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Technical Conference Paper

Geological Exploration for Storage Cavern Construction in the Zuidwending Salt Dome, the Netherlands

Max Wippich - DEEP. Underground Engineering GmbH – Germany

Margarethe Kleczar - DEEP. Underground Engineering GmbH – Germany

Fritz Wilke - DEEP. Underground Engineering GmbH - Germany

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Abstract

In order to realise the first cavern storage for natural gas in the Netherlands, N.V. Nederlandse Gasunie and NUON Storage B.V. are each building caverns in the north-western part of the Zuidwending salt dome structure east of Veendam (province of Groningen), where Akzo Nobel Industrial Chemicals B.V. holds a salt mining concession.

After having started out the project with little information about the Zuidwending salt dome, the knowledge about the stratigraphy and the internal structural style of the deposit increased tremendously with every cavern well drilled. In the second phase of the project (2009/2010), it was already possible to provide a reliable geological model for each location due to a comprehensive geological exploration programme. The level of knowledge reached allowed to make safe predictions and to forecast the geological section in some detail from one well to the other. Cavern layouts were optimized for the particular location and cavern shapes were exactly fit into the specific geological situation. Today, four caverns have been successfully leached while another three caverns are in the leaching phase, and one location has been prepared for cavern construction.

The following paper presents in detail the different methods of geological exploration and how the combination of these methods led to an optimized understanding of the internal geology of the Zuidwending salt dome.

Key words: domal salt; Zechstein; geology; drilling; GPR (ground penetrating radar); caverns for gas storage; the Netherlands.

Introduction

The first cavern storage for natural gas in the Netherlands is currently being developed by the Dutch companies N.V. Nederlandse Gasunie and N.V. Nuon Energy. The storage project is located in a domal salt structure near the village of Zuidwending, east of Veendam (province of Groningen). There, the salt producing company Akzo Nobel Industrial Chemicals B.V. holds a mining concession since the 1960s.

Drilling and construction of the Zuidwending storage facility started in 2006. The initial project comprised the development of four gas storage caverns with two access wells in each. Thus, eight wells were drilled and four caverns of approx. 600,000 m³ geometrical volume each were solution mined until spring 2010. In the second phase of the project, six wells were drilled in 2009/2010 in order to construct four additional caverns with two wells for leaching and gas operation in two of these.

The technical outline of the project is presented in more detail in a separate contribution to the current SMRI Technical Conference volume [1]. The present paper describes the methodology of geological exploration and will give examples of how a geological model of the salt body has been developed in the course of the project.

General Setting

In the subsurface of the eastern part of the Netherlands, thick Zechstein (Permian) salt deposits have been mobilized into diapiric structures. At Zuidwending, the base of salt (base Zechstein Group) is some 2,800 to 3,000 m deep, while the top of salt lies at a shallow depth of around 200 m below sea level.

In map view the Zuidwending dome has a length of roughly 10 km with a maximum width of some 3 km. The bow-shaped contour with the central constriction suggests that the larger Zuidwending structure is an amalgamation of two individual domes, each following a different structural trend: while the 'Zuidwending South' dome has a SW-NE orientation, the 'Zuidwending North' dome reflects an E-W direction (Figure 1). The outer contour of the salt dome, with steep flanks and a flat top surface, and some 50 m of residual 'caprock' suggests that the upper part of the Zuidwending structure has been eroded away by dissolution earlier in earth history with basically the 'stem' of the originally mushroom-shaped body left.

During salt dome formation, the upward movement of the once horizontally bedded salt and associated sulphate and carbonate rocks resulted in complex internal deformation. Owing to the different material properties and rheologic behaviour of the rocks involved, primary bed thicknesses may have been exaggerated or, vice versa, parts of the sequence may have been reduced in thickness or even fully suppressed.

