Visualization of vertical hydrocarbon migration in seismic data: Case studies from the Dutch North Sea

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Abstract

Previous 3D visualization studies in seismic data have largely been focused on visualizing reservoir geometry. However, there has been less effort to visualize the vertical hydrocarbon migration pathways, which may provide charge to these reservoirs. Vertical hydrocarbon migration was recognized in normally processed seismic data as vertically aligned zones of chaotic low-amplitude seismic response called *gas chimneys*, *blowout pipes*, *gas clouds*, *mud volcanoes*, or *hydrocarbon-related diagenetic zones* based on their morphology, rock properties, and flow mechanism. Because of their diffuse character, they were often difficult to visualize in three dimensions. Thus, a method has been developed to detect these features using a supervised neural network. The result is a "chimney" probability volume. However, not all chimneys detected by this method will represent true hydrocarbon migration. Therefore, the neural network results must be validated by a set of criteria that include (1) pockmarked morphology, (2) tie to shallow direct hydrocarbon indicators, (3) origination from known or suspected source rock interval, (4) correlation with surface geochemical data, and (5) support by basin modeling or well data. Based on these criteria, reliable chimneys can be extracted from the seismic data as 3D geobodies. These chimney geobodies, which represent vertical hydrocarbon migration pathways, can then be superimposed on detected reservoir geobodies, which indicate possible lateral migration pathways and traps. The results can be used to assess hydrocarbon charge efficiency or risk, and top seal risk for identified traps. We investigated a case study from the Dutch North Sea in which chimney processing results exhibited vertical hydrocarbon pathways, originating in the Carboniferous age, which provided the charge to shallow Miocene gas sands and deep Triassic prospects.

Introduction

Previous 3D visualization studies in seismic data have largely been focused on visualizing reservoir geometry. There has been less effort, however, to visualize the vertical hydrocarbon migration pathways, which may provide charge to these reservoirs. Vertical hydrocarbon migration is recognized in normally processed seismic data as vertically aligned zones of chaotic low- to high-amplitude seismic response called *gas chimneys*, *blowout pipes*, *gas clouds*, *mud volcanoes*, or *hydrocarbon-related diagenetic zones* (HRDZs) based on their morphology, rock properties, and flow mechanism (O'Brien and Woods, 1995; Cartwright et al., 2007). The vertically aligned, low-amplitude, chaotic seismic response of gas chimneys or gas clouds is related to the residual gas saturation remaining in the rock after one or more pulses of hydrocarbon migration have passed through the rock. The residual saturation is assumed to be highly variable in space. Small variations in low hydrocarbon saturation have a large effect on seismic velocities in porous media and therefore on acoustic impedance (Gassmann, 1951). The presence of residual gas also has an impact on frequency causing an attenuation of the high-frequency signal (Dupuy and Stovas, 2014). The lateral variation in residual saturation leads to a highly heterogeneous velocity field and impedance. Forward modeling (Arntsen et al., 2007) confirms this model. Mud volcanoes are due to complete mobilization of the sedimentary column, but will similarly have a vertically aligned low-amplitude, low-frequency response in the subsurface. They can often be recognized in the subsurface by the radial fracturing associated with them (Graue, 2000). However, the feeder pipe for the mud volcanoes may not be as aerially extensive as previously thought due to improved seismic imaging (Huuse et al., 2010). Carbonate cementation in shallow unconsolidated sands related to hydrocarbon migration (HRDZs) can similarly cause a heterogeneous velocity field and may have a high- or low-amplitude response based on the character of the surrounding rock. The major difference between gas chimneys and HRDZs is their velocity. Gas chim-

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Manuscript received by the Editor 12 January 2015; revised manuscript received 30 April 2015; published online 25 June 2015. This paper appears in *Interpretation*, Vol. 3, No. 3 (August 2015); p. SX21–SX27, 6 FIGS.

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neys will often show a velocity pull-down, whereas HRDZs will show a pull-up. However, a complex morphology of gas-filled sediment and related diagenesis can be expected. In this study, we did not attempt to distinguish these different expressions of hydrocarbon migration but lumped them under the term *chimney*.

