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Hydrocarbon Migration and Accumulation Above Salt Domes—Risking of Prospects by the Use of Gas Chimneys

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Abstract

In many cases, seismic data show indications of shallow gas accumulations above salt domes. Faults created by the upward movement of the salt are believed to act as hydrocarbon migration pathways. This involves a risk of leakage from the deeper reservoirs. Gas chimneys may provide additional indications on the risk of leakage of hydrocarbons from deeper reservoirs.

To enable the mapping of gas chimneys in a consistent manner, a method for the detection of chimneys in post-stack 3D seismic data has been developed. This recently developed method makes use of multiple seismic attributes and neural network technology. The output, after chimney detection, is a 3D cube in which high values have been assigned to samples inside chimneys and low values to the background, and from which the shape and the spatial distribution of the chimneys can easily be visualized.

Gas chimneys have been observed above hydrocarbon-charged, as well as dry structures. However, the way chimneys appear in the two cases seems to be different. Chimneys above dry structures coincide with faults across the top of the structures. Chimneys above hydrocarbon-charged structures are observed over a wide area above each structure and are not coincident with a fault.

Introduction

Interpretation of gas chimneys on seismic data has been performed in order to determine if gas chimneys can indicate the presence of hydrocarbons in underlying structures. During such studies, gas chimneys have been observed in areas above both hydrocarbon-charged, as well as dry structures. In order to improve the identification of gas chimneys in seismic data, and to map their extents and distribution in a consistent manner, a method for detection of chimneys has been developed (Meldahl *et al*., 1998, 1999 and Heggland *et al*., 1999). This method, with application examples, is probably best described in Heggland *et al*., 2000, Meldahl *et al*., 2001, and Aminzadeh *et al*., 2001. The detection of gas chimneys on 3D seismic data has resulted in examples showing a difference in the way gas chimneys appear above hydrocarbon charged and dry structures. Some of the examples involve vertical hydrocarbon migration associated with salt diapirs.

Method

The method makes use of multi-attribute calculations and a neural network. Multi-trace and multi-attribute calculations are performed on the input seismic data. In order to increase the contrast between the chimneys and the background, attributes which are determined the best to distinguish between chimneys and background are used. The different attributes that are input to the neural network are weighted according to their contribution to the enhancement of the chimneys. The attributes that give the highest contributions to the detection of gas chimneys seem to be trace-to-trace similarity, and energy (or absolute amplitude), which are both generally lower within chimneys than in the areas surrounding them, and the variance of the dip of seismic reflectors, which is higher inside than outside the chimneys due to the chaotic reflection pattern within chimneys. The neural network is trained on attributes extracted at chimney and non-chimney example locations. The example locations are chosen by the interpreter based on chimney interpretation experience. After training, the network is applied to the entire data set to recognize chimneys from the background. In the chimney detection process, multiple, vertical attribute extraction windows are used. This enables the network to distinguish between gas chimneys and objects having similar seismic characteristics but having a smaller vertical extent than the gas chimneys. In the final stage, the neural network makes a classification of the seismic data into chimney and non-chimney samples. The output samples are assigned a high value for chimneys (high probability) and a low value for non-chimneys (low probability), as shown in Figure 1. The resulting cube is named a chimney cube (Fig. 2).

The method has been generalized for the detection of other seismic objects as well, such as faults and diapirs, in which case the detection is steered along the orientation of the actual seismic object (see Tingdahl, 1999).

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Results

Gas chimneys are visible on seismic data as columnar disturbances, in which the continuity of reflectors is missing and the reflection amplitudes are weaker than in the surrounding areas. Gas chimneys interpreted from 3D seismic data, some of which have been confirmed by wells, have been sorted into two kinds of chimneys.

One category of chimneys involves those that are coincident with faults. These chimneys are typically circular and have a limited horizontal cross section and a diameter on the order of 100 metres. The presence of gas chimneys along faults indicates that the faults are open, or have been open for a time, in which case fluids and gas can migrate up through the faults at a relatively high flux rate. Gas chimneys are not the only indicators that a fault is, or has been, leaking. In cases where no gas chimneys are present at a fault, there may be other indications of leakage, such as high-amplitude anomalies attached to faults indicating the presence of sands being charged by gas migrating up the faults (Fig. 3). Pockmarks, or carbonate build-ups, along faults, can be other indications that gas is (or has been) migrating up the faults (Fig. 4). If gas chimneys are present along faults, across or near the top of a prospect, then the prospect is regarded as having a high risk of being dry. However, when chimneys are observed along faults vertically below, and cutting into a prospect, this is regarded as positive with respect to hydrocarbon charge of the prospect.

