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Using Gas Chimneys in Seal Integrity Analysis: A Discussion Based on Case Histories

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ABSTRACT

Gas chimneys are visible in seismic data as columnar disturbances, where the continuity of reflectors is missing, and reflection amplitudes are weaker than in the surrounding areas. In this chapter, gas chimneys interpreted from three-dimensional seismic data, some of which have been confirmed by wells, have been sorted into two kinds. Type 1 chimneys are associated with faults. These chimneys commonly have a circular and limited horizontal cross section with a diameter in the order of 100 m (330 ft). The presence of gas chimneys along faults indicates that the faults are open or have been open for a time, in which case fluids can migrate through the faults. Type 2 chimneys are not associated with faults, and their lateral extent can be in the order of several hundred meters. Because open faults are not capillary barriers for hydrocarbons, as opposed to shales, type 1 chimneys can indicate hydrocarbon-migration pathways where relatively high flux rates can occur. Because type 2 chimneys are not associated with faults, capillary resistance in the shales will prevent upward movement of free gas (and oil), and the chimneys are regarded to represent gas having a very slow or no upward movement (low to zero flux rate). However, fractures beyond seismic resolution may exist, which may account for gas migration through the shales. Another explanation for the presence of gas type 2 chimneys is that gas-saturated water may release gas during upward movement caused by a drop in the pressure.

Examples from the North Sea, Gulf of Mexico, Nigeria, and the Caspian Sea show a consistency in the appearance and distribution of types 1 and 2 chimneys above hydrocarbon-charged reservoirs, as well as above dry reservoirs. Type 1 chimneys have also been observed below hydrocarbon-charged reservoirs, in which case, they indicate migration pathways into the reservoir.

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INTRODUCTION

To find out if gas chimneys can be used to identify leaking faults and for the seal integrity analysis of cap rocks, gas chimneys have been mapped in different areas by the use of exploration three-dimensional (3-D) seismic data. It has been found useful to separate the observed chimneys into two types and, as such, help to distinguish between high-risk and low-risk hydrocarbon prospects.

- type 1, which can identify faults that are likely to be hydrocarbon-migration pathways
- type 2, which are associated with cap rocks of hydrocarbon-charged structures

METHODS

The diffuse character and common weak expression of gas chimneys in seismic data make them difficult to map, and in most cases, they are best visible in vertical seismic sections but not very visible on 3-D seismic time slices or attribute maps. 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 gas chimneys in poststack 3-D seismic data was developed (Heggland et al., 2000; Meldahl et al., 2001).

The method makes use of multiattribute calculations and a neural network (de Groot, 1999a, b). The inputs are standard 3-D seismic data and other seismic attributes. To distinguish the chimneys from background, attributes that best increase the contrast between the chimneys and the background are selected as input. 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 are trace-to-trace similarity, energy (or absolute amplitude), which both generally are lower in chimneys than in the areas surrounding them, and the variance of the dip of seismic reflectors, which is higher inside chimneys than outside because of the chaotic reflection pattern in chimneys. The neural network is trained on the attributes extracted at chimney and nonchimney example locations, which 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 with 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 nonchimney samples. The output samples are assigned a high value for chimneys (high probability) and a low value for nonchimneys (low probability). The resulting 3-D probability volume is called a chimney cube.

The method has since been generalized for the detection of other seismic objects, like faults and diapirs, in which case, the detection is steered along the orientation of the actual seismic object (Tingdahl et al., 2001).

RESULTS

For hydrocarbons to move through a shale, an open fault or a fracture system has to be present. This can only occur in an extensional regime as a result of overpressure in a reservoir, and the fault or fracture will be open for a time until the pressure has dropped (Bjørkum et al., 1998).

Water, as well as gas-saturated water, is not prevented by capillary forces to move through the shales. When water moves through a fault caused by overpressure in an underlying reservoir, some water is believed to move horizontally into the shale for a limited distance, i.e., in the order of 10–100 m (33–330 ft). If the water is gas saturated, gas may be released when the pressure drops. In the seismic data, this may appear to be a gas chimney. Alternatively, if gas is migrating through a fault, some of the gas may occupy fractures existing along the fault and generate what is observed in the seismic data to be a gas chimney. It is believed that if a fault is or has been open for a water flux, it will also be open for hydrocarbons (free gas or oil) to move through and, as such, represent the most likely migration pathway for hydrocarbons. Gas chimneys observed from the seismic data, which are found to be associated with faults, are here named type 1 chimneys.

During the upward movement of water, gas may be released when the pressure drops. In this case, chimneys can have a large lateral extent of several hundred meters. The gas chimneys are, in this case, believed to be free gas, which is trapped in the shales. Gas chimneys that are observed in the seismic data to have large lateral extents and are not found to be associated with faults are here named type 2 chimneys. The detection of gas chimneys on different 3-D seismic data has revealed chimneys of types 1 and 2. The detected chimneys have been displayed together with attribute maps generated from the 3-D seismic data to relate the chimneys to geological structures.