Although the distribution of different rock units in a salt dome may at first sight appear chaotic, a consistent magnitude and overall structural style of folds can be identified in most cases as well as the original stratigraphical order and primary thickness of units can usually be reconstructed. However, to achieve this, a high-quality data set acquired with the help of a comprehensive geological investigation programme of specialized applications is required.

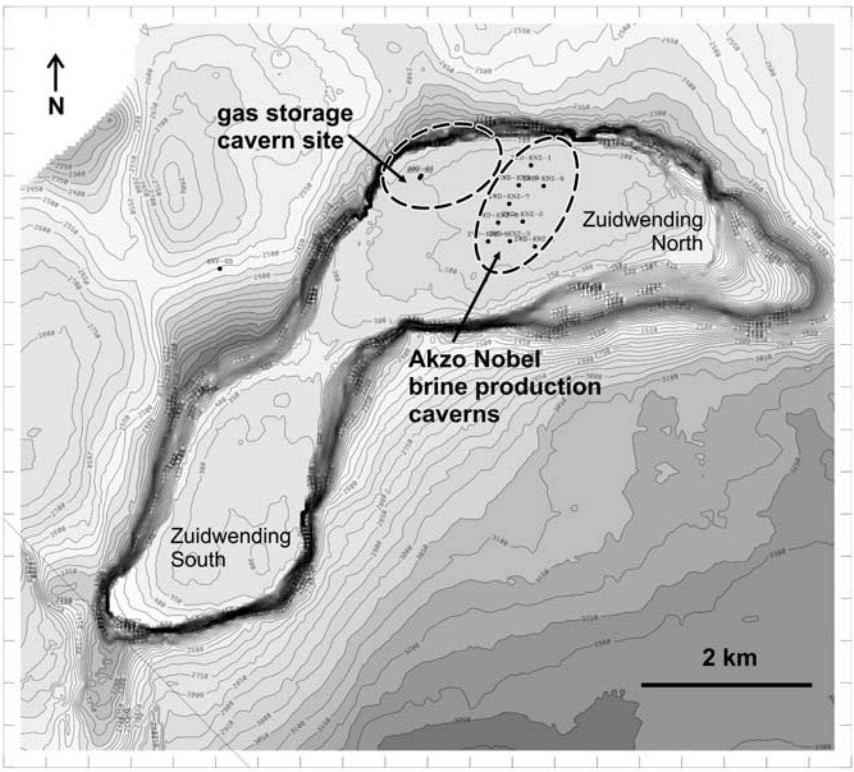

Figure 1: Depth contour map of the Zuidwending salt dome structure (top Zechstein Formation, modified from [2]) and general location of the project area.

Initial Situation

When the first phase of the storage project started out in 2006 little more than the outer shape of the Zuidwending dome was known from the results of a 3D seismic survey [2]. Storage cavern locations had been planned in a fixed grid in order to make the best use of the available mining area and the wells had been designed to be drilled vertically from predetermined surface locations.

In the first cavern well drilled, a 2D salt proximity VSP survey was performed to verify the distance towards the northern salt dome flank [3]. The survey proved the flank to be some 150 m more inward than previously interpreted. Consequently, cavern positions where shifted south, resulting in s-shaped well paths for the wells still to be drilled.

By then, little attention had been paid to the internal architecture of the salt dome. For decades, Akzo Nobel drilled and solution mined clean salt and the general notion prevailed that no other lithologies than pure rock salt would made up at least the central part of the structure.

However, it was at the same time known that E&P wells of Nederlandse Aardolie Maatschappij (NAM) drilled through the north-western corner of the dome had encountered anhydrite blocks (the so-called 'floaters') and beds of potash salt.

As in 2009 the second project phase commenced, the next row of cavern locations had to be developed closer to the northern salt dome flank. It was quite clear from the beginning that apart from keeping a safety distance from the flank, the special challenge would lie in avoiding those beds which may bear a potential risk for safe and controlled cavern construction and at the same time in using the full capacity of the salt concession by identifying locations with sufficient volumes of leachable salt.