Another category of chimneys includes those that are not coincident with faults, in which case their lateral extent can be on the order of several hundred meters. This kind of chimney is often present on top of hydrocarbon-charged reservoirs, and the presence of gas in the chimney is regarded as static, or moving upwards at a low flux rate (Figures 5 and 6). When this kind of chimney is present on top of a structural closure, it is believed to be a positive indication with regard to the presence of hydrocarbons in the prospect.

The following examples from the Gulf of Mexico and the North Sea show seismic indications of vertical hydrocarbon migration associated with salt diapirs and faults. The example from the Gulf of Mexico (Figs. 7 and 8) shows how gas chimney detection can help to identify a leaking fault above a salt dome. The next two examples are from the North Sea. The first North Sea example (Figs. 9 and 10) shows other indications of leaking faults above salt diapirs. The last example, also from the North Sea (Fig. 11), shows a chimney of the second kind (not associated with a fault) located on top of a hydrocarbon-charged reservoir overlying a salt diapir.

Figure 7 is a 3D visualization of a seismic volume from the Gulf of Mexico. A salt dome has been detected using a modified version of the chimney detection method, and is displayed in the white-bluish colour. Seismic high-amplitude anomalies (red) from the 3D volume represent the outline of two prospects.

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Detected chimneys (yellow) from a chimney cube show possible gas migration between the two prospect levels, as well as to the seabed (brown surface). Two other horizons (green and blue) were mapped. An amplitude map of the green surface (Fig. 8) shows that the chimneys are coincident with a fault (the low amplitude feature in black) across the highest part of the structure. This is believed to indicate that the fault is, or has been, open for hydrocarbon migration. An exploration well penetrating the two prospect levels is dry, probably due to the presence of the non-sealing faults that cut through the tops of the two objective reservoirs.

Figure 9 shows a seismic section from a 3D survey in the North Sea. The presence and upward movement of a salt dome is believed to have generated faults in the overburden, which function as hydrocarbon migration pathways. The updoming caused by the salt movement and the presence of a sand body above it has generated a possible trap for hydrocarbons migrating up the faults, provided proper sealing conditions exist. Anomalously high amplitudes in the shallow section indicate the presence of gas in this trap. Possible gas-water contacts can be seen below the high amplitude reflectors. The amplitude anomalies have been mapped by making a summation of absolute amplitudes in a time interval including the anomalies.

The result is a map (Fig. 10) showing the average absolute amplitudes in the time interval. High amplitudes are displayed in white and zero amplitudes in black. From this map, it can be seen that the amplitude anomalies are limited by an outer structural closure that has been segmented into different traps by the faults. The faults are visible as low amplitude features in black. Since the anomalous high-amplitude segments are not in communication with each other and are partly bounded by the faults (Fig. 9), it is believed that the gas charge is related to vertical migration through the faults generated by the salt, and not laterally through the sand body. Whether such a reservoir can hold hydrocarbons depends on the presence of faults or fractures above the reservoir and whether or not they are sealing.

The final example (Fig. 11) is from the North Sea. It shows a chimney located on top of a hydrocarbon-charged reservoir overlying a salt diapir. In this case, the chimney extends over most of the reservoir, and does not seem to be related to faults generated by the upward movement of the salt. Wells penetrating the chimney show a sudden increase in gas content in the drilling fluid when encountering the top of the gas chimney. The gas is not believed to have a significant upward movement, or if it does, the flux rate appears to be very low.

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Conclusions

Detection and mapping of gas chimneys on seismic data, has made it possible to distinguish between chimneys representing hydrocarbon migration through faults, and chimneys representing no, or very slow, upward movement of hydrocarbons (gas). Mapping of other seismic anomalies associated with vertical gas migration through faults or fractures can also be used to identify hydrocarbon migration pathways.

The ability to discriminate between gas chimneys which indicate vertical migration pathways for hydrocarbons, above, below, or at the flank of prospects, and gas chimneys not related to faults, indicating presence of hydrocarbons in a prospect, is significant in the process of risking hydrocarbon prospects.