Type 1 Chimneys

Several 3-D seismic examples show the presence of chimneys along faults and fractures. This is believed to indicate that the faults are or have been working as fluid-migration pathways. Depending on the location of the faults, the presence of chimneys along the faults can indicate fluid-migration pathways between a source rock and a reservoir, or they can indicate leakage from a reservoir, either through a fault across the top of the structure or through a fault located at the flank of the structure (Figure 1a, b). If the leaking fault is located at the top of a structure, only small amounts of hydrocarbons are expected to remain in the reservoir. If the leakage is occurring through a fault at the flank of a structure, a hydrocarbon column may still be preserved in the reservoir. Figure 2 shows an example from the Danish North Sea, where gas chimneys are surrounding a deeper oil-charged reservoir (Heggland, 1998). In this example, conventional exploration 3-D seismic data show buried depressions (pockmarks) on top of the gas chimneys just below the seabed. The depressions are indications that gas has escaped through the seabed. A high-resolution, deep tow sparker profile across one of the depressions shows high reflectivity in the water column above the crater (Figure 3). This indicates that escape of gas through the seabed is still occurring. Some chimneys are grouped as lineaments, indicating that they are appearing from faults present at the flank of the deeper reservoir.

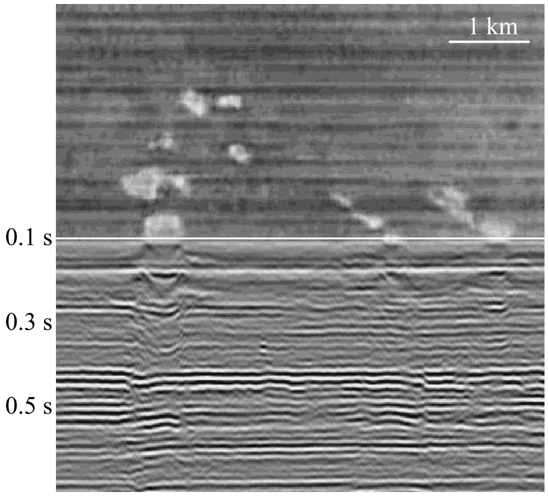

Figure 2. Composite display of a time slice at seabed level and a vertical section from 3-D seismic data from the Danish North Sea. A cluster of gas chimneys is surrounding a deeper, oil-charged structure. Buried depressions are present on top of the chimneys. Some of the chimneys form lineaments, indicating that the chimneys appear from faults at the flank of the deeper structural closure (cf. Figure 1b).

An example from the Gulf of Mexico is presented (Figure 4), in which two reservoirs contain only small amounts of hydrocarbons (shows). This is assumed to be caused by leaking faults across the top of the structure. Figure 4a shows a 3-D visualization with three mapped horizons from a 3-D seismic volume, the seabed (brown), and two subseabed horizons (green and blue). Seismic high-amplitude anomalies (red), clustered at two levels between the lowest horizon and the salt diapir at the base, represent the outline of two prospects. Detected chimneys (yellow) indicate gas migration between the two prospects and the seabed. An average amplitude map centered at the green surface (Figure 4b) shows that the chimneys are located along faults across the crest of the structure, indicating a nonsealing fault. The faults are visible as low-amplitude features in black. A well through the two

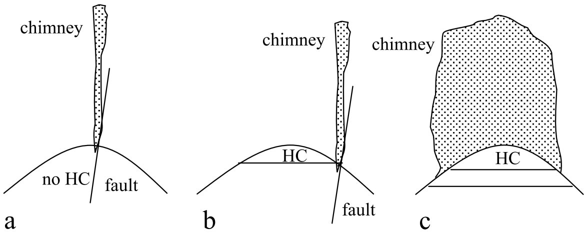

Figure 1. Illustrations of chimney types. (a) Type 1 chimney on top of a structural closure. The chimney is associated with a fault, which involves a risk that hydrocarbons (HC) have left the trap. (b) Type 1 chimney on the flank of a structural closure. In this case, a column of hydrocarbons may be preserved. (c) Type 2 chimney covers a large area on top of a structural closure. This may be an indication that hydrocarbons are present in the underlying structure.

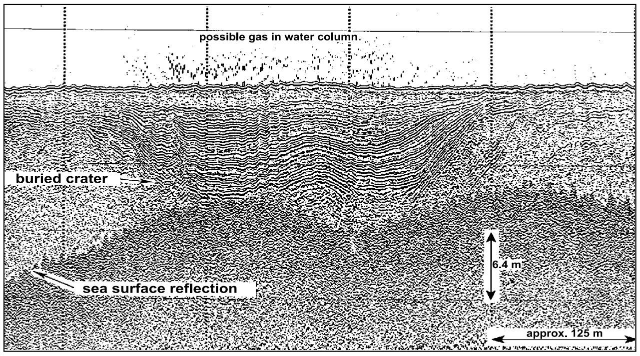

Figure 3. High-resolution sparker section through one of the buried depressions in Figure 2. High reflectivity in the water column across the buried depression indicates gas seepage.