Methodology

In developing the Zuidwending underground storage 14 cavern wells were drilled totalling in more than 21,000 m of footage. The entire drilling activities were accompanied by a comprehensive geological investigation programme, during which almost 20,000 m were wireline logged, and some 650 m of cores were extracted and analyzed. The exploration methods used and their significance are described in the following.

Standard Formation Logging

Drill cuttings circulated to surface by the drilling mud were collected with 4 m sample spacing and analyzed on-site with standard petrographical methods. In the Zechstein sequence, the proportion of non-salt lithologies as anhydrite, dolomite, clay etc. is semi-quantitatively identified. Kieserite (magnesium sulphate) can be recognized as well. The constant monitoring of drilling parameters, such as the rate of penetration, can be used to locate formation boundaries.

Bromide Analysis

With progressive evaporation in each of the Zechstein depositional cycles, the trace element bromine became enriched in seawater and the chloride anion increasingly substituted by bromide in the crystal lattice of the precipitated halite (rock salt, NaCl). Therefore, bromide contents in halite (usually given in ppm) increase towards the upper (younger) portions of each cycle. In the Zechstein 2 cycle, bromide values are known to peak around the potash seam (‘Kaliflöz Staßfurt’ equivalent) at the top of the unit [4].

When sampled and analysed in narrow and equidistant intervals, the bromide signature along the well path provides a tool for relative age-dating. Variations in the bromide profile gives indirect information on the alternation of older and younger units and thus, on the degree of folding and structural style around the well (Figure 2). With increasing knowledge in one particular cavern field, absolute bromide values can directly be linked with the stratigraphical information from cores and allow for the creation of a site-specific bromide 'standard profile'.

Salt cuttings were sampled at 2 m intervals and analyzed by ion chromatography immediately after the respective section was drilled. This approach allows to do a stratigraphical interpretation of the section almost in parallel to the drilling progress, thereby forecasting the occurrence of potassic layers and possibly reacting, in due time, with a modification of the exploration or mud programme.

Geophysical Well Logging

Well logging means the continuous measurement of physical formation properties in the open borehole with a wireline suspended downhole tool. The standard logging programme in salt exploration includes the formation density log and the natural gamma ray log. These two log types usually suffice to differentiate between rock salt and the 'heavier' lithologies such as anhydrite, carbonate, etc. and to identify gamma emitting (i.e. mainly potassium bearing) lithologies as clay and potassic salt. The combination of these different logs has proven to provide the best data set for further geological interpretation (Figure 2).

