KMS Technologies – KJT Enterprises Inc.

Subsalt imaging in Northern Germany using Multiphysics (magnetotellurics, gravity, and seismics)

C. Henke, M. Krieger, K. Strack, and A. Zerilli

PUBLISHED in Interpretation Nov 2020

www.KMSTechnologies.com

Subsalt imaging in Northern Germany using multiphysics (magnetotellurics, gravity, and seismic)

Christian H. Henke[1], Markus Krieger[2], Kurt Strack[3], and Andrea Zerilli[4]

Abstract

Imaging subsalt is still a challenging task in oil and gas exploration. We have used magnetotellurics (MT) to improve the integration of seismic and gravity data to image the Wedehof salt dome, Northern Germany. High-resolution natural field source broadband MT data were acquired and enhanced the definition of the top and overhanging salt structures in addition to the description of the salt dome root. Salt boundaries show strong resistivity contrasts with the surrounding sediments and thus represent a good target for electromagnetic measurements, especially for mapping the top salt horizon. Using broadband array data acquisition and advanced processing techniques, difficulties with cultural noise sources could be solved. With integrated 3D gravity modeling focusing on the salt dome's flanks at intermediate depths, an improved model could be achieved. The revised salt geometries provided sound input to a seismic reprocessing and led to an improved imaging of the subsalt areas proven by subsequent exploration drilling. The integrated interpretation of MT, gravity, and seismics combines the strengths of the different physics, thus increasing [1]~~he~~ imaging reliability and reducing exploration drilling risks. In this case, we used a conservative workflow that includes a survey feasibility study with field noise evaluation and careful acquisition parameter testing at the beginning of the survey. Only with this c[3]~~uld we~~ overcome the cultural noise issues associated with the survey area being near large cities and their associated electromagnetic noise.

Introduction

Complex subsalt imaging is still one of the remaining difficulties in hydrocarbon exploration (Rowan et al., 2001). Extensive improvements have been made to tackle this problem with seismic new acquisition designs such as wide and full azimuth, long offsets, broadband acquisition, and advanced depth imaging such as reverse time migration and full-waveform inversion (e.g., Jones and Davidson, 2014; Warner and Guasch, 2016). However, not every subsalt problem has been solved, and many challenges remain. In areas where salt structures are extremely complex, project costs may still be prohibitively expensive, seismic signal-to-noise ratio may still be limited and therefore complicate subsalt imaging. For electromagnetics, salt is almost transparent because it is electrically isotropic and the salt-to-host rock boundaries are a [5]~~erfect~~ target with their high resistivity contrast (salt is usually several hundred-ohm-m resistivity and the surrounding sediments between 1 to 10 ohm-m).

Located among many others, at the southern edge of the South Permian Basin in Lower Saxony, Germany, the salt dome Wedehof has been the subject of an intense geophysical search for hydrocarbon structures and related exploration drilling. Historically, the main [4]~~bject~~ has been the search for hydrocarbons in the overhang regions and in the higher flanks of the structure. At later exploration periods, 3D seismic has been applied to obtain data in the deeper flanks and their downward extension into the Triassic series. The large uncertainty in the top salt imaging translates directly into large uncertainties (imaging, depth conversion) at base salt levels. The Wedehof High Resolution MagnetoTelluric (HRMT) project was designed to improve top salt interpretation and subsequently enhance seismic depth imaging of base salt and subsalt structures through an integrated geophysical approach. Figure 1 shows the location map of the survey.

We anticipated severe electromagnetic noise problems due to the proximity of big cities (Bremen, Hannover, and Hamburg), airports, and electric trains; thus, we first carried out a feasibility study including 2D [6]~~umerical~~ modeling and detailed site inspection as well as locating a remote site for remote reference operation.

[1]Wintershall Dea, Ueberseering 40, 22297 Hamburg, Germany. E-mail: henke.energy@gmail.com (corresponding author).
[2]TERRASYS Geophysics, Baumeisterstr. 2, ~~22099~~, [7]amburg, Germany. E-mail: krieger@terrasysgeo.com.
[3]KMS Technologies — KJT Enterprise Inc., 11999 Katy Freeway, Suite 160, Houston, Texas 77079, USA. E-mail: kurt@kmstechnologies.com.
[4]Formerly KMS Technologies, Via Liberazione 36, 29017 Fiorenzuola (PC), Italy. E-mail: azerilli@libero.it.
Manuscript received by the Editor 22 January 2020; published ahead of production 6 April 2020.
This paper appears in *Interpretation*, Vol. 8, No. 4 (November 2020); p. 1–10, 12 FIGS.
http://dx.doi.org/10.1190/INT-2020-0026.1.

Kommentarzusammenfassung für INT-2020-0026 1..10

Seite: 1

Nummer: 1 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:29:41

Nummer: 2 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:30:33
We could

Nummer: 3 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:30:17
o

Nummer: 4 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:33:22
objective

Nummer: 5 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:32:20
"perfect"

Nummer: 6 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:35:14

Nummer: 7 Verfasser: mhk Thema: Eingefügter Text Datum: 29.05.2020 11:40:14
20099

The survey area is located in a densely populated area with [1] ~~a lot of~~ villages, fields, and highways. The data base included relatively sparse onshore 3D seismic with a low fold, receiver/shot line spacing of 400 m, and a maximum offset of 4000 m.

The prestack depth migration gave initially only limited improvements of the seismic quality. Figure 2 shows the seismic section for the salt dome (Buehnemann et al., 2002). The structural interpretation of the target area in the bottom of the figure is only weakly

Figure 1. Location map of the MT survey in Northern Germany.