Salt domes can generate faults that function as hydrocarbon migration pathways, as well as creating structural closures that can trap the hydrocarbons. An evaluation of the presence of non-sealing faults or fractures above a prospect of this kind, by detection of gas chimneys and mapping of other gas leakage anomalies, can indicate the risk of the prospect being dry or productive.

Acknowledgments

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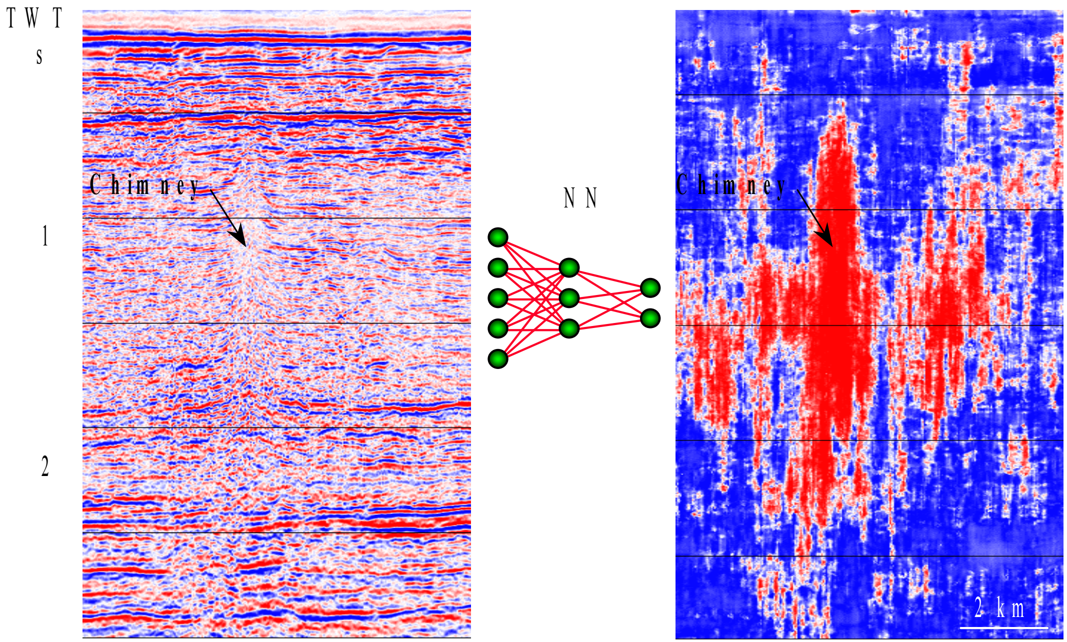

Figure 1. 3D seismic section before (left) and after chimney detection (right).

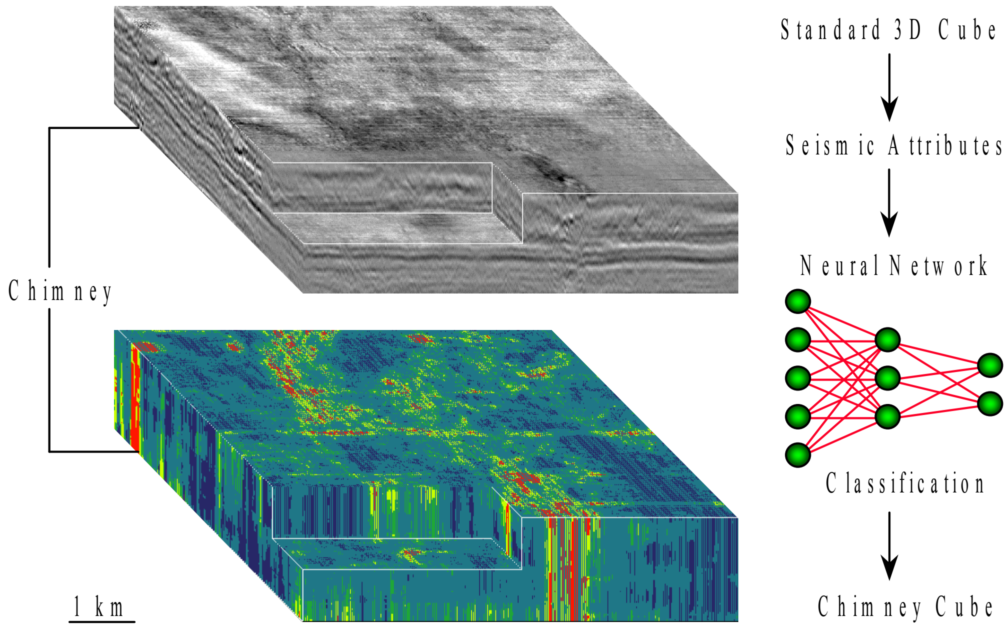

Figure 2. 3D seismic volume before and after chimney detection.