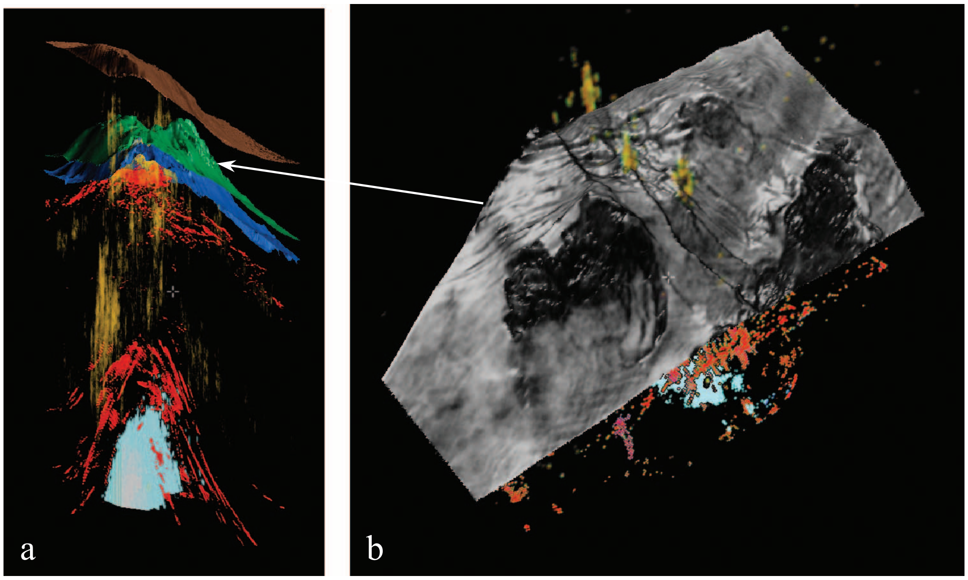

Figure 4. (a) High-amplitude clusters (in red) indicate the outline of two prospects in the Gulf of Mexico. Three mapped surfaces are displayed, the seabed (brown) and subseabed surfaces (green and blue). A salt diapir has been detected at the base using a modified version of the chimney-detection method. (b) Average absolute amplitude map centered at the green surface and detected chimneys. Faults are visible as low-amplitude features in black. The chimneys are located along faults across the top of the structure. This involves a risk that hydrocarbons have left the underlying structures. A well drilled through the two prospects encountered only small amounts of hydrocarbons (shows).

prospects encountered only small amounts of hydrocarbons (shows). The latter observation of chimneys indicating nonsealing faults may explain why only small amounts of hydrocarbons were present in these reservoirs.

Figure 5a shows a seabed azimuth map generated from 3-D seismic data from offshore Nigeria. Figure 5b shows the same map as in Figure 5a with detected gas chimneys (white) superimposed. Type 1 gas chimneys show a continuous presence along an east–west-extended