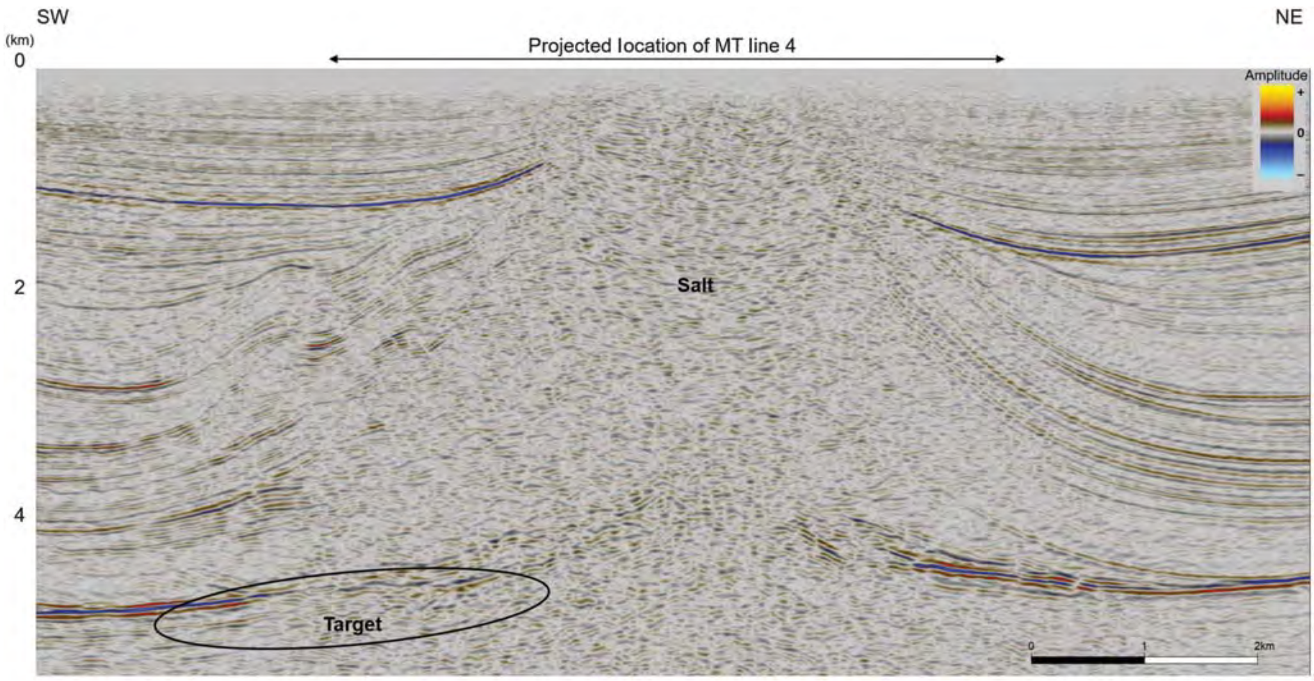

Figure 2. Seismic section through the Wedehof salt dome (2000 processing) prior to the integration of MT data, located parallel to MT line 4 (marked in red in Figure 3). Exploration target in the Rotliegend Formation marked.

Seite: 2

Nummer: 1 Verfasser: kurtstrack Thema: Cross-Out Datum: 28.05.2020 18:33:58

supported by the data. The top salt structures cannot be resolved [1]~~with~~ the seismic data. This caused us to use detailed gravity and HRMT jointly, shown in Figure 3, to drive the integration and to provide a more reliable structural interpretation. For the HRMT, the site spacing was 50 m on the cross lines (mandatory minimum lines 1 and 2 in Figure 3) and 100 m on the fill-in lines (contingency — remaining lines). The gravity and seismic existed initially, but it was thought that another method that could look below the salt using different physics was needed.

A Rotliegend gas discovery has been made close to the Wedehof salt dome in 1994 on the basis of 2D seismic and 3D seismic acquired in 1993. Since then, various 3D seismic reprocessing campaigns took place that resulted only in minor subsalt imaging improvements. The diffuse seismic image in Figure 2 at shallow depth is caused by suberosion of the salt diapir from Quaternary glacial deposits and Tertiary morphology (Sirocko et al., 2002). In a previous study, gravity data, which were acquired concurrent to the seismic surveys, could not define the shallow salt boundaries sufficiently. Thus, we used electromagnetics to better define the top of salt and potentially improve also the base of salt image jointly with gravity. Due to the [4]~~dense~~ industrialization [6]~~the area,~~ we anticipated increased electromagnetic noise and first carried out a 2D feasibility study including survey area inspection to map electromagnetic noise sources. In addition, near-surface static effects caused by the above-mentioned suberosion were anticipated as problematic. A possible solution to this were high-frequency magnetotelluric (MT) measurements (audio magnetotellurics — AMT), continuous electric dipole measurements, or using loop source time domain electromagnetics for static shift correction. Based on the 2D modeling results from the feasibility study, we selected the following approach: First, we verified the salt structure image using the MT/AMT data in the feasibility study. This gave us the confidence that the data would be sufficient to resolve the target. The remaining unknown was the actual noise, and for that we reserved to use continuous electric fields that were also measured (and reserved for corrections in postprocessing). After the initial parameter testing, we were satisfied with the quality of the MT/AMT approach and the continuous electric field postprocessing wasn't used. All sites were recorded/processed using a faraway remote reference site near Essen (Oldenburg).

Figure 3 shows the gravity and HRMT data base. On the mandatory ~~lines,~~[2]the site spacing is 50 m; on the other lines, it is 100 m. In hindsight, we realized that most likely this dense spacing was the most important contributor to the success of the survey.

Methodology and workflow

We selected MT as the method of choice as [3]~~the result of the~~ feasibility study and did not have to add other survey methods. Techniques such as controlled-source electromagnetics (CSEM) may have better coupling to the subsurface, but their cost, availability, and effort make these only a second choice.

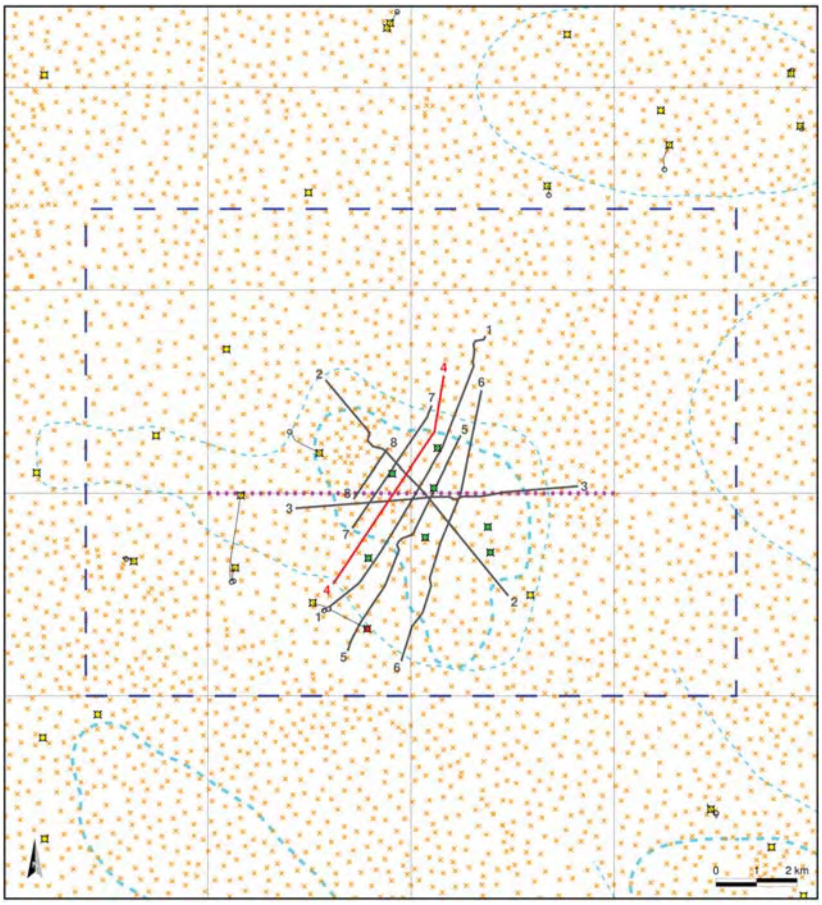

Figure 3. Overview of the gravity and MT database, the survey site, and its surroundings. The bold dashed outlines in cyan roughly delineate the known salt domes, based on previous studies, with Wedehof in the center, the finer lines indicate deeper salt uplifts; the dashed blue rectangle represents the gravity output area (16 km by 12 km), shown in Figure 7 (reference gravity and attribute ~~map);~~[7]orange crosses are gravity stations (with nominal spacing of approximately 375 m); MT profiles 1–8 are displayed in gray, except line 4 in red, shown in Figure 9 (resistivity image) and in Figures 2 and 11 (seismic images); the dotted pink crossline locates the 2D profile shown in Figure 6 (model for the MT feasibility study); yellow dots are exploration wells (some with their paths) existing previous to this study, the red well was drilled afterward, the green dots are shallow wells used for top salt verification.