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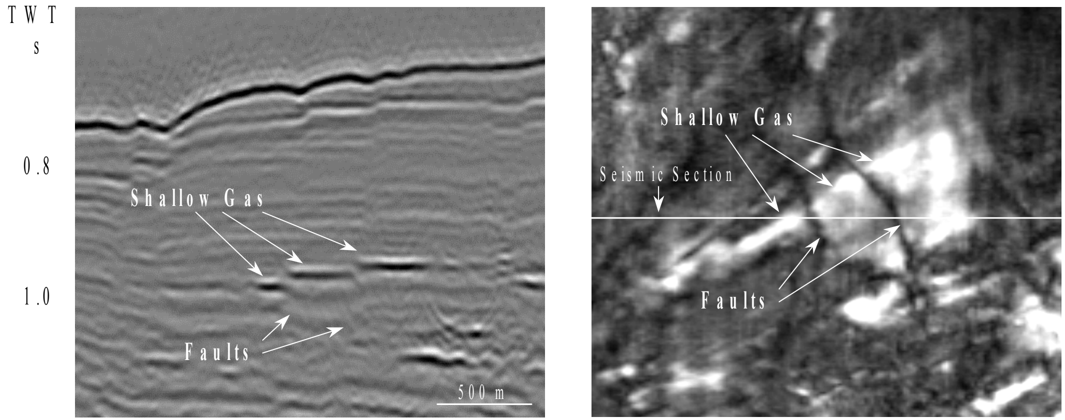

Figure 3. 3D seismic section (left) and average absolute amplitude map (right) showing a possible sand segmented by faults, Nigerian continental slope. The sand is believed to be charged by gas migrating up the faults.