Chimney detection methodology

Because of their diffuse character, gas chimneys are often difficult to map in three dimensions. Thus, a method has been developed to detect these features in normally processed seismic data, and thus, we visualize them in three dimensions (Meldahl et al., 1998, 2001; Heggland et al., 2000). The method of chimney detection uses a supervised neural network. The methodology requires that the interpreter find good examples of chimneys within normally processed 3D seismic data. The seismic needs to be processed so that events are properly migrated, but not filtered to reduce the seismic noise that is caused by the hydrocarbon migration. These chimneys need to be supported by documented surface seepage, by direct hydrocarbon indicators, or by known hydrocarbon shows in wells. The quality of the chimney-processing output is only as reliable as the input data. The interpreter selects example locations, or picks, in the areas of the data that are believed to be reliable chimneys and also picks nonchimney sites in areas in which there is low-amplitude chaotic seismic character that is definitely not related to vertical hydrocarbon migration. These areas may be related to debris flows, well-imaged faults, or salt.

Attributes are then chosen that show the chimneys most clearly on key seismic lines. Chimneys are generally low-amplitude chaotic events; therefore, similarity, dip variance, and energy envelope (amplitude) are often used. Chimneys also tend to be more vertical than faults on 3D seismic (due to the buoyancy of gas). Thus, attributes are compared over designated vertical windows. Residual gas may also cause an attenuation of high frequencies. Thus, seismic attributes that measure this attenuation over large windows are also typically used in the neural network training. The frequency and similarity response associated with chimneys also changes with increasing depth. Thus, a two-way time (TWT) or depth attribute often needs to be used. In addition, different stratigraphic intervals can have a very different response to hydrocarbon migration. Highly reflective zones may have a much more subtle response. Similarly, zones affected by polygonal faulting may have a more chaotic seismic response not related to hydrocarbon migration. A "layer attribute," which segments the volume along chronostratigraphic surfaces or major mapped horizons, can provide the neural network this stratigraphic input. Finally, gas chimneys can often be distinguished more accurately on far-angle stacks than on near-angle stacks because the far-offset P-waves will be more affected by residual gas at higher angles of incidence. The chosen attribute set is then calculated at the picked chimney and nonchimney sites and fed into the neural network for training.

Neural network results can then be displayed on the key lines used for chimney picking. The objective is for the high-probability chimneys detected by the neural network to match the reliable chimneys detected by the interpreter. The chimney picks and attribute set are modified until the best match is achieved. At this point, the neural network training can be applied to the entire 3D seismic volume to create a chimney probability volume.

Validation of chimney processing results

Not every high-probability chimney represents a true vertical hydrocarbon migration pathway. Thus, the processing results need to be validated using systematic criteria. Four critical questions need to be answered to validate the processing results:

1) Are the apparent chimneys due to seismic artifacts? Shallow stratigraphic features (channels/reefs), gas-filled sands, and gas chimneys or mud volcanoes themselves can cause seismic artifacts in the underlying seismic data. Thus, it is important to visualize the chimneys on near-mid and far-angle stacks (Heggland, 2013). Shallow seismic artifacts will have a cone-shaped distortion on the far-angle stacks due to undershooting, whereas valid chimneys will be imaged in the same position. Based on these considerations, near- and far-offset similarity and amplitude attributes (with corresponding vertical offsets) can also be used in the neural network training.
2) Are the apparent chimneys due to fluid migration, rather than poor seismic imaging? Vertical gas migration may be widely dispersed as a gas cloud, but it is frequently detected along fault zones because these faults provide a focus for vertical fracturing. Faults are often poorly imaged, due to velocity contrasts across the faults that are not resolved by the seismic processing. We need to be able to distinguish this "fault shadow" effect from true hydrocarbon migration.
    - Criteria: Pockmarked morphology on time or depth slices. Actual vertical fluid flows will have a circular pockmarked morphology on time or depth slices (Ligtenberg, 2005). Poorly imaged faults will have a more diffuse morphology.
3) Are apparent chimneys due to hydrocarbon migration? Fluid flow could be due to dewatering of unconsolidated shales rather than to hydrocarbon migration. This dewatering causes polygonal faulting, which can often be confused with true chimneys (Cartwright et al., 2007). Geothermal brines, related to volcanic activity, may also cause vertical fracturing, which can be confused with hydrocarbon migration.