Seite: 3

Nummer: 1 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:38:45
by

Nummer: 2 Verfasser: mhk Thema: Eingefügter Text Datum: 29.05.2020 11:41:12
lines 1 and 2

Nummer: 3 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:44:51
indicated by

Nummer: 4 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:41:37
area's dense

Nummer: 5 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:41:14

Nummer: 6 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:40:42
n t

Nummer: 7 Verfasser: mhk Thema: Eingefügter Text Datum: 29.05.2020 11:41:30
maps

The MT method uses the electromagnetic source in the ~~earth's~~ [1]onosphere, and for higher frequencies it uses thunderstorms in the middle atmosphere. Because the location of the signal source is not known, it uses the ratio of electric and magnetic fields to cancel the need for the source location. Thus, it is called a passive electromagnetic method, whereas CSEM are active methods.

Figure 4 shows a generic field layout of the MT equipment as an array system over a salt dome as applied for the [3][4]~~rvey~~ carried out in 2002. Usually an MT site consists of three magnetic and two electric field components, acquired in the x, y, z directions to give a tensor measurement. They represent the secondary response of the subsurface caused by the electromagnetic wave reaching the [6]~~earth~~ from the atmosphere/ionosphere (indicated by the red wave-train in the figure). The secondary fields are generated by the resistivity contrast of adjacent strata — in this figure, around the salt dome. These are converted to directionally independent apparent resistivities that represent the subsurface resistivity structure as a function of frequency (Vozoff, 1991; Chave and Jones, 2012; Naidu, 2012). If the apparent resistivity of the two perpendicular directions is the same, the subsurface is horizontally layered.

Typically, only the x, y components are used with the vertical component of the magnetic field giving some 3D indicator. If the ratios are different, we see a [2]~~2D~~ structure such as a depth-dependent salt dome boundary. The lower the frequency, the deeper the [5]~~penetrating signal~~. Each receiver site can have subacquisition controllers to get denser spacing. In addition to acquiring the data at a receiver site we also used a distant remote reference site. The assumption is that this site gets cleaner data and that the signals are correlated and the noise is not. Thus, we can derive algorithms to remove the noise (Clarke et al., 1983).

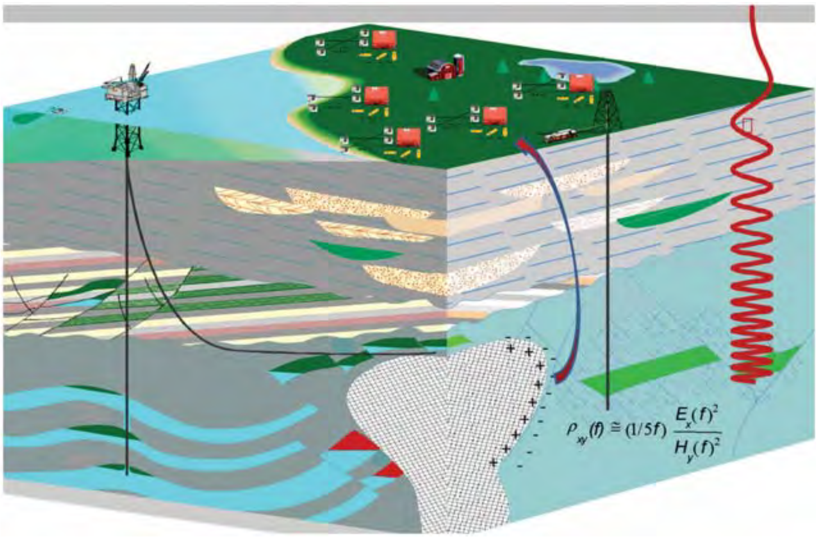

Figure 4. Setup of the array MT system. Today, the acquisition is typically done with wireless nodes.

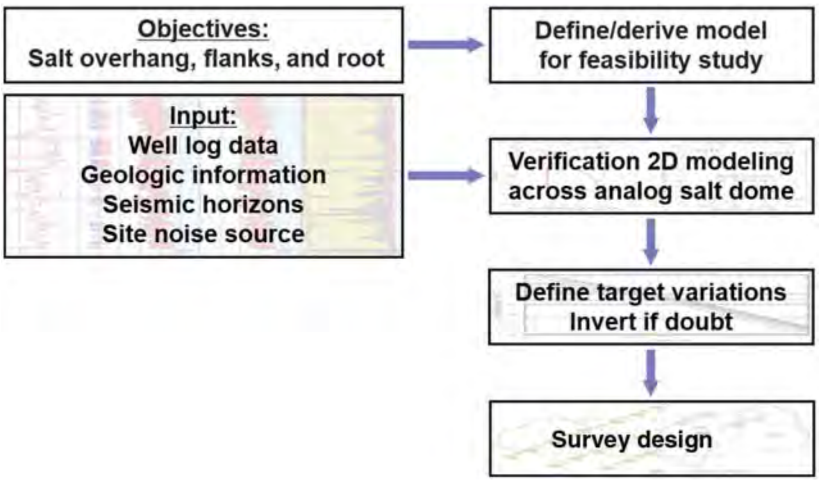

Figure 5. Workflow of the subsalt imaging MT feasibility study leading to survey design.

Another potential pitfall with MT worth mentioning are static effects that are caused by variable grounding resistance on the electrode side (Andrieux and Wightman, 1984; Sternberg et al., 1988; Cummings and Mackie, 2010). There are multiple ways to address this. We choose between time-domain EM, continuous electric fields, and high-frequency MT as an additional measurement. The latter was selected given that we anticipated careful parameter testing at the beginning of the survey.

Because central Europe has electric trains and a high population density, we anticipated significant cultural noise. We carried out a feasibility study that included resistivity [7]~~model~~[8]~~derivation~~ from a priori information, 2D modeling, and detailed site inspection focusing on mapping cultural noise sources.

The results of the study delivered the specifications for the survey tender. The feasibility workflow is shown in Figure 5. Whereas the initial goal was to map the top of the salt dome due to its unclear definition from the seismic data, it became clear after talking to geologists and asset managers that the base [9]~~f the~~ shape of the salt root was also important ~~and~~ [10] getting an image of the salt overhang was a hoped-for benefit. Because no resistivity data from logs were available, we used regional geologic studies done by the [11]~~eological~~ Survey (Hoffmann et al., 2005) to get an idea about the [12]~~sistivities~~. Unfortunately, available vintage data in the upper 5 km were too

Seite: 4

Nummer: 1 Verfasser: kurtstrack Thema: Inserted Text Datum: 28.05.2020 18:32:42
Earth's

Nummer: 2 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:53:03
2D/3D

Nummer: 3 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:49:27
Wedehof survey

Nummer: 4 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:49:10

Nummer: 5 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:53:33
penetration

Nummer: 6 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:50:25
Earth

Nummer: 7 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:56:19
models construction

Nummer: 8 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:55:49
der

Nummer: 9 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:57:27
and

Nummer: 10 Verfasser: mhk Thema: Eingefügter Text Datum: 29.05.2020 11:42:28
, and

Nummer: 11 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:58:11
German Geological

Nummer: 12 Verfasser: Andrea Thema: Cross-out Datum: 28.05.2020 23:58:39
area resistivities

noisy to derive a resistivity strata correlation. We thus used previously interpreted gravity models to get the approximate salt-sediment boundaries confirmed with the geologist and correlated this to the formation, and then we used analogues from other resistivity measurements in the basin to get a resistivity model of the salt dome. We then calculated the 2D MT response and carried out some test inversions on the modeled data. Once we were confident that we could define the salt boundaries, a minimum survey plan was derived, and a contingency plan was included in case the survey went well. Together with site inspection and mapping the locations of potential electromagnetic noise sources, the survey lines were defined.