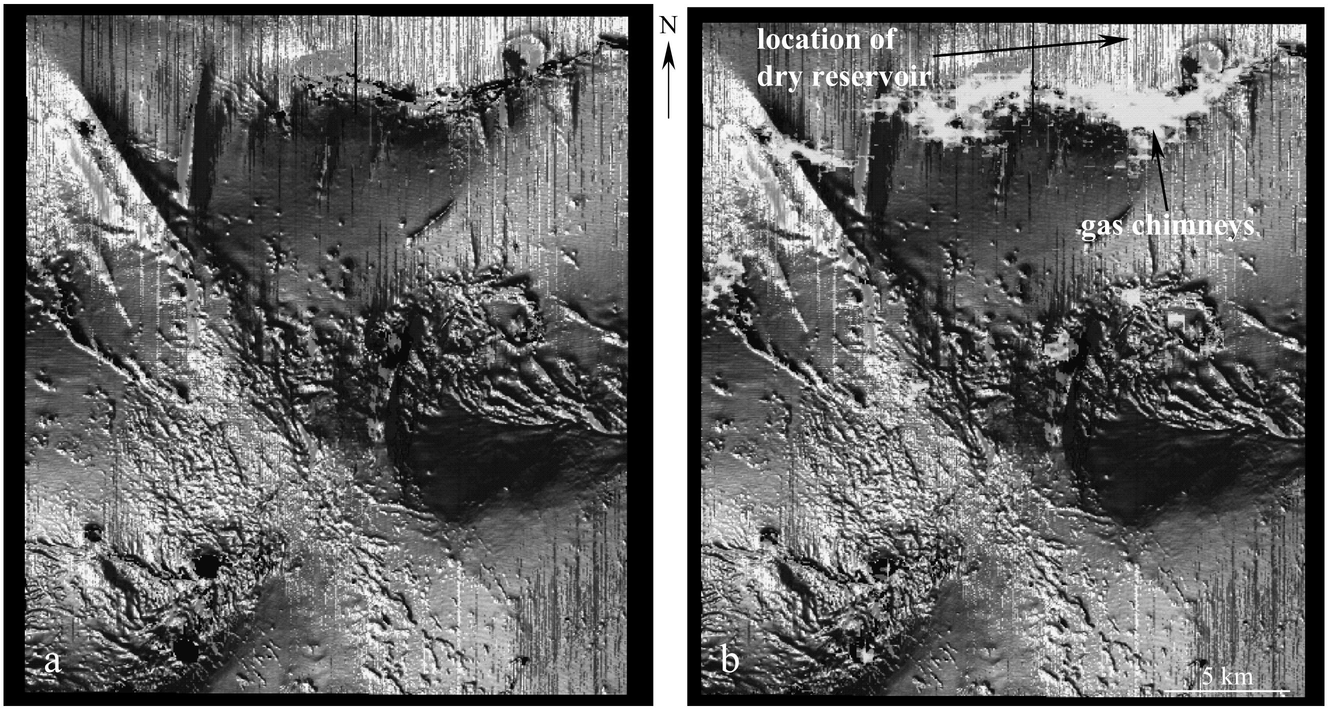

Figure 5. (a) Seabed azimuth map from 3-D seismic data offshore Nigeria. (b) The same map with detected chimneys (white) superimposed. Type 1 chimneys are associated with a fault. A prospect on the north side of this fault was originally believed to be sealed by the fault. A well was drilled and found to be dry. The latter observation of chimneys along this fault indicates that it was nonsealing.

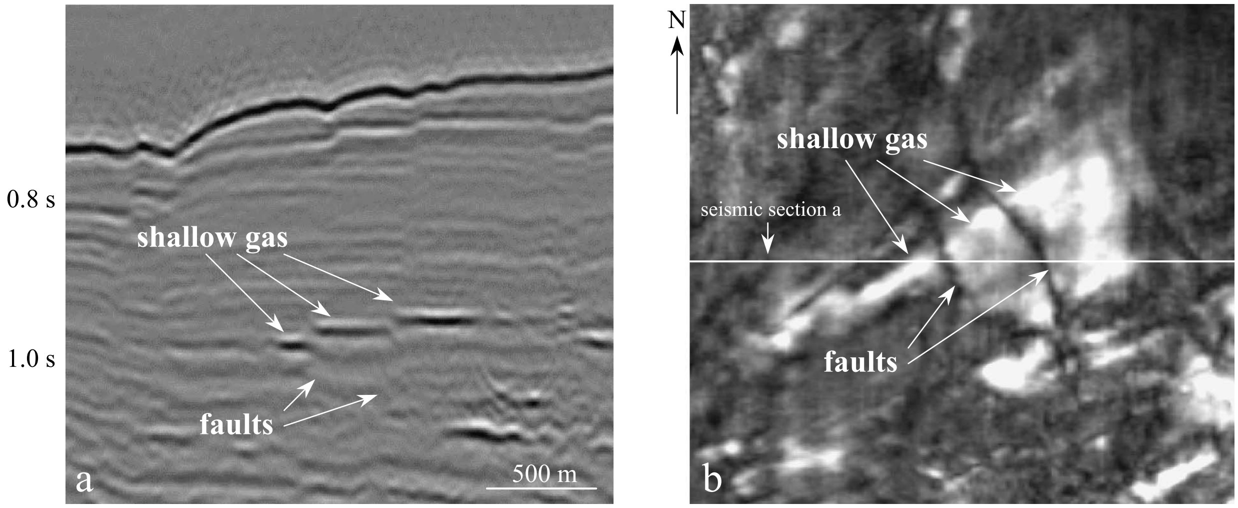

Figure 6. (a) This seismic section from 3-D data offshore Nigeria shows three high-amplitude reflectors. (b) An average absolute amplitude map over a time interval, including the three high-amplitude reflectors. These high-amplitude anomalies (white) are interpreted to represent a gas-charged sand. The sand is segmented by faults visible as low-amplitude features in black. Gas is believed to have migrated through the faults, charging the sand and migrating to the seabed. The presence of pockmarks along the faults at the seabed supports this interpretation (cf. Figure 7).

fault. A prospect on the north side is connected to the fault, which was originally believed to be sealing, and a well drilled into the prospect was found to be dry. The later discovery of gas chimneys along the fault indicates that the fault is nonsealing, which may explain the lack of hydrocarbons in the prospect.