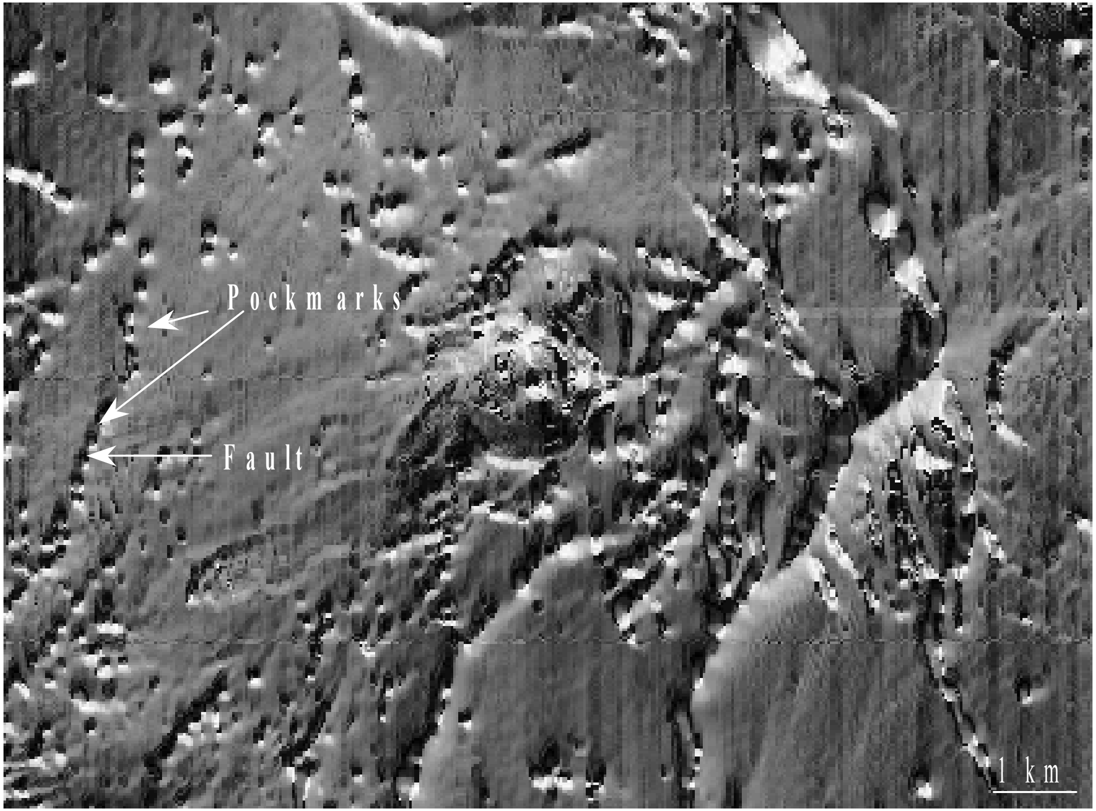

Figure 4. Azimuth map from 3D seismic data showing pockmarks present along seabed fault lines, Nigerian continental slope.

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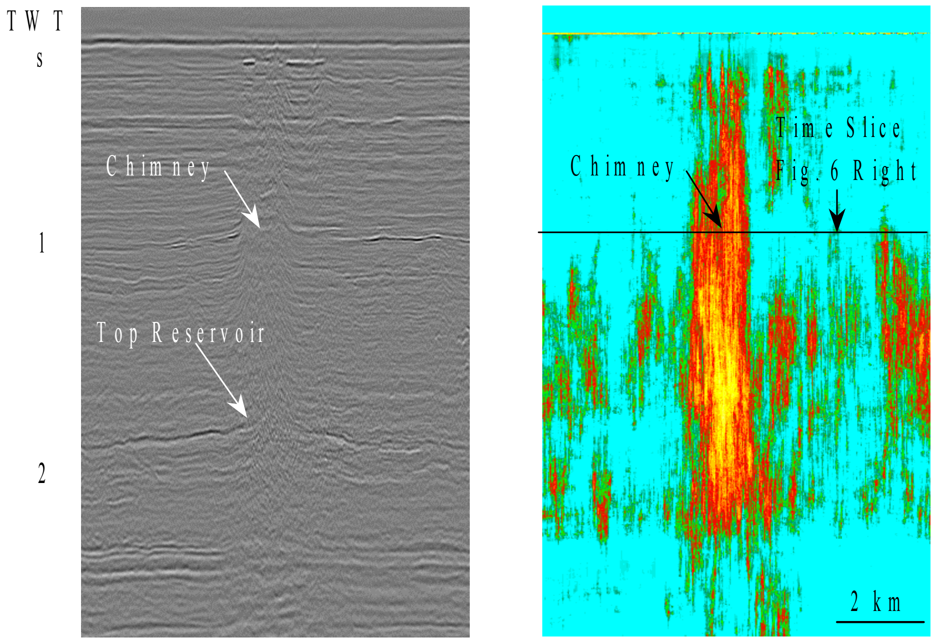

Figure 5. 3D seismic section before (left) and after chimney detection (right). The chimney is located on top of an oil and gas reservoir and covers most of the top of the reservoir, North Sea, see Figure 6.

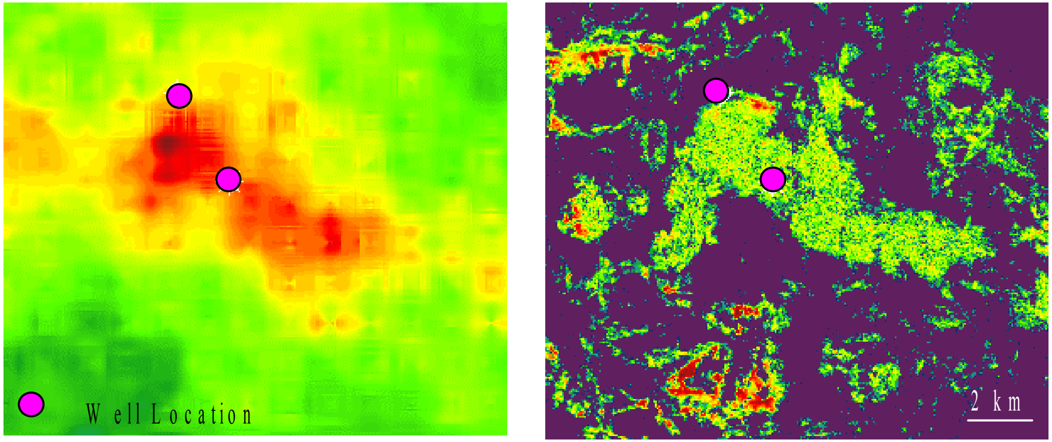

Figure 6. Left, a time map of top of the reservoir in Figure 5. Right, a time slice through the detected chimney above the reservoir. The gas chimney covers most of the underlying reservoir.