Figure 6a shows some results of the feasibility study. Every 50 m, we placed a receiver site on the profile and calculated the synthetic response. Based on the known density for the formations, the resistivities were blocked in larger intervals, and then the synthetics were generated. To gain a quantitative understanding on how the method would be effective in determining the depth to the top of salt, we computed several variations of the Wedehof salt model for various depths to salt. The two data examples (Figure 6) illustrate the top of salt at approximately 2000 and 400 m, respectively. The synthetics represent different MT quantities. The results for the TE (transverse electric) mode (electric currents flowing along the strike) and TM (transverse magnetic) mode (currents flowing across the strike) are presented in the figures (TE, red dots; TM, blue dots) along with the invariant (average of TM and TE, pink line). Model responses were computed for an array of measurements with 50 m dipole spacing (continuous). We can see a clear shift of the curve increase in the period to the shorter period at the right-hand example, which is interpreted as more resistive salt at a shallower depth. The variations of the apparent resistivity curves indicate a significantly variable salt-sediment boundary. All of the model plots show easily detected variations in the computed apparent resistivities.

The data were recorded following acquisition strategies developed and verified during the test phase to cover a frequency range from [4]600 Hz to 1000 sec (0.001 Hz). To cover this range, six different sampling rates (in different bands) were applied and then combined: [6]8, 9600, 4000, 1000, 500, and 25 Hz. Each band was usually acquired for a period long enough to produce, after stack, a good signal-to-noise ratio and therefore high-quality data. The acquisition strategy evolved out of the acquisition tests performed and was instrumental in improving the data quality significantly. The issues in this survey were near-surface static effects, and special procedures were developed for the electrode planting and recording with a very dense electrode spread (50 and 100 m). Because of the dense spacing, we called this survey type HRMT. As mentioned above, we decided on this methodology for static correction be-[1] cause it improves the data quality.

Usually a few seconds of acquisition are enough to stack good data for the frequency range covered by the first three bands. More critical here was the acquisition at the lowest frequencies for approximately 15 h. The length of the acquisition period for this band was based on the required depth of investigation and the feasibility study.

Based on the experience during earlier MT measurements carried out in northwest Germany, it was decided to install the remote reference site near the town of Essen (Oldenburg). The selection of this site, approximately 100 km away from the survey area, was based on the area's lack of electric railroads, major pipelines, and power lines and the results of previous measurements carried out by the University of Muenster. In addition, the area is characterized geologically by a thick very low resistivity section, which [2]erves to attenuate noise. The robust processing method proposed by Zerilli et al. (1997) was used to improve[3]the data quality and greatly reduce the effects of noise bias. This scheme is a combination of use of the far fixed remote reference

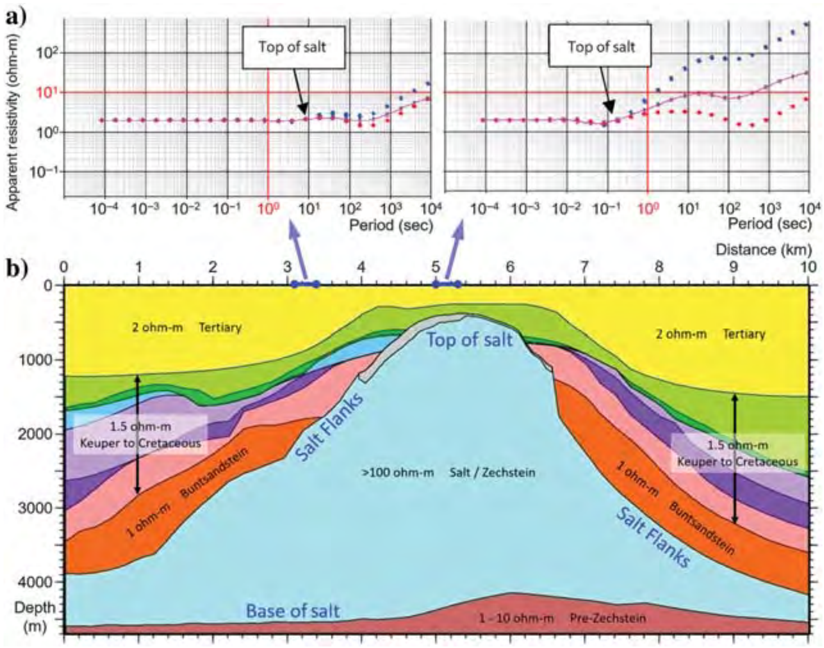

Figure 6. Previous model used for the MT feasibility study and two examples with significant results. (a) Two examples of the feasibility data used to design the survey. Displayed are apparent resistivities as a function of the period with the increasing period representing an increase at depth. Model results demonstrate that the MT method is highly sensitive to the resistivity contrasts of the salt body and the surrounding sediments, in particular at the top of the salt-sediment boundary. (b) Existing model to 4.5 km [7]depth, based on an earlier seismic-gravity interpretation, with the top of the salt body indicated at a depth of approximately 400 m.

Seite: 5

Nummer: 1 Verfasser: Andrea Thema: Cross-out Datum: 29.05.2020 00:10:37

improved

Nummer: 2 Verfasser: Andrea Thema: Cross-out Datum: 29.05.2020 00:11:45

served

Nummer: 3 Verfasser: Andrea Thema: Cross-out Datum: 29.05.2020 00:12:01

Nummer: 4 Verfasser: Andrea Thema: Cross-out Datum: 29.05.2020 00:41:06

12000

Nummer: 5 Verfasser: Andrea Thema: Cross-out Datum: 29.05.2020 00:42:06

48 kHz

Nummer: 6 Verfasser: Andrea Thema: Cross-out Datum: 29.05.2020 00:08:58

48 kHz,

Nummer: 7 Verfasser: mhk Thema: Eingefügter Text Datum: 29.05.2020 11:43:17

4.7 km

tested to be free of regional correlated noise sources and a selection of subsets of data based on coherence, followed by filtering using a reweighted least median of squares for the magnetic data and a recurrent neural network approach for the electric data.

Seismic imaging with prestack depth migration (PSDM) over the Wedehof salt dome before the co-operative workflow provided a high-resolution image of the sedimentary sequence but poor imaging of the salt structure preventing the focusing of the Rotliegend Formation target in the image (Figure 2).

The gravity data, obtained from exploration ground surveys covering the area seamlessly with a nominal grid distance of approximately 375 m (Figure 3), were terrain and Bouguer corrected and then selectively filtered to illuminate different parts of the subsurface volume (Henke and Krieger, 2000). In Figure 7a, we [1] ~~have~~ the processed gravity data band-passed for wavelengths from 0.3 to 50 km as an appropriate reference field for 3D gravity modeling down to a depth of approximately 6 km. Superimposed are the MT sites and the salt outlines based on previous studies. The ~~right map~~ [2]s the second vertical derivative (SVD) of the gravity data; it helps to delineate the salt dome top lateral boundary, approximately at the zero-contour line outside of the orange-colored elliptic high. However, due to the weak gravity response from shallow depths caused by locally limited density contrasts, the HRMT results are expected to support the upper salt geometries significantly. Having thus a better control of the shallow part of the model, gravity could in turn improve the salt root definition, where the salt-sediment density contrasts are typically high.

