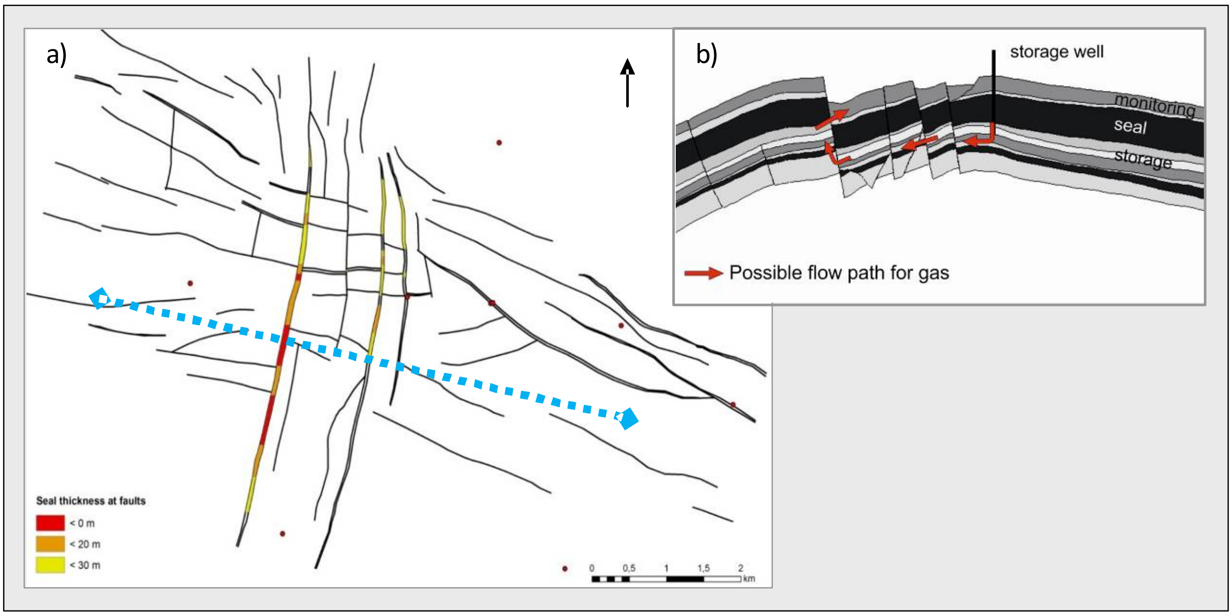


Figure 5. Results of macro-scale fault analysis at structural model. a) Map view of problematic seal thickness along faults. b) Vertical section of a critical gas migration path along main fault.

Consequently a safe operation of an underground storage facility in Hinrichshagen anticline is not possible by using both the Western and Eastern section. Therefore a revised development plan was designed which excluded the Western part by limitation of the GWC with lateral safety distance of min. 50 m to main fault (see figure 6).

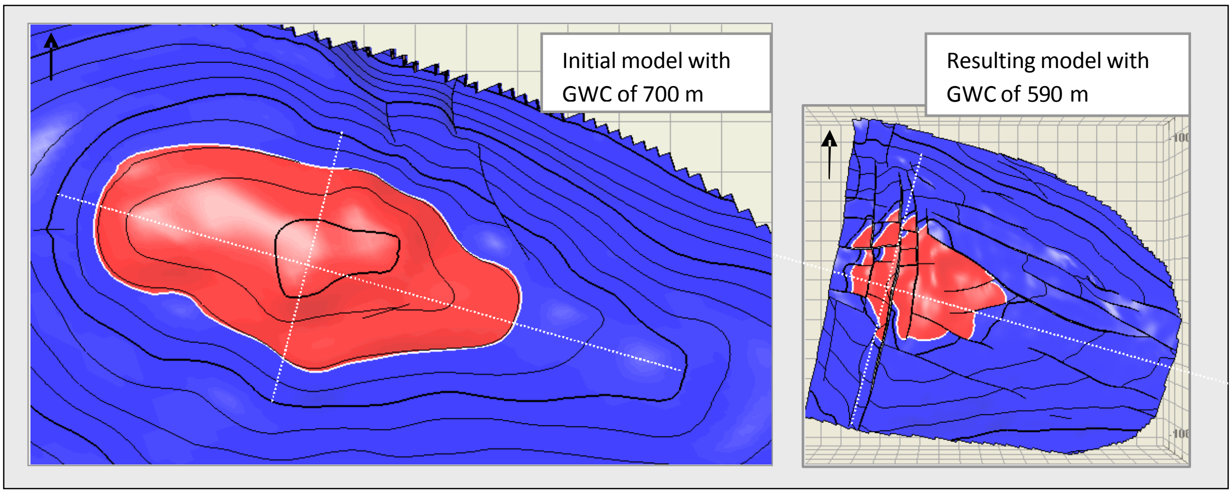


Figure 6. Comparison initial vs. resulting structural model. Red – area above GWC, blue - area below GWC.