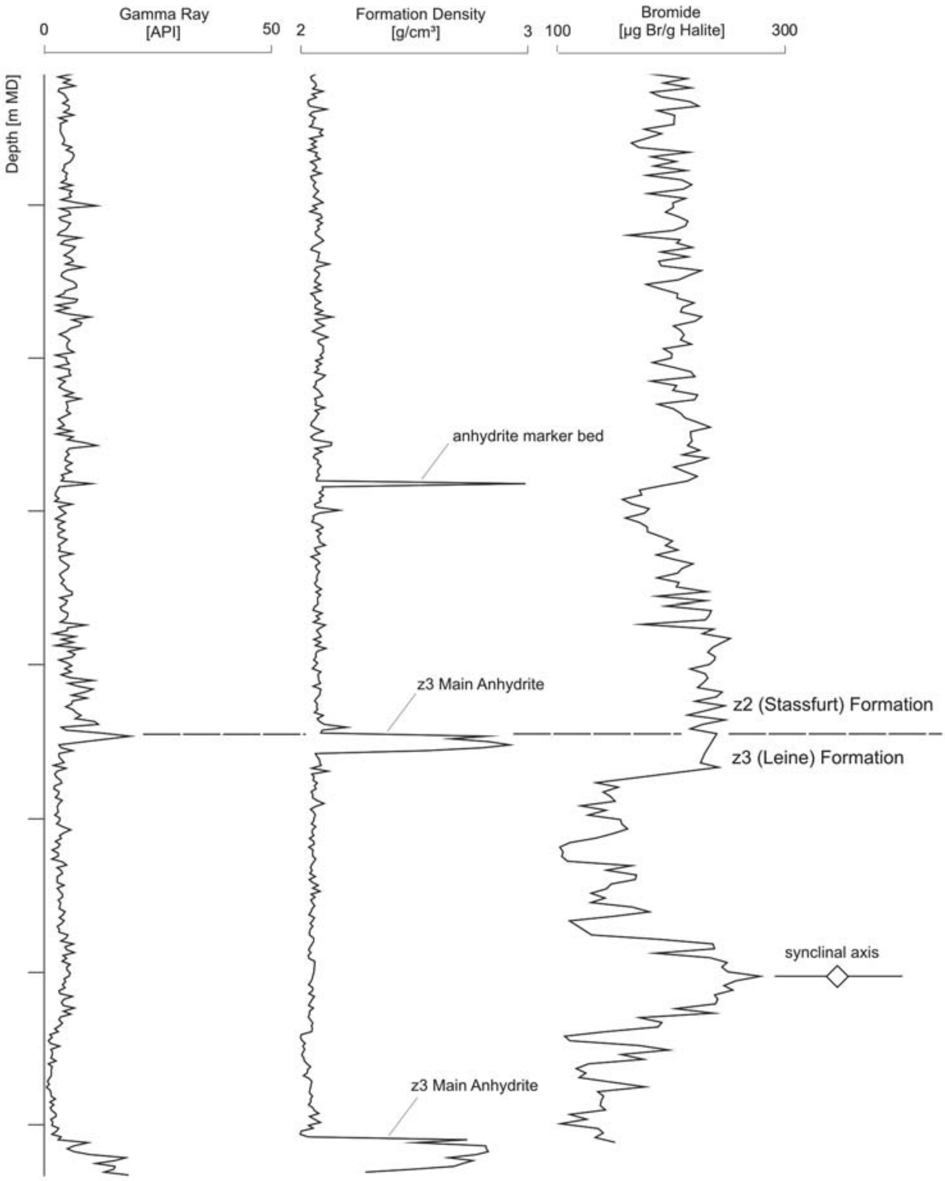

Figure 2: Data set of gamma ray and density logs as well as bromide profile for a defined depth interval. The correlation of the curves allows for geological interpretation (each increment of the vertical axis is 200 m).

Oriented Coring

Although drill cores are only 'spot exposures', coring however provides the only direct exposure of the undisturbed formation and therefore is the prime source of lithological and structural information. For analyzing the dip and strike of bedding planes and oriented fabrics, orientation of cores is an indispensable requirement. While cutting the core, it is continuously scribed by three differentially spaced knives as it enters the core barrel. The reference scribeline has a fixed, known relation to magnetic north.

Cores of 9 m length and 4” diameter were cut at selected depth within the Zechstein sequence. A typical coring programme involved between 6 and 9 cores per cavern. The extracted cores were petrographically described and photographically documented in transmitted and reflected light (see Figure 4).

Ground-penetrating radar (GPR)

The ground-penetrating radar (GPR) technology becomes increasingly established in salt dome exploration and cavern planning [5, 6]. Depending on the geological setting, a GPR survey can provide information on the orientation and distance of formation changes and structural boundaries in a radius of up to several hundreds of meters around the well. However, the GPR results can only be positively assigned to geological structures in correlation with other exploration methods.

The GPR sonde is a wireline-operated downhole tool with an omni-directional transmitting dipole antenna and a receiving antenna. Two different tool configurations are used: the 50 MHz antenna of two orthogonally oriented frames is direction sensitive whereas the 10 MHz antenna records the signal without any angular information. The received signal contains reflections from boundary layers ('reflectors') between materials of different electric impedance. In a salt dome, geological reflectors may be boundary layers between rock salt and other lithologies, such as anhydrite, clay, or potassic salt.