In some cases, other indications suggest that leakage is (or has been) occurring through faults. High-amplitude anomalies along faults can indicate reservoirs that have been charged by gas migrating up the faults. Figure 6 shows an example from offshore Nigeria, where high-amplitude reflectors are interpreted to represent a sand that is segmented by faults and possibly charged with gas that has migrated up the faults. Pockmarks at the seabed (Figure 7) are located along the faults, indicating that gas has migrated to the seabed. Core samples from the seabed have confirmed the presence of gas at fault locations, whereas core samples taken at a distance from the faults showed no gas contents.

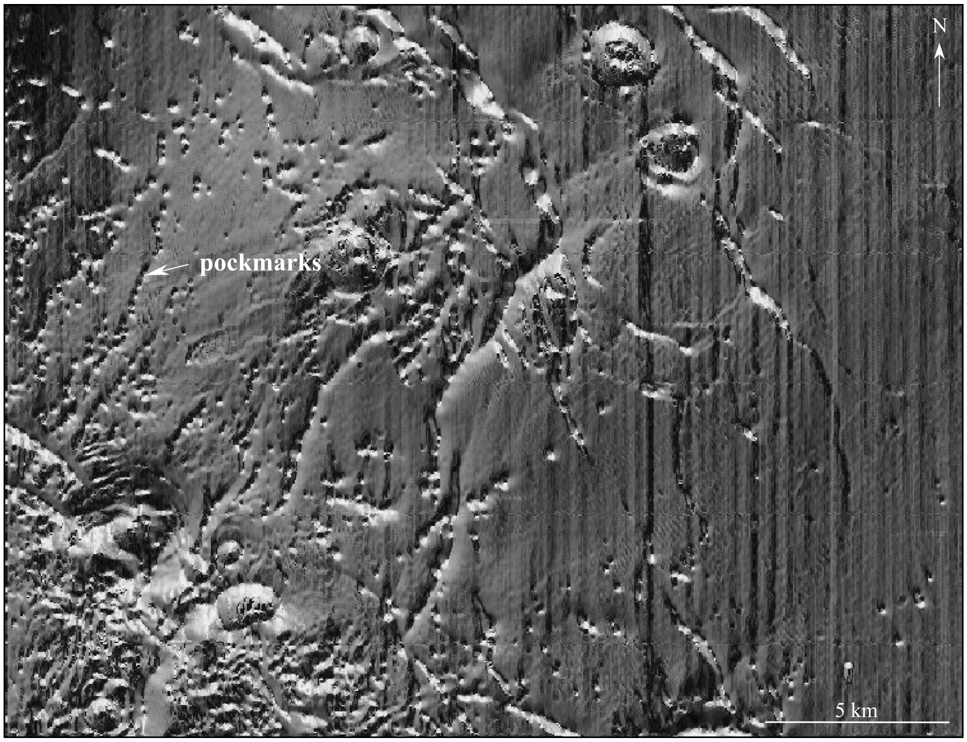

Figure 7. A seabed azimuth map generated from the same 3-D data as in Figure 6 shows pockmarks along faults reaching the seabed, indicating gas escape through the faults. Seabed samples taken at fault locations have showed contents of gas. Core samples taken at a distance from the faults showed no gas contents.