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- Criteria: Link to shallow direct hydrocarbon indicators (DHIs) (amplitude-variation-with-offset anomalies/chemosynthetic buildups). Dewatering effects related to polygonal faulting can often be confused with chimneys but will not have associated bright spots.

4) Are chimneys due to thermogenic hydrocarbon migration? Shallow chimneys may be related to biogenic gas.

   - Criteria: Chimneys originate from a known or suspected thermally mature source rock interval. Basin modeling can provide an important tool for predicting the thermal maturity of the suspected source rock interval.
   - Criteria: Chimneys are linked to surface macro- or microseeps indicating thermogenic hydrocarbons. Surface geochemical surveys (onshore) or piston core data (offshore) can provide biomarker data, which supports a thermogenic source for the hydrocarbons (Dembicki, 2013a).
   - Criteria: Chimneys correlate with C2+ hydrocarbon that shows or pays in wells. Wells that have drilled into the gas clouds overlying oil fields in the North Sea encountered an increase in heavy hydrocarbons (C2 and higher) compared with wells drilled outside the gas cloud (Løseth et al., 2009).

Details of the chimney detection methodology are provided by Connolly et al. (2013), Meldahl et al. (2001), and Aminzadeh and de Groot (2006). These articles describe in more detail the rationale for the seismic attributes used in the neural network training.

Limitations

Examples of reliable chimneys in the seismic data are necessary for reliable chimney processing results. Hydrocarbon migration may not be able to be resolved in areas with severe imaging issues, related to subsalt or structural complexity. However, good imaging of hydrocarbon migration, tied to surface geochemical data, has been achieved in areas in which the salt was fairly tabular (Dembicki and Connolly, 2013). Some older seismic data are too noisy for reliable results. However, modern processing can often improve the data quality. Seismic processing, such as median dip filtering, or f-x filtering, which smooths the data too severely and removes too much seismic noise, can also limit good results. Sometimes, the chimneys are at depths that are difficult to image. Later diagenesis can potentially restrict residual gas saturation and, thus, limit our ability to visualize the chimneys.

Visualization of vertical hydrocarbon migration

Chimney probability results can be displayed on seismic lines with low-probability chimneys made transparent. However, it is difficult to assess the validity of chimneys on seismic lines alone. Chimney probability results can also be displayed on time, depth, or horizon slices. Displaying chimney data over similarity data is especially useful. Chimney probability results can also be displayed on fault surfaces themselves. This allows the interpreter to understand which part of the fault is migrating fluids (Ligtenberg, 2005). Often, we observe the chimneys occur at bends in the fault in which faults undergo more intense strain. Chimneys can also be displayed in three dimensions by making the lower probability chimneys transparent. However, these 3D displays may show reliable and unreliable processing results. To address this problem, geobodies of reliable chimneys (based on the chimney validation process) can be created with designated probability cutoffs. These geobodies can be color coded. One approach is to give chimneys colors based on what stratigraphic interval they originate. Thus, primary hydrocarbon migration from a known or suspected source rock interval can be distinguished from secondary leakage from a potential reservoir interval. Thermogenic hydrocarbons can be distinguished from biogenic gas, based on the origin and possible termination of the chimney. The color saturation of the geobody can indicate the reliability of the chimney. Highly reliable chimneys have high color saturation, whereas moderately reliable chimneys have low color saturation. Unreliable chimneys would not be displayed.

The 3D volumes and three geobodies will show both chimneys with extensive vertical dimensions and limited vertical extent, which may not represent valid hydrocarbon migration pathways. Therefore, a chimney tracking method, such as ant tracking (used for fault detection in Pedersen et al., 2002), can be used to image the hydrocarbon migration pathways more clearly (Heggland, 2014).