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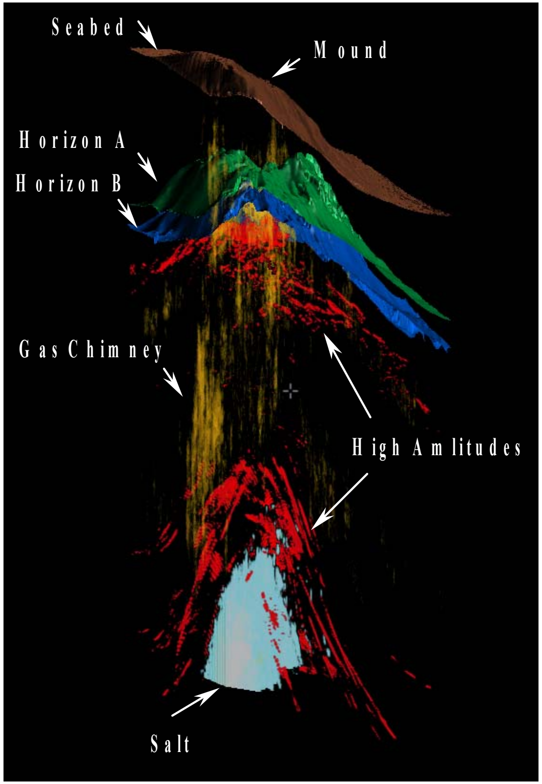

Figure 7. Visualization of 3D seismic data, Gulf of Mexico. Mapped horizons (brown, green, blue), high amplitude clusters outlining two prospects (red), detected salt diapir (white-blueish) and detected chimneys (yellow).

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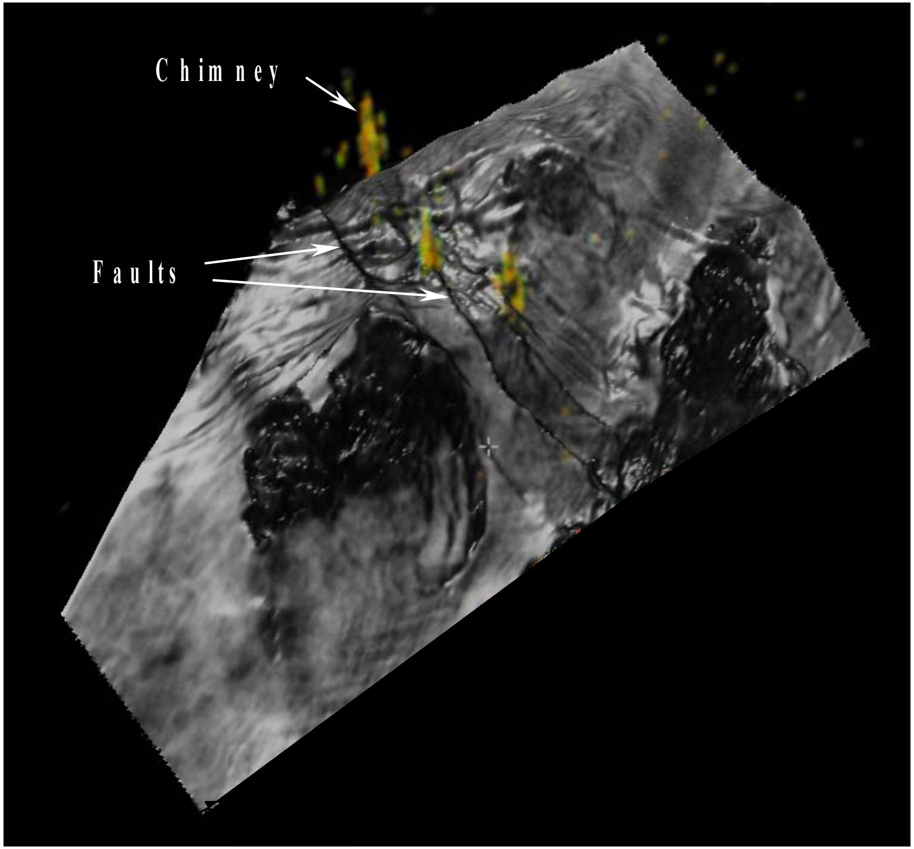

Figure 8. Average absolute amplitude map of the green horizon in Figure 7. Chimneys (yellow) are located at faults visible as low amplitude features (dark) on the amplitude map in display.