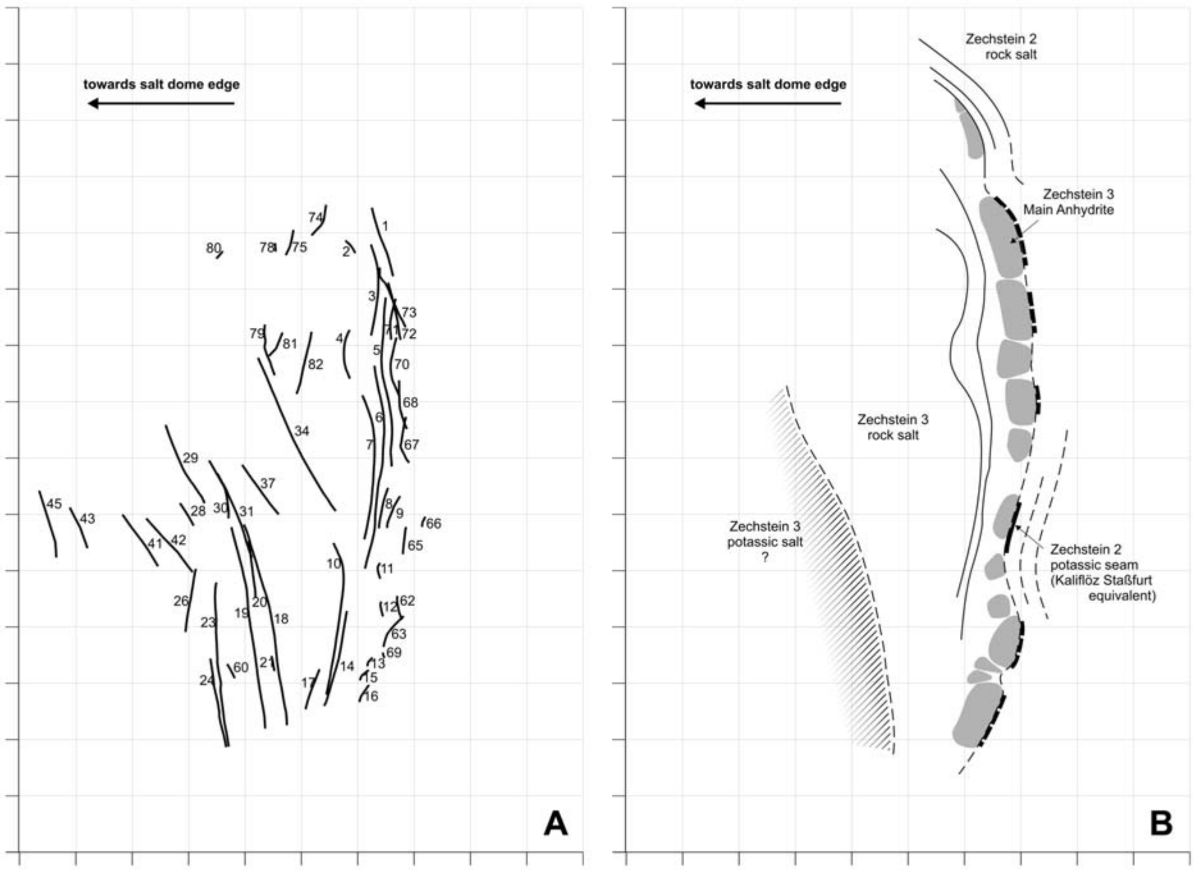

Figure 3: GPR data set of more than 40 reflectors with angular information (A) and stratigraphical/structural interpretation (B). Grid spacing is 50 m.