Visualization of hydrocarbon expulsion from source rock

Once we are able to visualize chimneys in seismic data, we can then potentially determine from which interval or intervals they originate (a possible source rock). Critically, these chimneys should be absent over rich source rocks that are not thermally mature. The lateral extent of the chimneys can then provide clues to the extent of the thermally mature kitchen or the lateral extent of organic-rich source rock. An example from the North Sea showing chimneys associated with thermally mature Upper Jurassic Kimmeridgean shales is discussed in Ligtenberg and Thomsen (2003). Case studies from the Texas State Waters, Gulf of Mexico (Connolly et al., 2013) show chimneys originating from the gas-prone Eocene interval. Another example from deepwater Namibia shows widespread chimneys overlying a Cenomanian source rock interval (Connolly et al., 2014). These chimneys are often overlooked in the seismic record because (1) this vertical migration may be quite widespread and not have a chimney morphology, (2) hydrocarbon migration often occurs in shale-prone intervals, which are poorly imaged due to low acoustic impedance contrasts, (3) hydrocarbon migration may provide lubrication for décollement surfaces, which also have a chaotic seismic signature, and (4) hydrocarbon migration often occurs in the deep overpressured interval below major producing reservoirs. This vertical migration may be quite widespread until the hydrocarbons encounter a laterally extensive reservoir that can provide a lateral migration pathway. The lateral migration pathways may then focus hydrocarbons to structural highs or faulted barriers, which are potential traps. Leakage from these highs or along the faults will occur at their weakest points, and thus, have a more pipelike chimney morphology. If the point-sourced leakage is at the crest of the structure, the trap may have a good chance of being breached (Heggland, 2013). This is Heggland's class 1 trap. If this leakage is not at the crest of the structure, there is a good chance that the trap updip of the chimney contains hydrocarbons (class 2 trap). If the leakage from these reservoirs has more widespread "gas cloud" morphology, there is also a very good chance of hydrocarbon presence (class 3 trap).

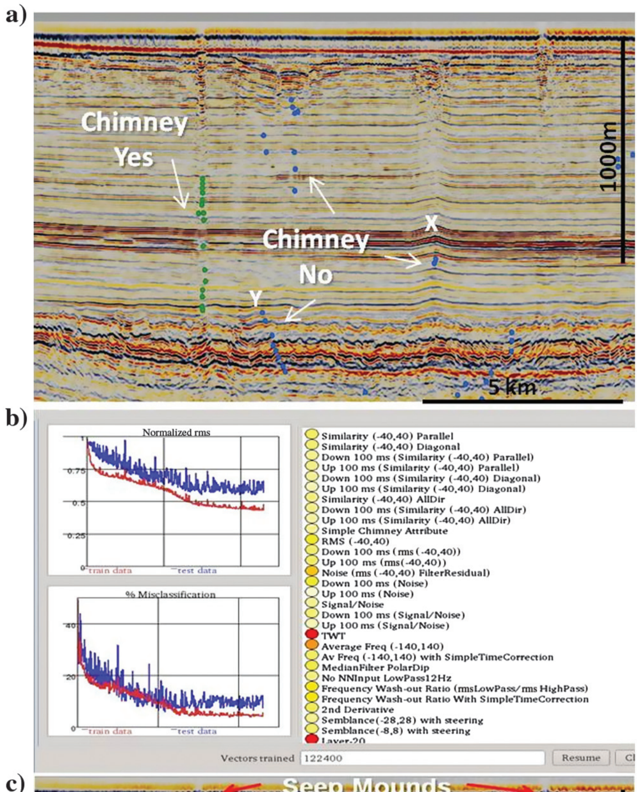

Figure 1. Chimney detection methodology. Representative lines showing good examples of chimneys are selected. (a) Examples of chimneys (green dots) and nonchimneys (blue dots) are picked on the key lines. A set of directional attributes are calculated and run through the neural network training process. (b) Attributes most important in the neural network training are shown in orange to red. (c) Resultant chimney probability results can be overlain on the seismic.

Case study: Dutch North Sea

Shallow gas sands have been encountered in the northwestern sector of the Dutch North Sea. However, the origination of the shallow gas is not well understood. The A-15 nos. 2 and 3 wells encountered shallow gas in stacked sands of Miocene age. The disturbed zones indicating potential gas chimneys were noted below these shallow gas anomalies. However, it was difficult to determine if this seismic response represented true vertical gas migration or was a seismic processing artifact due to poor imaging below the shallow gas anomalies. A gas chimney detection project was undertaken in a 3D seismic survey to assess the reliability of these suspected chimneys and determine from which interval they originated (a potential biogenic or thermogenic source rock). We also wanted to understand if there was a correlation between other undrilled shallow gas anomalies in the survey area and chimneys. By understanding the hydrocarbon migration pathways, we may be able to delineate deep prospective traps and high-grade additional shallow gas leads. A study, using similar methods, in the Danish Basin, showed that chimneys providing charge to shallow Miocene gas sands originated from a deep presalt (Carboniferous) interval. The gas migrated though the salt via deep faulting (Andresen et al., 2014).