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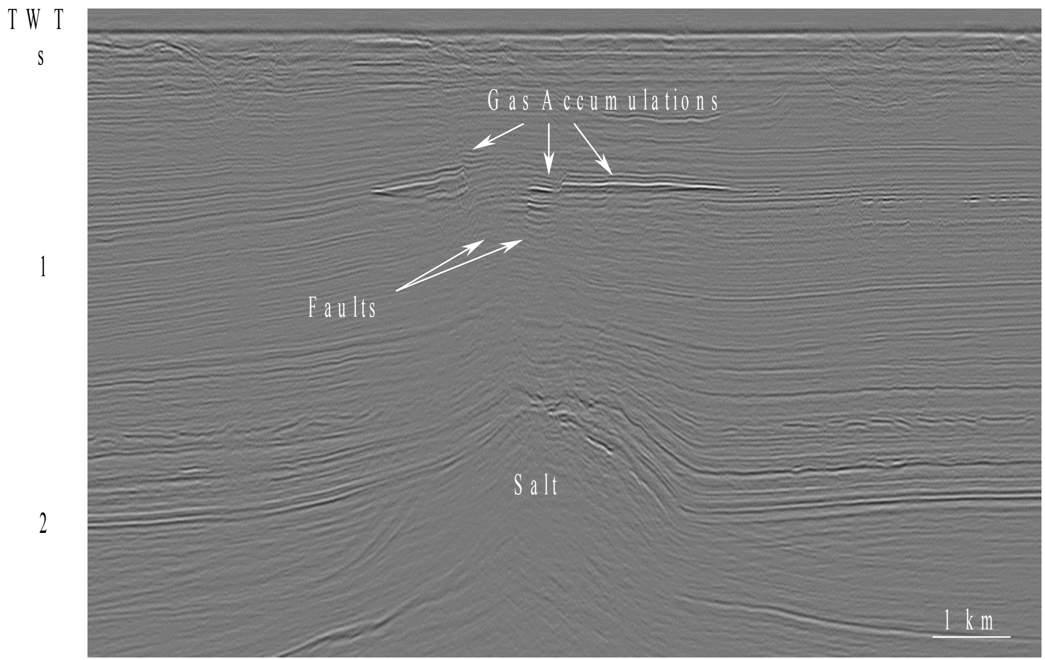

Figure 9. 3D seismic section, North Sea. A possibly gas charged reservoir is present above a salt dome. Possible gas-water contacts can be seen below the high amplitudes. Gas is believed to have migrated through faults generated by the salt dome.

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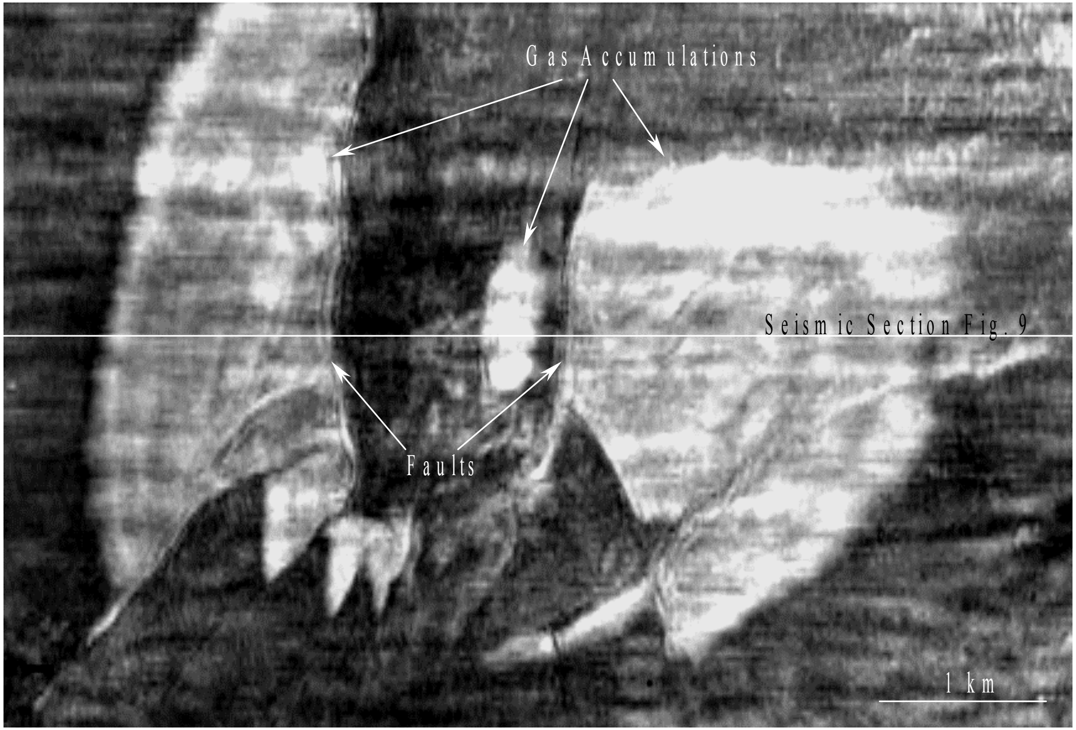