Development of the Geological Model and Cavern Design

At an early stage, the stratigraphical re-interpretation of well data provided by NAM already allowed to predict that the Zechstein 2 (Stassfurt) potassic seam and overlying Zechstein 3 (Leine) Main Anhydrite occur at the salt dome flank. The cavern wells revealed that rock salt of the Zechstein 2 (Stassfurt) Formation generally forms the central part of the structure while the Zechstein 3 (Leine) Formation is distributed marginally. This distribution of rock units proven for the northern salt dome flank is believed to be the general structural style of the entire Zuidwending dome.

By considering recurrent patterns in the bromide curves and by identifying marker beds and characteristic lithologies, it was possible to establish a local standard section which includes to a certain degree the reconstruction of the primary thickness of the different units. This data helped a lot in extrapolating geological information from the well path or in correlating geological features between wells. When drilling the wells of the second project phase in 2009/2010, it was already possible to make quite reliable predictions on the occurrence of distinct beds at certain depth. Based on that knowledge, an assessment of the volumes of available leachable salt and the definition of required safety distances towards 'risk horizons' was made when designing the storage caverns.

The most important geological feature along the northern flank of the Zuidwending dome is the boundary sequence between the Zechstein 2 (Stassfurt) and the Zechstein 3 (Leine) Formations. This interval of – originally – approx. 40 m true thickness involves a thin Stassfurt potassic seam and a massive carbonate/anhydrite section of the basal Leine Formation. It is particularly those beds which had to be avoided in selecting the location and depth interval of the storage caverns.

The potassic salt and carbonate/anhydrite rocks have a composition and rheologic behaviour very different to rock salt. In particular, the Stassfurt potassic seam is highly soluble and highly mobile while the Leine Carbonate and Main Anhydrite tend to break (or to be 'boudinaged') in larger slabs instead of plastically deform. Owing to those properties, the formation boundary was found to be variously developed wherever it was penetrated by the wells. The sequence is either complete with the potassic seam in place and a full exposure of some 30 to 35 m (true thickness) of Zechstein 3 (Leine) Main Anhydrite or, at the other extreme, several tens of meters of section are missing and Stassfurt salt resting directly on Leine salt. Where the characteristic layers were not directly intersected by the well, it was however possible to estimate the distance towards those unfavourable beds by correlating the available information (bromide values, gamma ray and density logs) with the structural information from cores.

Geometrically, the formation boundary plane can be figured as a 'curtain' of vertical folds that runs parallel to the steep outer flank of the dome. Although some smaller-scale superimposed folding may be involved, the larger structure appears to be relatively simple with fold wavelengths of more than 1,000 m. A comparable structural setting is shown in Figure 5.

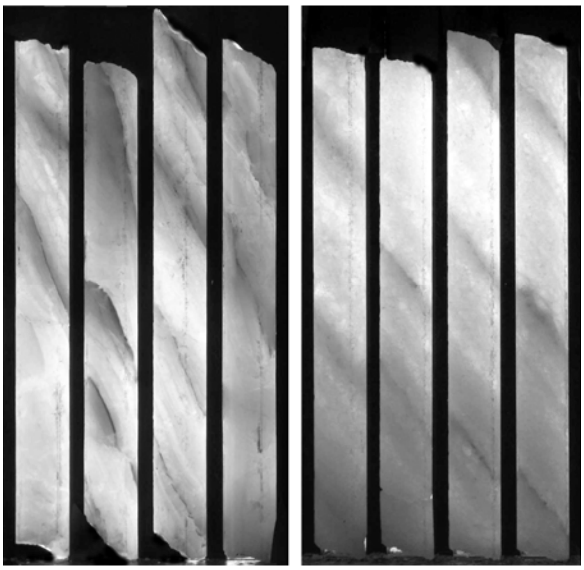

Figure 4: Rock salt from the Zechstein 2 (left) and Zechstein 3 cycles (right). Each core piece is approx. 1 m long. Note how thin anhydrite streaks indicate internal structures. Photographs are taken with lighting from behind.