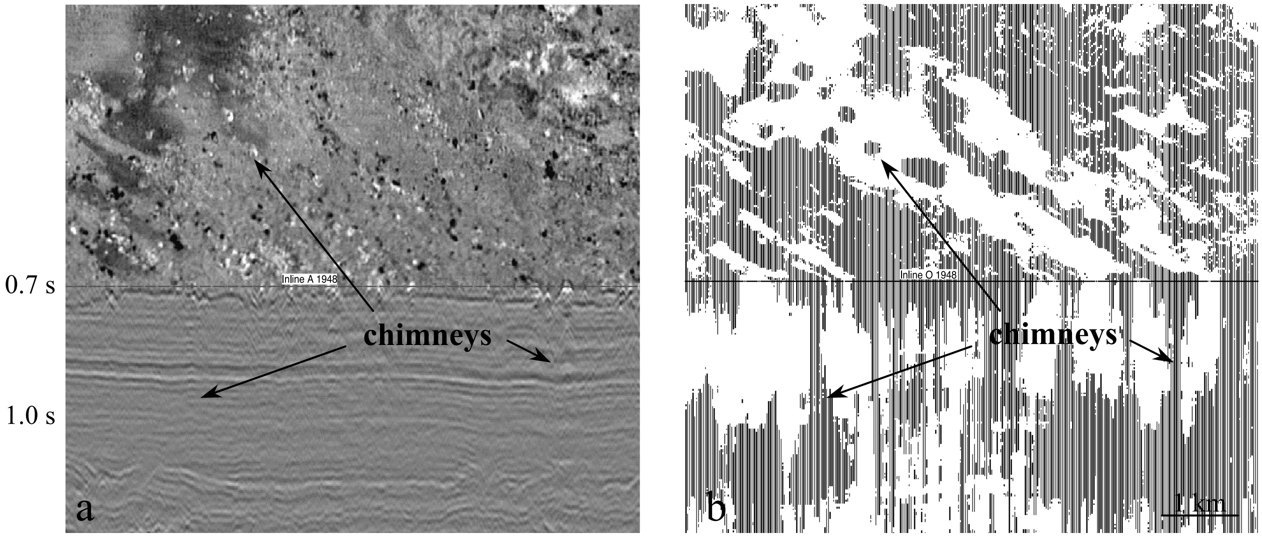

FIGURE 8. (a) Composite display of a time slice and a vertical section from Norwegian North Sea. The time slice is taken through a level of possible carbonate buildups in the late Pliocene. (b) Chimney cube version of the composite display in (a) that shows possible gas chimneys in the vertical section as well as in the time slice. The chimneys are located below the possible carbonate buildups along detected faults forming lineaments like the ones formed by the buildups. Based on this observation, carbonate buildups are believed to have been formed at gas seepage locations in the late Pliocene.

High-amplitude anomalies on an average absolute amplitude map generated from 3-D data from the Norwegian North Sea show structures in the late Pliocene that are believed to be carbonate buildups formed on top of gas seeps from faults in the late Pliocene. The structures form a pattern of straight parallel lines, indicating the presence of underlying faults. Gas chimney detection has revealed chimneys below the buildup structures (see also Heggland, 1997) and faults. The standard 3-D seismic data (Figure 8a) do not show chimneys in time slices. In the chimney cube (Figure 8b), however, chimneys are visible in time slices as circular features, and they are distributed along faults picked up by the chimney detection.

Type 1 chimneys are believed to indicate faults that are or have been open for fluid migration. Flux rates may be large enough to be a risk with regard to remaining hydrocarbons in a reservoir or could charge a reservoir from beneath with hydrocarbons. Type 1 chimneys can represent a risk or can be a positive indication with regard to the presence of hydrocarbons in a structure, depending on the location of the faults relative to the structure.

Type 2 Chimneys

Gas chimneys are also found to be present in areas where seismic data show no faults or fractures. In such a case, the chimneys occupy a much larger space (i.e., several hundred meters lateral extent) than when chimneys are associated with a fault. In some cases, such chimneys are present on top of hydrocarbon-charged reservoirs, such as in Figure 1c. An example from the North Sea (Figure 9) shows a chimney present between the top of an Eocene oil and gas reservoir and the seabed. Figure 9a shows a standard 3-D seismic section. Figure 9b shows the corresponding section after chimney detection. Figure 10a shows a time map of the top of the Eocene structure. In Figure 10b, a time slice from the chimney cube at 1-s two-way time is displayed, and it can be seen that the gas chimney almost images the outline of the structural closure. The two wells displayed on the maps encountered columns of gas and oil in the Eocene reservoir.

An example from the Caspian Sea is presented in Figure 11. In this case, type 2 chimneys are present on top of two hydrocarbon-charged reservoirs. The blue surface is the top reservoir time map. Mud volcanoes are present at the flanks of the reservoirs. The mud trajectories below the mud volcanoes have been picked up by the chimney detection, because they have similar seismic characteristics as chimneys.

Type 2 chimneys are believed to be gas that either has come out of solution from upward-moving water and got trapped in the shales (zero flux rate), or gas migrating with a relatively slow flux rate through small faults or fractures beyond seismic resolution. The amount of gas transported through the top seal is regarded to be small, in which case, type 2 chimneys are not regarded to represent a risk with respect to remaining hydrocarbons in a reservoir, but rather an indication that hydrocarbons are present in the underlying