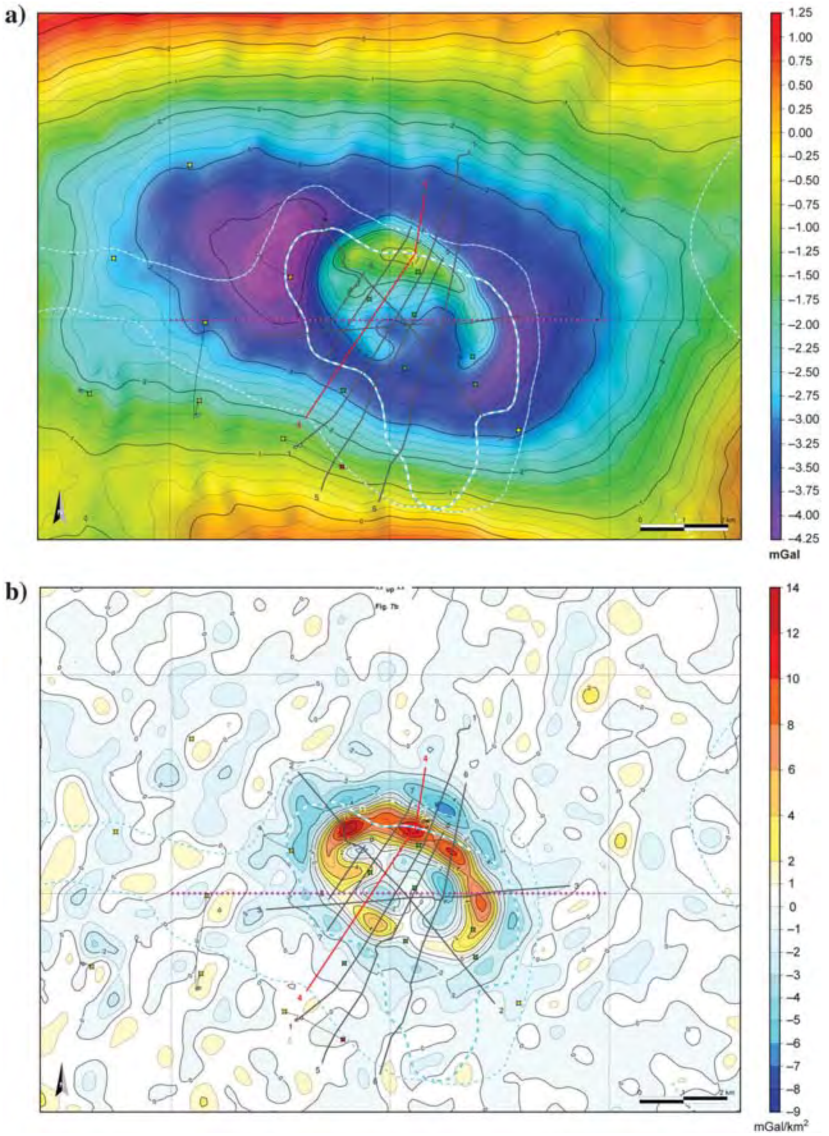

Figure 7. Gravity data maps (the output area), with the MT sites superimposed: (a) processed Bouguer reference gravity field (excluding wavelengths <0.3 and >50 km) ~~and~~ [3]) the SVD of the gravity field, as an example for an attribute map supporting the qualitative interpretation, in this case focusing on the edges of the salt dome. Additional map features are explained in Figure 3.

Results

Data processing began at the field office as soon as the survey and remote reference data were returned from the field. Much of the data, in particular that acquired near the beginning of the survey, was later reprocessed, as the processing sequence evolved during the course of the survey and was optimized for the specific objectives of the project. Evaluation of the data for validity and quality was done concurrent to field acquisition. The parameter testing took much longer than anticipated, but once production started the acquisition process went fast and approximately 360 sites were acquired in two months. The profiles across the salt dome confirmed the feasibility results and the salt dome could be seen in the processed data — as predicted. The MT data were processed and inverted using a 2D inversion algorithm (and checked with a 3D inversion algorithm). These sections were then compiled and integrated with the gravity and seismic data. This integration process took several weeks.

Joint interpretation with the new HRMT data including further constraints from seismic, geology, and well data revealed that the annular relative gravity maximum in Figure 7 is caused by the combined effects of the steeply uplifted sedimentary sections below the salt overhang and the slightly positive density contrast of the shallowest part of the salt, including variable fractions of high-density anhydrite caprock. It further

Seite: 6

Nummer: 1 Verfasser: Andrea Thema: Cross-out Datum: 29.05.2020 00:13:56

show

Nummer: 2 Verfasser: mhk Thema: Eingefügter Text Datum: 29.05.2020 11:44:00

map below (Figure 7b)

Nummer: 3 Verfasser: mhk Thema: Eingefügter Text Datum: 29.05.2020 11:45:35

, and

indicates that the previous salt boundaries need to be partly reinterpreted.

Figure 8 represents two different snapshots of the integration effort including gravity, MT, and seismics obtained from the 3D visualization. The left view shows a resistivity section of HRMT profile 4 combined with the SVD of the gravity field, superimposed on the seismic and horizon data. It shows that the HRMT clearly defined the top of the salt. Where the gravity SVD zero line (in white) coincided with a resistivity contrast in the MT, we interpreted the lateral salt boundary, which is a correction to what we obtained from previous single-method interpretations. When we display the data in a more transparent mode with the seismic, an additional unit below the salt will become visible (as discussed below). On the right figure, the salt structures and the seismic data are more emphasized (now viewed from the northwest), whereas the transparent reference Bouguer field is displayed together with the MT resistivity image of the well-resolved part. These snapshots roughly indicate how the integrated interpretation of multiphysics data greatly improves the salt dome imaging.

In Figure 9 we analyze the sensitivity of the MT data focusing on the deep section (the low frequencies). We know from the inversion that they are not well-resolved. In the image, which shows the 2D section of line 4, we see a smooth transition in resistivities between the salt root and the Permian sediments. This can be easily explained using a log from a similar well shown on the right of the figure. It shows the log section and core photographs through the Rotliegend-Zechstein transitional succession in well North Sea C1 (after Legler et al., 2005); flooding surfaces (the base of the laminated horizon or the base of the limestone) in core photos are marked by arrows. The shale laminations typical for this type of transgression/regression environment are visual in the gamma-ray log. The shale laminations reduce the MT response and increase the electrical anisotropy, but you still have a bulk density contrast; however, the base of the salt dome can still be resolved in the MT data.

Figure 10 shows a significantly improved definition of the complex geometry of the Wedehof salt structure produced by the cooperative multiphysics interpretation workflow in which the ambiguity and/or lack of information of any single geophysical data set are resolved or mitigated. This was achieved by combining different data set modalities that either measure complementary properties of the region of interest (ROI) being investigated or by illuminating the ROI differently than previous studies based on seismic alone. Using a combined approach, the thickness and shape of the caprock and the top of salt can be well determined. The dome extends more to the north than previously assumed and has steep flanks and overhangs.