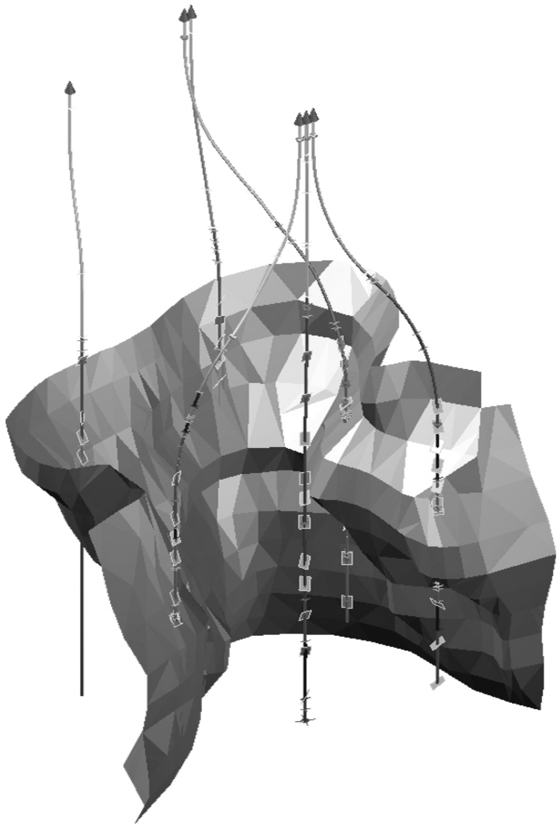

Figure 5: Example of a 3D triangulation model of a curtain-like formation boundary plane penetrated by deviated cavern wells.

Caverns are leached, or are planned to be leached, both in the Zechstein 2 (Stassfurt) and Zechstein 3 (Leine) salts on both sides of the 'curtain'. Where the potash seam and/or anhydrite was penetrated by the well or where the drilled section indicated the proximity of the boundary sequence a GPR survey was performed in order to exactly assess the geometry and the distance of the these beds relative to the well. Three GPR surveys were carried out, which recorded reflectors in a distance of up to 650 m from the well into the formation. The largest data set obtained from a single survey comprises altogether almost 100 geological reflections, approximately 80 of these with angular information.

For one particular well, the advanced geological knowledge gained in the course of the project allowed to draw a very precise picture of the stratigraphical and structural situation even without performing a GPR survey. There, consistently high bromide values and marker beds proven by the wireline logs along with the near-vertical dip of structures identified in the cores indicated the well path to run through young Zechstein 2 (Stassfurt) salt over a length of more than 1,000 m parallel to the boundary plane between the Zechstein 2 (Stassfurt) and Zechstein 3 (Leine) Formations. It was quite clear that the lateral distance towards the boundary and the associated 'risk horizons' would not suffice to accommodate a cavern of the desired diameter and volume. Consequently, the borehole was abandoned and sidetracked by approx. 100 m towards the centre of the salt dome in order to locate the well in older Zechstein 2 (Stassfurt) salt away from the formation boundary. The geological model was then fully corroborated by the results of the sidetrack well. While drilling the sidetrack the simultaneous interpretation of the geological data even allowed to exactly placing a core in the formation boundary deeper in the well to selectively expose this particular interval.

A comprehensive 3D modelling of the north-western part of the Zuidwending salt dome would additionally support the understanding of the geological structure and would provide a planning basis for any potential further expansion of the storage site.

Conclusions

As shown by the example of the Zuidwending salt dome, the combination of the proper geological exploration methods and the 'real-time' evaluation of the results is a successful approach for a complex cavern project. For the Zuidwending case, the benefit was that a detailed prognosis could be given for every new well, and, if necessary, caverns were re-located in consideration of geology and safety distances. By developing a structural/geological model of the environment of every well it was possible to adopt the cavern layout to the specific situation. In conclusion, none of the eight pre-planned cavern locations in this geologically challenging part of the Zuidwending dome had to be abandoned, four caverns have been successfully leached and four locations have been prepared for construction of caverns of up to 1 million m³ geometrical volume.

Acknowledgement

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