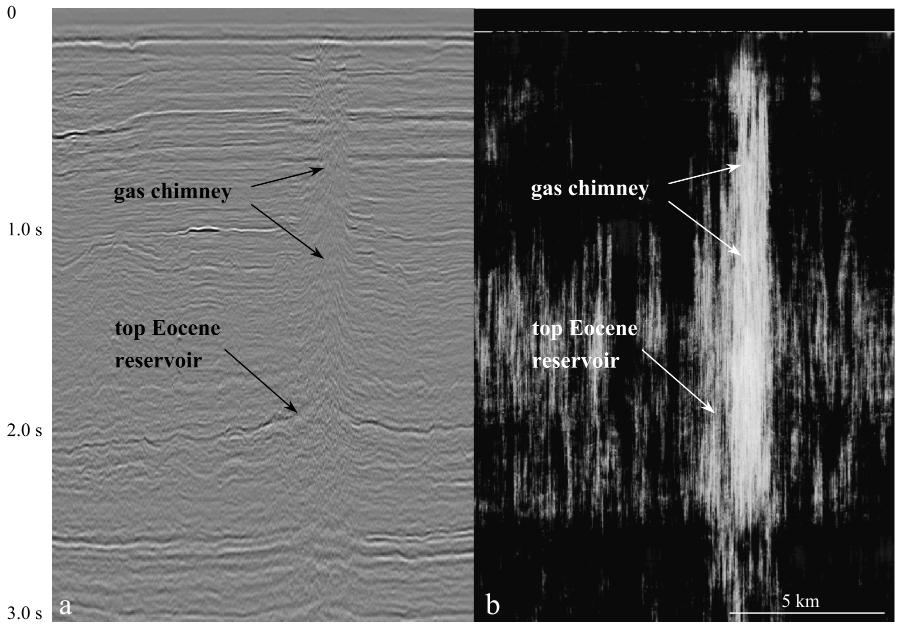

FIGURE 9. A 3-D seismic section from the Norwegian North Sea. (a) Gas chimney present above an oil and gas reservoir in the top Eocene. The base of the actual gas chimney is believed to be at the top of the reservoir, and a shadow zone is believed to exist below it as seen in the seismic section. (b) Corresponding section from the chimney cube (detected chimneys).

structure. Type 2 chimneys have, in many cases, been observed to be present on top of oil- and gas-charged reservoirs.

CONCLUSIONS

To evaluate sealing vs. nonsealing faults, the presence of chimneys along faults may indicate which faults are likely to be hydrocarbon-migration pathways. Cases also exist where chimneys are not present, but other seismic anomalies can indicate current or previous fluid migration, like pockmarks, high-amplitude reflectors, and buildup structures. These structural features are observed to exist at the present-day seabed and at paleoseabeds. A cap rock can be evaluated in a similar manner. If a fault is cutting across (or near) the top of a potential hydrocarbon trap, and if gas chimneys or other features indicating fluid migration are present along the fault at the structural high, the prospect can be regarded as a high risk with respect to presence of hydrocarbons.

Chimneys having a large lateral extent and that cannot be related to faults are believed to represent the absence of or very slow flux rates. If such a chimney is present on top of a prospect, it can rather be an

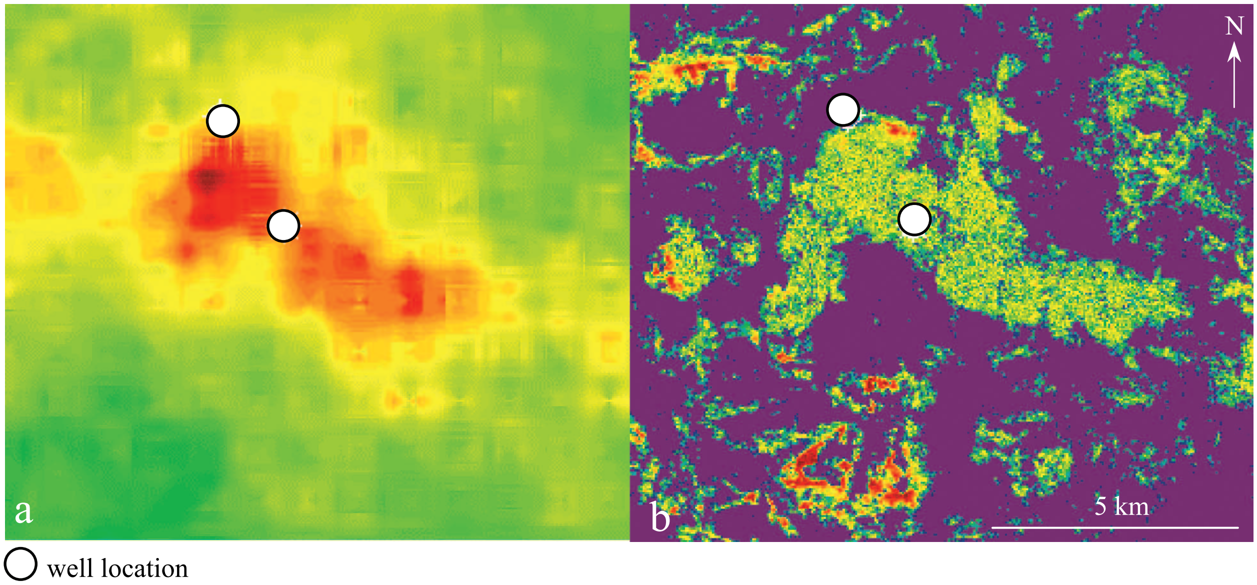

FIGURE 10. (a) Time map at the top of the Eocene reservoir. (b) Time slice at 1-s two-way time through the chimney cube, showing that the gas chimney has a similar lateral extent and shape as the underlying oil and gas reservoir. The two wells displayed on the maps encountered columns of gas and oil in the Eocene reservoir.