Methodology of chimney detection

Line 16361 (Figure 1a) is a good seismic line showing the character of vertical hydrocarbon migration in the study area. Chimney yes picks (green) were made in reliable chimneys connected to seep mounds at the sea bottom. Nonchimney picks (blue) were made in the velocity pull-up zone, which is immediately below a suspected shallow chimney (X) and in faults not associated with obvious vertical chimneys (Y). A set of directional attributes were calculated at the picked locations (Figure 1b), and the results were fed into a neural network for training. The most important attributes used in the neural network training are shown in orange to red (most important). The layer attribute and the TWT attribute were the most important attributes, probably due to the differing character of the chimneys with depth. The noise attribute was also important reflecting the chaotic character of chimneys. The frequency attribute was also important probably related to the attenuation of high frequencies due to residual gas in the

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rock matrix (Dupuy and Stovas, 2014). The chimney probability results were then overlain on the seismic (Figure 1c) with high-probability chimneys in yellow to green. Displayed on lines, however, it is not clear if the neural network results are reliable.

Validation of chimney processing results

Are any high-probability chimneys due to seismic artifacts? A shallow channel in the near surface causes data quality degradation ("Bad Data" in Figure 1c) in the underlying section, which is difficult to distinguish by neural network training. A horizon slice at the Lower Tertiary S2 horizon (Figure 2) shows, however, that the high-probability chimneys do not correlate with either the channels or the shallow gas anomalies, although chimneys are present below both features. The very high probability chimneys (>80% — yellow) have a pockmarked morphology, indicating they are probably related to fluid movement.

Are the high-probability chimneys related to thermogenic hydrocarbon migration? Deeply sourced chimneys related to faulting through the regional Upper Jurassic to Upper Cretaceous (Ekofisk) regional seal (Figure 3) are directly linked with the shallow Miocene gas sands and amplitude anomalies within the Lower Tertiary interval. These chimneys probably originate from the Carboniferous (Figure 4), a gas-prone source rock expected in this area, based on regional studies (Geluk et al., 2002). Similar chimneys originating from the Carboniferous (Figure 5) tie closely to Triassic gas shows in the A8 #1 well.

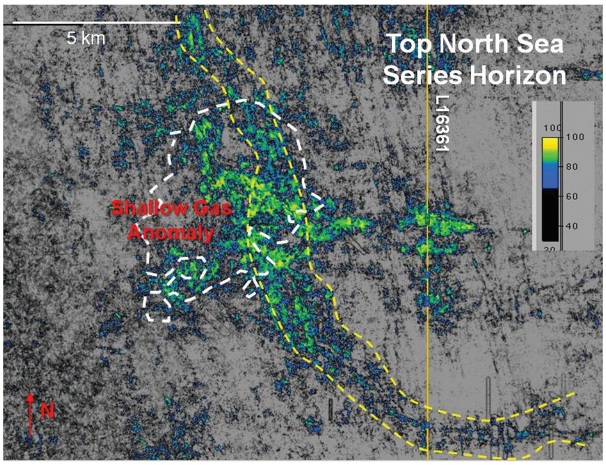

Figure 2. High-probability chimney results (green to yellow) are overlain on similarity data (gray scales) for an interpreted horizon. Chimneys often have a pockmarked morphology indicating likely related to fluid migration (not poor seismic imaging). Moreover, chimneys do not directly correlate to a shallow gas occurrence (white dashed line) or shallow channel (yellow dashed line).