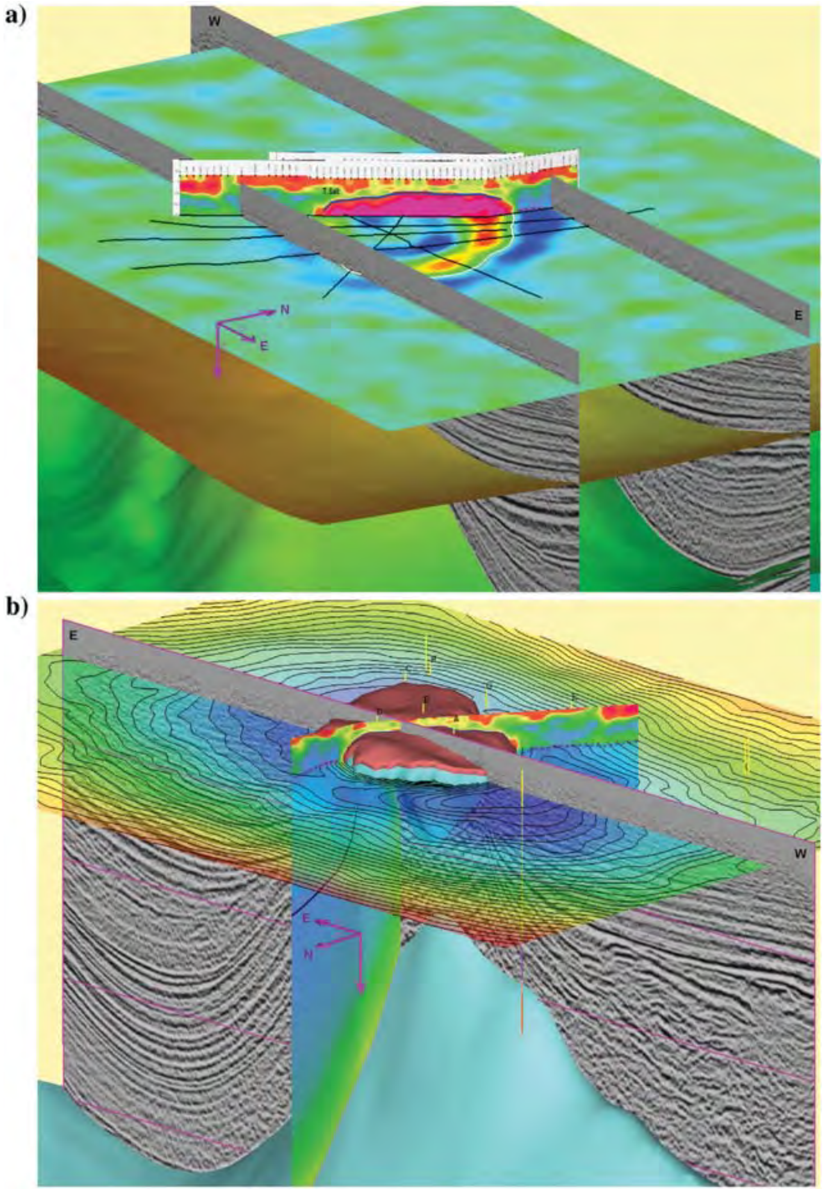

Figure 8. Snapshots of the data integration of gravity, MT, and seismic obtained from the 3D visualization: (a) HRMT sections (profile 4 visible; for the color bar see Figure 9) combined with the SVD of the Bouguer gravity field (the zero line in white, blue negative, red positive values), superimposed on the PSDM processed seismic data and two sedimentary horizons (view from the southeast) and (b) PSDM processed seismic section through the Wedehof salt dome (salt in cyan, caprock in red) and its deeper salt uplift, displayed with the reference Bouguer gravity field (transparent; for the color bar see Figure 7a) and the well-resolved part of the MT resistivity image of profile 4 (view from the northwest).

Seite: 7

Nummer: 1 Verfasser: Andrea Thema: Cross-out Datum: 29.05.2020 00:39:34

Nummer: 2 Verfasser: mhk Thema: Eingefügter Text Datum: 29.05.2020 11:46:15
upper

Nummer: 3 Verfasser: mhk Thema: Eingefügter Text Datum: 29.05.2020 11:46:58
well determined

Nummer: 4 Verfasser: mhk Thema: Eingefügter Text Datum: 29.05.2020 11:46:28
Figure 8b below

Nummer: 5 Verfasser: Andrea Thema: Cross-out Datum: 29.05.2020 00:20:48
a comparable

Nummer: 6 Verfasser: Andrea Thema: Cross-out Datum: 29.05.2020 00:21:34
by

Nummer: 7 Verfasser: Andrea Thema: Cross-out Datum: 29.05.2020 00:22:37

Nummer: 8 Verfasser: mhk Thema: Eingefügter Text Datum: 29.05.2020 11:46:01
, and

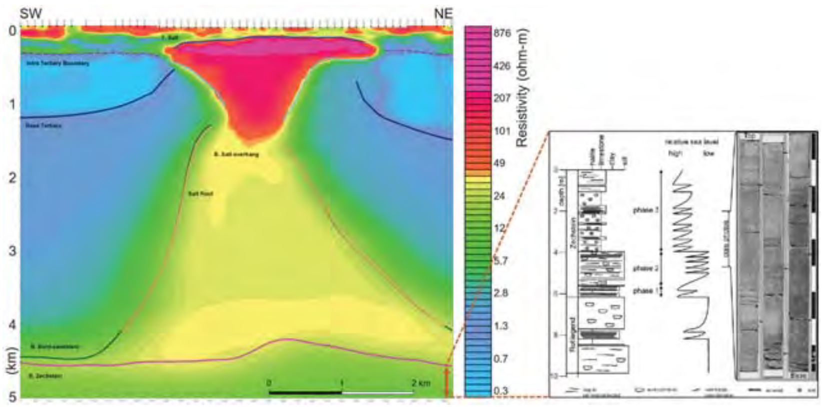

Figure 9. Resistivity image section derived from MT measurements on line 4 including the deep part of the section that is only partially resolved in the inversion. On the right is the lithology and gamma ray log explaining that the low resistivity contrast is caused by cyclic layering with shales in the Zechstein unit (after Legler et al., 2005).

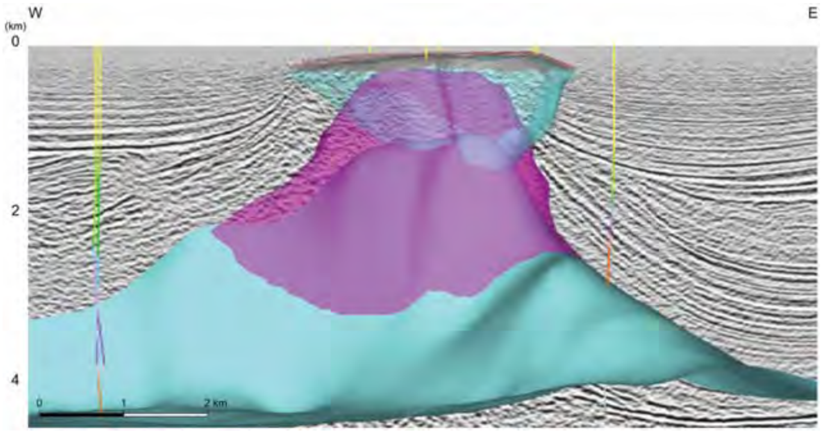

Figure 10. Wedehof salt dome geometry from the cooperative multiphysics interpretation workflow (light blue) compared to the previous model (pink, shown in Figure 6).