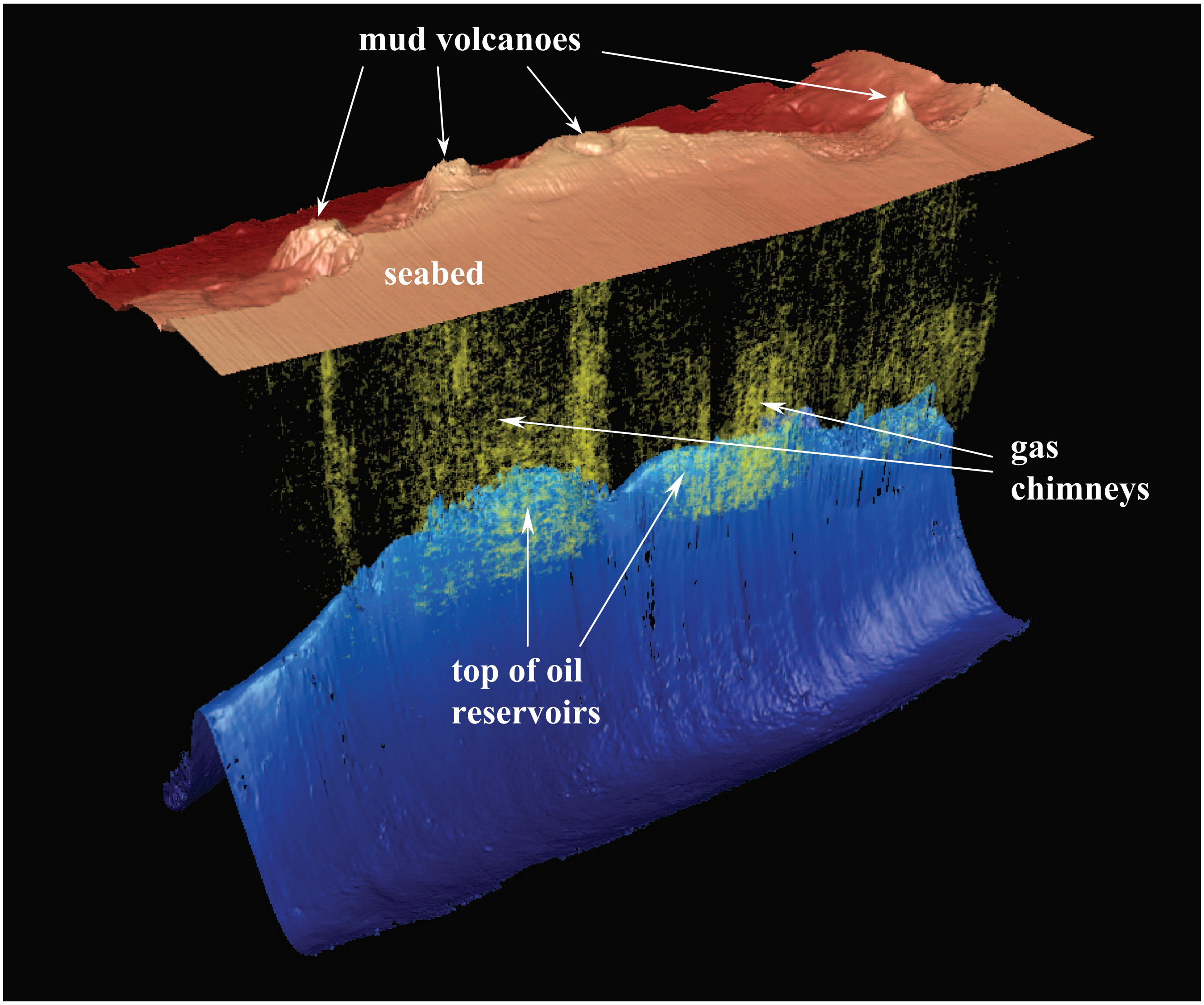

FIGURE 11. Three-dimensional visualization from the Caspian Sea. Type 2 chimneys are present on top of two oil reservoirs (blue surface). The seabed map (brown) shows the presence of mud volcanoes. The mud transport pathways have been picked up in the chimney-detection process.

indication of the presence of hydrocarbons in the underlying structure.

The chimney detection has revealed chimneys lining up not only with faults but also with features associated with gas seepage (e.g., pockmarks, carbonate buildups, and mud volcanoes), shallow gas accumulations, and deeper hydrocarbon accumulations and, as such, have revealed potential hydrocarbon-migration pathways. The chimneys indicate fluid migration between hydrocarbon source rock and reservoirs, between reservoirs (remigration), and between reservoirs and the seabed. As such, detection of gas chimneys in seismic data, as well as mapping of other features that can indicate fluid-migration pathways, have significance in fault seal and top seal integrity analysis and in the process of risking hydrocarbon prospects.

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