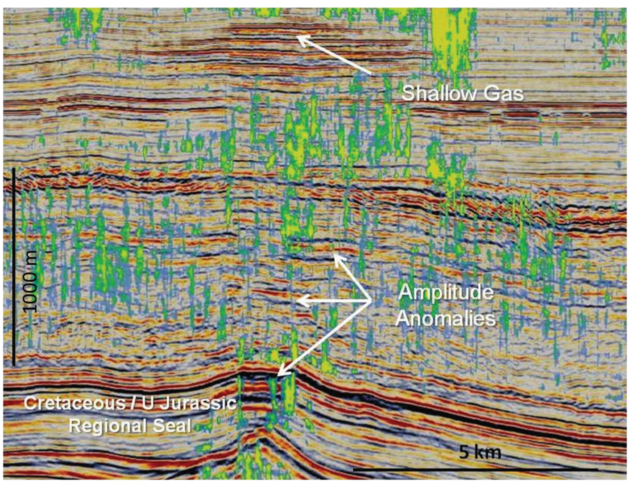

Figure 3. Chimney probability results overlain on seismic. High-probability chimneys (yellow) are directly linked to shallow gas occurrences and amplitude anomalies. Moderate-probability chimneys (green to blue) are more likely due to polygonal faulting related to dewatering of impermeable shales in the low-amplitude Tertiary North Sea series.

The 3D visualization of reliable chimneys

Geobodies were created for the major reliable chimneys. Cutoffs for the geobodies were generally >80% because chimneys that had a reliable pockmark morphology on depth sections showed probabilities >80% (yellow). A display of these geobodies on the Top Permian Zechstein Salt Horizon (Figure 6) shows that most chimneys are located above salt structures that provide a focusing mechanism for vertical migration. Hydrocarbons probably originating from the Carboniferous exploit faults and thins in salt and migrate vertically in the fractured zone in the salt/sediment interface (Davison, 2009). Hydrocarbons move vertically to charge potential Triassic or Jurassic reservoirs. These deeply sourced chimneys largely terminate below the regionally pervasive Upper Jurassic shale seal. There are only two chimneys in the study area that penetrate this interval. Chimney 1 (Figure 6) is located at the intersection of major east–west- and north–south-trending fault systems and directly underlies the Miocene stacked gas

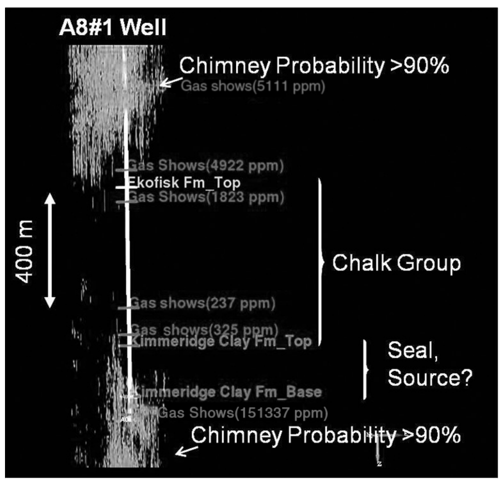

Figure 4. A 3D image of chimneys with probability >90% in the vicinity of the A8 #1 well. Highly probable chimneys correlate with gas show >5000 ppm.

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sands tested by the A15 #2 and #3 wells. Chimney 2 is located along an east–west fault on the western flank of the study area. This chimney underlies another Miocene amplitude package that is untested, but expected to contain shallow gas. Significantly, the two largest shallow amplitude anomalies directly tie to the only deeply rooted gas chimney. This suggests that deeply sourced thermogenic hydrocarbons are necessary to charge large (economic) shallow gas accumulations.

Implications for exploration

The 3D visualization of gas chimneys in this portion of the Dutch North Sea indicates that major shallow gas accumulations are charged by deep vertical thermogenic hydrocarbon migration. This gas originates in part from deep Carboniferous gas-prone source rocks. This gas probably originates from coaly measures, which are dominantly composed of methane. The shallow gas sands may also be receiving charge from interbedded biogenic gas. Biodegradation of the shallow gas makes it difficult to distinguish the relative gas mix of biogenic and thermogenic hydrocarbons (Dembicki, 2013b). However, the size of these accumulations relative to other shallow anomalies in the study area indicates the thermogenic component is dominant.