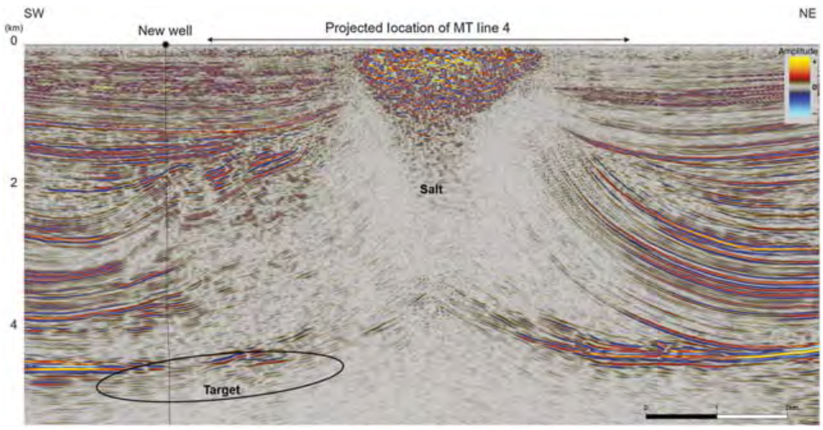

Figure 11. Seismic section parallel to MT line 4 (marked ~~red~~ [3] in Figure 3) through the Wedehof salt dome after reprocessing using the MT and gravity results; with projected location of the new gas discovery well.

Moreover, the updated salt model reveals major improvements of the base of salt and subsalt geometries.

In a subsequent seismic reprocessing, the velocity model building was [1] ~~founded~~ on the new integrated salt geometry interpretation. Utilizing this workflow, significant imaging improvements of the subsalt target areas could be achieved (Figure 11).

Future improvement

Although this pioneering survey was carried out over [2] ~~several~~ years ago, most of its methodology and workflow still applies. Today's broadband MT hardware is more efficient, and so is data processing and inversion including 3D inversion as a standard tool. To improve the feasibility study, nowadays we acquire noise data in the field area to verify the prediction on a real target parameter resolution and to demonstrate the information content focusing below the receiver.

To improve the resolution, one would follow up with a CSEM survey because it has larger coupling to the resistivity of the subsurface. In fact, new focusing methods (Paembonan et al., 2017) for CSEM could very well revolutionize the EM capabilities.

Because today's acquisition hardware allows us to get reliable data, we will now be able to focus more on the information value and risks associated with its reliability after interpretation. This will tie the geophysical measurements more directly to the commercial value of a prospect.

Ambiguity is usually addressed through more awareness from case studies illustrating the value of integrating new data acquisition technologies such as gravity gradiometry, high-resolution magnetics, CSEM, sparse seismic nodes, deep borehole tools, surface-to-borehole EM measurements, and advanced simultaneous joint inversion (SJI) in which two or more geophysical data sets are inverted simultaneously, usually using all available geologic constraints.

The Wedehof multiphysics data set is still unique, within Wintershall Dea and within the industry. This should be taken advantage of. It is recommended that the data set be used to thoroughly test the relationships between different physical properties that must be managed during multigeophysics analysis

Seite: 8

Nummer: 1 Verfasser: Andrea Thema: Cross-out Datum: 29.05.2020 00:24:49
based

Nummer: 2 Verfasser: Andrea Thema: Cross-out Datum: 29.05.2020 00:25:44
eighteen

Nummer: 3 Verfasser: mhk Thema: Eingefügter Text Datum: 29.05.2020 11:47:36
in red

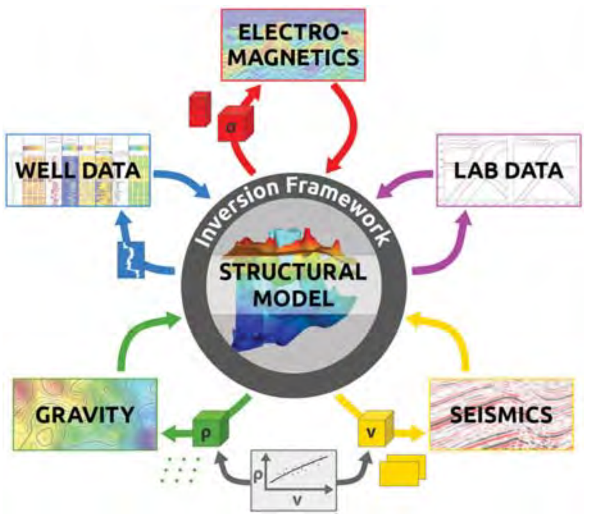

Figure 12. Integrated multiphysics interpretation based on a common structural model and distributed cooperative or simultaneous joint inversion: The central framework exports (adapted) model descriptions to and imports the model effects from specialized externally running forward calculation modules (after Smilde et al., 2018).

and further develop new cooperative and SJI (Figure 12). Furthermore, it will be helpful to determine if the geophysics, petrophysics, and geologic constraints used for this project could be improved upon or if a more efficient approach is feasible or could be developed.

Conclusion

This case history is one of few where high density MT measurements were carried out and the survey planning included a complete presurvey feasibility study. The parameter testing took almost two weeks, and once the feasibility results were confirmed, data acquisition yielded high-resolution results.

For the definition of the salt dome geometry, it was paramount to integrate the MT, gravity, and seismic because each method saw only part of the formation boundaries. The salt dome surface lateral extents were derived from gravity and MT, whereas the salt overhangs and the salt flank-sediment boundary are based mainly on MT. Gravity contributed to the salt root definition, and the smooth resistivity transition indicated laminated salt or sediments below.

The updated model, combining the strengths of different physics, served as input to a new seismic depth migration cycle, produced a greatly improved image of subsalt proven by subsequent drilling.

Although, since then, numerous case studies in diverse geologic environments have demonstrated added value, the concept of integrated imaging is still undervalued in the geophysical community and in the oil and gas industry as a whole.

Acknowledgments

We appreciate the permission from Wintershall Dea to publish the material. The survey was carried out by KMS Technologies and TERRASYS Geophysics, with the acquisition being done by Geoinvest S.R.L. The following individuals significantly contributed to its success: A. Ambrogio, J. Buehnemann, C. Mueller, H. J. Zoch, and P. Buerger. H. Joedicke guided us in the remote reference site selection and the background resistivity determination and supported our acquisition strategy. The reviewers are thanked for their diligence and interest in our paper and for their helpful comments and suggestions.

Data and materials availability

Data associated with this research are confidential and cannot be released.

References

Andrieux, P., and E. Wightman, 1984, The so-called static corrections in magnetotelluric measurements: 54th Annual International Meeting, SEG, Expanded Abstracts, 43–44, doi: 10.1190/1.1893968.

Buehnemann, J., C. H. Henke, C. Mueller, M. H. Krieger, A. Zerilli, and K. Strack, 2002, Bringing complex salt structures into focus — A novel integrated approach: 72nd Annual International Meeting, SEG, Expanded Abstracts, 446–449, doi: 10.1190/1.1817278.

Chave, A. D., and A. G. Jones, 2012, The magnetotelluric method: Theory and practice: Cambridge University Press.