Figure 10. Average absolute amplitude map showing the extents of the amplitude anomalies (white) indicating the presence of gas.

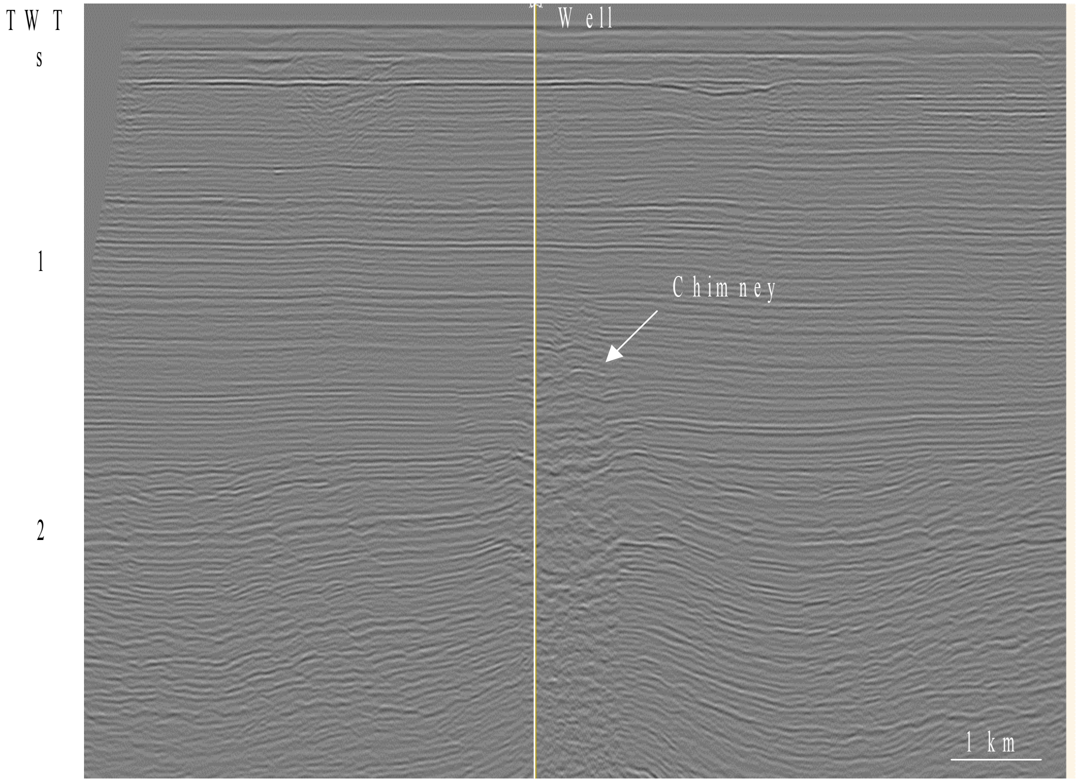

Figure 11. Seismic section from the North Sea showing a gas chimney located on top of a reservoir above a salt diapir. The gas chimney covers a large part of the reservoir and does not seem related to faults generated by the salt diapir.