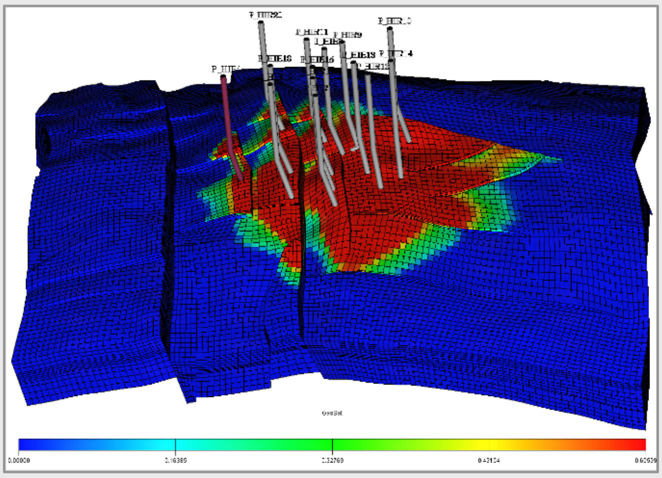
But also the residual Eastern part of the structure is significantly influenced by fault systems. As a result the seal thickness along faults is partly highly reduced. A reliable risk assessment of leakage along fault planes needs further exploration with focus on testing the tightness of seal by crossing the faults.

Resulting reservoir simulation model

For the two phase flow simulation a sector model of the central part of the anticline was used to decrease the computing time and to perform several runs for a sensitivity analysis of the different reservoir parameters. The two phase permeability and the rock compressibility were of major interest for the dynamic modelling.

Several simulation runs were executed to calculate total gas capacities as well as necessary number and positioning of further drillings. For determining the needed number of wells the limitations due to pressure depression at bottom hole (72-87 psia) were considered to avoid an increasing abrasion of drainage filter. The locations of those drillings were designed with respect to the structural position, efficiency of storage facility as well as the further storage development concept (cluster design of drilling sites). As a result of these runs a realistic basic/initial scenario with a total gas volume of 920 mmscm and a working gas capacity of 450 mmscm was found. 14 operation wells including the three already drilled and installed exploration wells would be necessary for the operation of the storage site.

The prognostic calculations for a loading of Hinrichshagen storage facility were executed by a cyclic injection and withdrawal process for a period of 10 years (01.2016 – 02.2026). Main storage parameters obtained from these calculations are documented in figure 7.



parameter		unit	value
total gas		mmscm	917
working gas		mmscm	450
cushion gas		mmscm	467
working-cushion gas ratio		-	1 : 1,04
number of wells	injection	-	13
	production	-	14
total rates	injection	mmscm/d	2,46
	production	mmscm/d	Ø 5,0 (6,0 – 3,0)
Ø rate per well	injection	mmscm/d	0,19
	production	mmscm/d	0,36
storage pressure	min.	psia	609 - 638
	max.	psia	1073 - 1102
BHP injection	min. - max.	psia	754 - 1131
BHP production	min. - max.	psia	522 - 1044
THP injection	min. - max.	psia	725 - 1073
THP production	min. - max.	psia	406 - 1044

Figure 7. Simulation model with summary of main operation parameters according to simulation results. BHP – Bottom-Hole-Pressure; THP –Tubing-Head-Pressure.

However, as a consequence of both the resulting reduced available storage volume and especially of the limited production capacity of 6 mmscm/d, which failed to meet Gazproms demand, Gazprom Germania has put the development plan for the Hinrichshagen structure on hold. Nevertheless it was decided to finalize a new, adjusted development plan for the structure for potential future usage as a storage site on a reduced volumetric scale.

Resulting development plan

As a result of the simulation model the development plan for a storage facility in the Eastern part of Hinrichshagen anticline contains 14 operation wells (whereof 1 is for withdrawal only), 3 monitoring wells (monitor horizon), 1 monitoring well (reservoir) and 1 disposal well for reinjection of formation water. According to the development plan these new wells could be drilled in two different cycles, appropriate to the stages of the storage site construction.

The favoured design of well clusters furthermore was developed with respect to

– limitations of max. realisable deviated sections of drillings (radius 220 m) for ensuring a nearly vertical installation of the filter for epoxy resin graveling
– a minimized impact on the surface area with special considerations to environmental protection areas and known breeding sites of protected species.

As part of the development concept the integration of partly plugged old wells located at central structure is intended. For the two relevant wells a work over with partially deconstruction and reinstallation as monitoring wells is planned.