Clarke, J., T. D. Gamble, W. M. Goubau, R. H. Koch, and R. F. Miracky, 1983, Remote-reference magnetotellurics: Equipment and procedures: Geophysical Prospecting, **31**, 149–170, doi: 10.1111/j.1365-2478.1983.tb01047.x.

Cummings, W., and R. Mackie, 2010, Resistivity imaging of geothermal resources using 1D, 2D and 3D MT inversion and TDEM static shift correction illustrated by a glass mountain case history: Proceedings World Geothermal Congress.

Henke, C. H., and M. H. Krieger, 2000, High-resolution potential field data: Solutions and limitations: 20th Mintrop Seminar, DGG, Conference, 101–131.

Hoffmann, N., H. Joedicke, and L. Horejschi, 2005, Regional distribution of the lower carboniferous Culm and carboniferous limestone facies in the North German Basin derived from magnetotelluric soundings: Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, **156**, 323–340, doi: 10.1127/1860-1804/2005/0156-0323.

Jones, I. F., and I. Davidson, 2014, Seismic imaging in and around salt bodies: Interpretation, **2**, no. 4, SL1–SL20, doi: 10.1190/INT-2014-0033.1.

Legler, B., U. Gebhardt, and J. W. Schneider, 2005, Late Permian non-marine–marine transitional profiles in the Central Southern Permian Basin: International Journal Earth Science, **94**, 851–862, doi: 10.1007/s00531-005-0002-5.

Seite: 9

Nummer: 1 Verfasser: Andrea Thema: Cross-out Datum: 29.05.2020 00:29:41

this

Nummer: 2 Verfasser: Andrea Thema: Cross-out Datum: 29.05.2020 00:28:47

were

Naidu, G. D., 2012, Deep crustal structure of the Son–Narmada–Tapti lineament, Central India: Springer theses (Chapter 2: Magnetotelluric basic theoretical concepts): Springer-Verlag.

Paembonan, A. Y., R. Arjwech, S. Davydycheva, M. Smirnov, and K. Strack, 2017, An application of LOTEM around salt dome near Houston, Texas: AIP Conference Proceedings.

Rowan, M. G., R. A. Ratliff, B. D. Trudgill, and J. B. Duarte, 2001, Emplacement and evolution of the Mahagony salt body, central Louisiana outer shelf, northern Gulf of Mexico: AAPG Bulletin, **85**, 947–970, doi: 10.1306/8626CA37-173B-11D7-8645000102C1865D.

Sirocko, F., T. Szeder, C. Seelos, R. Lehne, B. Rein, W. M. Schneider, and M. Dimke, 2002, Young tectonic and halokinetic movements in the North-German-Basin: Its effect on formation of modern rivers and surface morphology: Netherlands Journal of Geosciences, **81**, 431–441, doi: 10.1017/S0016774600022708.

Smilde, P. L., C. Mueller, M. H. Krieger, and S. Petersen, 2018, Interpretation benefits from a flexible multi-physics joint inversion approach: 80th Annual International Conference and Exhibition, EAGE, Extended Abstracts, doi: 10.3997/2214-4609.201801890.

Sternberg, B. K., J. C. Washburne, and L. Pellerin, 1988, Correction for the static shift in magnetotellurics using transient electromagnetic soundings: Geophysics, **53**, 1459–1468, doi: 10.1190/1.1442426.

Vozoff, K., 1991, The Magnetotelluric Method, *in* M. N. Nabighian, ed., Electromagnetic methods in applied geophysics, 2, Application, Parts A and B: SEG, 641–712.

Warner, M., and L. Guasch, 2016, Adaptive waveform inversion: Theory: Geophysics, **81**, no. 6, R429–R445, doi: 10.1190/geo2015-0387.1.

Zerilli, A., M. Botta, and B. Apolloni, 1997, Improving magnetotelluric data degraded by coherent noise by robust regression analysis and recurrent neural networks: 67th Annual International Meeting, SEG, Expanded Abstracts, 366–369, doi: 10.1190/1.1885907.

Christian H. Henke is general manager of exploration governance and new ventures at Wintershall Dea. He received a Diploma (1989) and a Ph.D. (1995) in geophysics from Hamburg University. He worked as research scientist, provided reconnaissance seismic acquisition services worldwide, and developed a 3D gravity modelling tool and co-founded Terrasys prior joining Wintershall Dea in 1999. He served as senior advisor, chief geophysicist, and exploration manager in exploration, new ventures, and field development. He promotes integration and effective use of new technologies and seeks continuous improvement of business processes and workflows especially full cycle quality management. He is a member of AAPG, DGG, SEG, and EAGE, where he serves as a chairman of the PACE committee since 2014.

Markus H. Krieger is chief geophysicist and managing director of TERRASYS Geophysics and holds a Diploma in geophysics. After numerous worldwide research projects at Hamburg University, he co-founded TERRASYS in 1993 as a geophysical consultancy specializing in gravity and magnetics, with offices in Hamburg and Houston. Due to his background in applied geophysics, he moved the company to become a service provider for the oil & gas industry, focusing on integrated interpretation. Always striving to provide the most advanced solutions, he kept good connections to the scientific community and established a strategic R&D culture at the company. With increasingly complex geological scenarios to be addressed, TERRASYS develops adequate tools adjusted to the client's needs, e.g., simultaneous joint inversion techniques on multi-physics data. He is a member of AAPG, AGU, ASEG, BDG, DGG, EAGE, DFG-VK, DGMK, EGU, IAMG, PESGB, and SEG.

K.M. Strack is president of KMS Technologies specializing in integrated seismic/electromagnetic technology for land & marine E&P for the geothermal/petroleum industry. Emphasis is to enabling smooth energy transition to zero carbon footprint. Kurt also serves as adjunct professor at University of Houston, Mahidol University, and Khon Kaen University, Thailand and Yangtze University, China. He was chief scientist for Baker Atlas after various management positions, where he spawned their Research Department and numerous new logging tools. Before that, Kurt pioneered LOTEM (Transient electromagnetics for hydrocarbon exploration) development and advanced borehole geophysics technologies in Germany, Africa, Australia, China, India, and the USA. Kurt holds a Ph.D. (University of Cologne) and M.Sc. (Colorado School of Mines). Kurt has over 200 publications, 1 textbook & authors/co-authors more than 30 patents. He received two Fulbright scholarships and numerous international grants/awards. He is a member of SPWLA, AAPG, ASEG, BDG, DGG, EAGE, EEGS, GRC, SPE, SEG, and TSEG, and he served on committees and as distinguished lecturer. The SPWLA granted him Distinguished Technical Achievement Award in 2003 for new logging technologies, the SEG the Reginald Fessenden Award for the development of through casing resistivity and 3D induction logging, the SEG's President 2007 Special Services Award, and in 2012, Kurt for KMS Technologies the Cecil H. Green Enterprise Award. The Russian Academy of Science elected him as a foreign member and gave him the Kapitsa Gold Medal of Honor for his innovations to borehole geophysics and pioneering work to surface geophysics (Lotem).

KMS Technologies
Innovating Solutions

KMS Technologies – KJT Enterprises Inc.
11999 Katy Freeway, Suite 160
Houston, TX 77079, USA
Tel: +1.713.532.8144
Fax: +1.832.204.8418
info@kmstechnologies.com

www.kmstechnologies.com
www.lemisensor.com