The presence of these deep chimneys has significant implications for exploration in the area. First, the chimneys originate from the Carboniferous and are thus gas prone. Thus, the deep exploration potential is probably gas. Oil, generated by mid- to upper-Jurassic source rocks, is still possible, but it is not supported by the chimney processing results. Second, the chimney results show prospective structures in which potential reservoir intervals show evidence of gas charge and effective top seal. Indeed, the A15 #1 had gas shows in the Triassic interval. Chimney processing results show abundant chimneys in the horizon slice 100 m below the reservoir. Chimney results also show no chimneys in the horizon slice 100 m above the reservoir, indicating effective top seal.

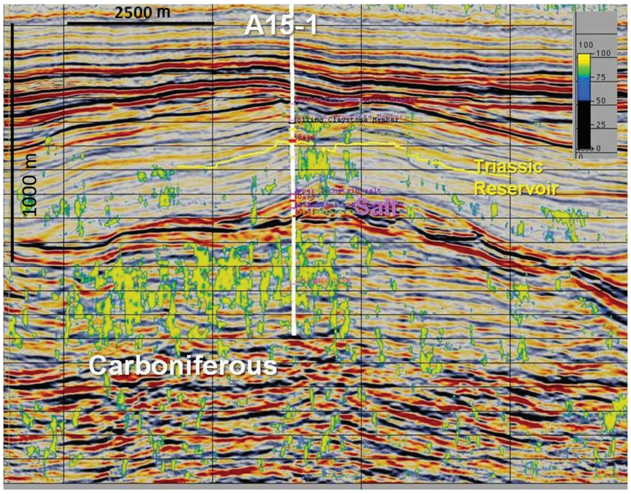

Figure 5. Seismic line through A15 #1 with chimney overlain. Chimneys originate from presumed Carboniferous gas-prone source rock interval and penetrate overlying Permian salt interval to charge Triassic gas sands. Chimneys terminate in overlying Triassic evaporite facies, which provides an effective top seal for the accumulation.

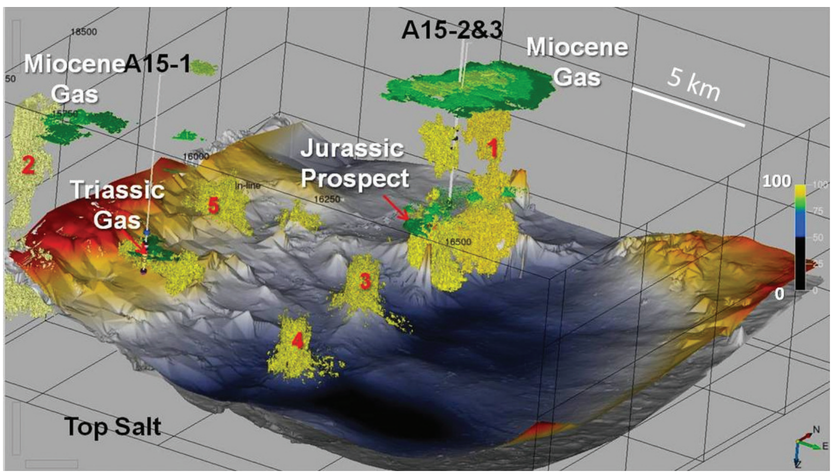

Figure 6. The 3D visualization of a high-probability gas chimney (yellow) and potential gas reservoir (green) geobodies overlain on the Top Salt horizon. The A15 #2 and #3 wells tested gas in the Miocene, whereas the A15 #1 well tested gas in the Triassic. Chimneys 1 and 2 provide charge to tested and untested shallow gas anomalies. Chimneys 3, 4, and 5 charge possible deep Triassic leads.

Conclusions

Visualization of chimneys in a 3D seismic data set in the Dutch North Sea shows that shallow Miocene gas sands are sourced in part from deep thermogenic Carboniferous gas-prone source rock. Large accumulations of shallow gas are located over areas in which chimneys penetrate the Upper Jurassic to Cretaceous seal via regional east–west-trending faults. There is exploration potential in the area for Triassic sand reservoirs that overlie deep salt structures. Deep prospects need to be located over structures in which hydrocarbons penetrate the underlying salt, but do not leak through the overlying Upper Jurassic seal.

Acknowledgments

We would like to thank E. Rosendahl with Energie Beheer Nederland (EBN) for providing the seismic data and regional geologic understanding.

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