An assumed concept of storage development of Hinrichshagen structure as well as estimated durations for the single activities from a certain starting time is documented as follows.

	activities	duration [a]
	Planning 2. phase of exploration	1
	Execution/analysis of exploration	1 – 3
	Licence planning of storage development	2 – 4
	Technical planning /acquisition subsurface	4 – 5
	Technical planning /acquisition surface	3 – 4
	Drilling operational wells 1. cycle	5 – 7
	Built-up surface facility	5 – 7
	Drilling operational wells 2. cycle	7 – 8
	Drilling residual operational wells	after 10

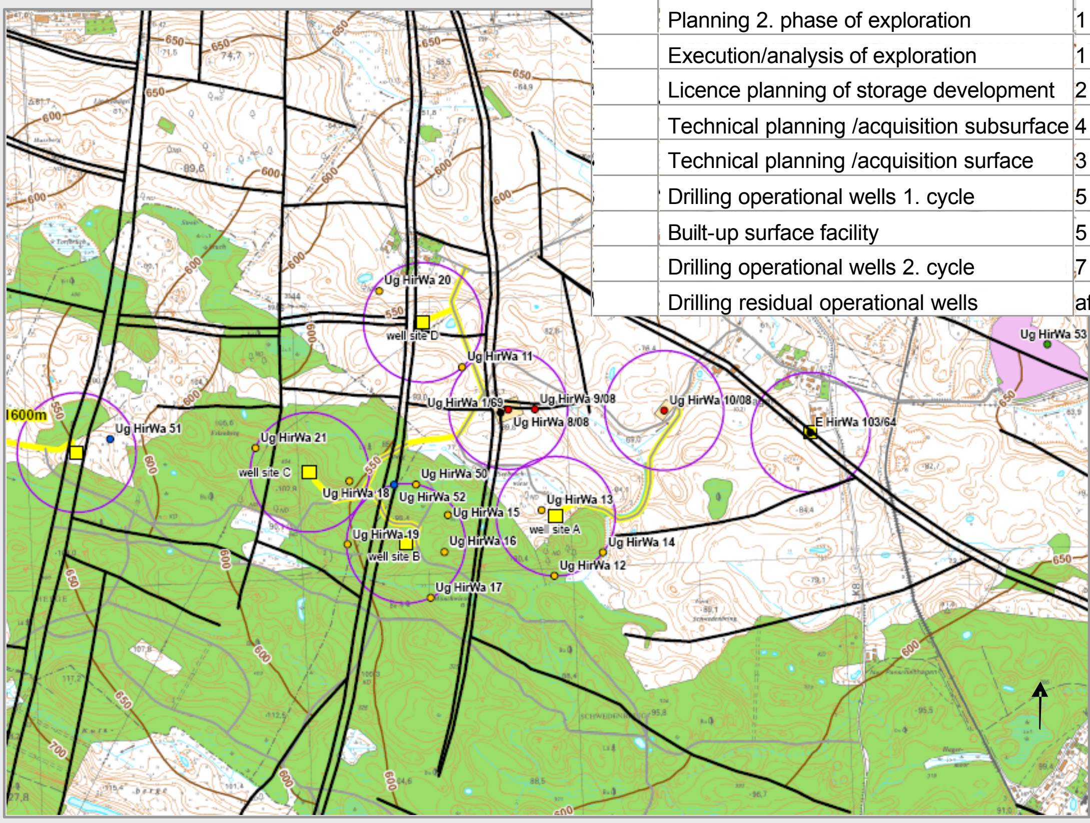


Figure 8. Map view of planned storage facilities with schedule of storage development concept. Points: red - existing operation wells, yellow – planned operation wells, black – work over operation wells, blue – planned monitoring wells, green – disposal well; lines: brown – isobaths of top reservoir, black – faults, grey – streets, yellow – planned streets; rectangle: orange – existing well sites, yellow – planned well sites; circles – 220 m radius around well sites.

Summary

The initial evaluation of the anticline in the 70s based on 13 wells and dozens of km of 2D seismic resulted in a proof of suitability and led to a recommendation for further development of a storage site. Although the initial data pool seemed to be very good and the model of the structure and the storage operation was free of any contradictions the decision to perform a second phase of exploration was of vital importance for that project. Only by this new exploration a detailed knowledge of structure was recognized and a new development concept was created before any investment in surface facilities, pipeline connections or further wells was done.

Old data and especially 2D seismic data are only of limited value and their reliability should not be overestimated. The use of modern techniques and especially the combination of different state-of-the-art technologies is of paramount importance for any reliable technical planning and should therefore be used as a base for any business case.

Regarding the Hinrichshagen structure an unprofitable investment of in sum several millions of Euros as well as severe safety issues regarding potential gas migration were prevented by using state-of-the-art exploration techniques for maximizing both economic and technical safety.

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