INTERPRETER'S CORNER

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Identifying faults and gas chimneys using multiattributes and neural networks

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Modern visualization and image processing techniques are revolutionizing the art of seismic interpretation. Emerging technologies allow us to interpret more data with higher accuracy in less time. The trend is shifting from horizon-based toward volume-based. New insights are gained by studying objects of various geologic origins and their spatial interrelationships. The standard way of highlighting objects is through seismic attribute analysis. Various attributes are tested in a trial-and-error mode, and one is selected as the optimal representation of the desired object. The selected attribute, which may be a mathematical composite of several attributes, is not sensitive to a particular geologic object but highlights any seismic position with similar attribute response.

We set out to develop a seismic-object detection method that in our opinion produces more accurate results and does not require expert knowledge. The method recombines multiple attributes into a new attribute that gives the optimal view of the targeted object. Including specific spatial knowledge about the targeted object allows us to separate objects of different geologic origin with similar attribute characteristics. The method comprises an iterative processing workflow using directive seismic attributes (i.e., attributes steered in a user-driven, or data-driven, direction), a neural network, and image processing techniques (Meldahl et al., 1999). Figure 1 is a generalized workflow of the object detection method, which has a worldwide, patent-pending status. Objects that can be detected by the method include faults, reflectors, seismic chimneys, time-lapse differences, stratigraphic features, and direct hydrocarbon indicators. The first products from simple application of the method are named TheChimneyCube and TheFaultCube.

This paper presents the basic concepts of the technology. Examples of the method to detect faults and chimneys are shown. Special emphasis is given to seismic chimneys and their interpretation, because the detection method has produced fresh insights in hydrocarbon migration and trapping mechanisms and has resulted in a new and powerful exploration tool (Heggland et al., 1999).

Computational method of classifying objects using neural networks. Seismic objects are 2- or 3-D bodies characterized by a certain seismic response that differs from the surrounding response. The difference in response can be highlighted by various attributes. Each attribute contains information on the object that we wish to detect. None of the attributes is expected to be sensitive to the targeted object only. This means that other objects are highlighted by the same attribute. In our method we can separate bodies from different origins by careful selection of attributes and extraction windows. We do this by training a neural network to recognize objects that we have identified in a seed interpretation. The network transforms all attributes into one new attribute, which indicates the probability of the object at the seismic position. The resulting object-probability cube can be further enhanced by image processing techniques and iterating the process. Knowledge of object shape and orienta-

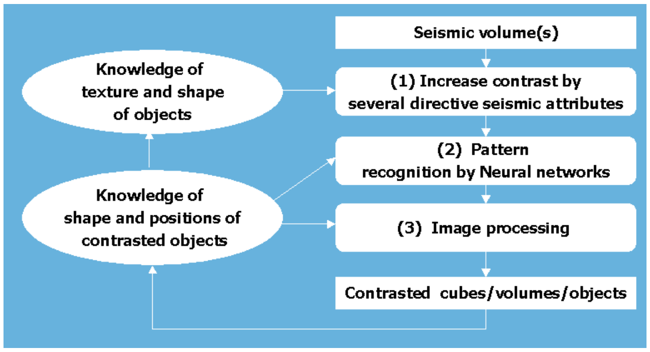

Figure 1. The iterative detection workflow using directive seismic attributes, neural networks, and image processing techniques.

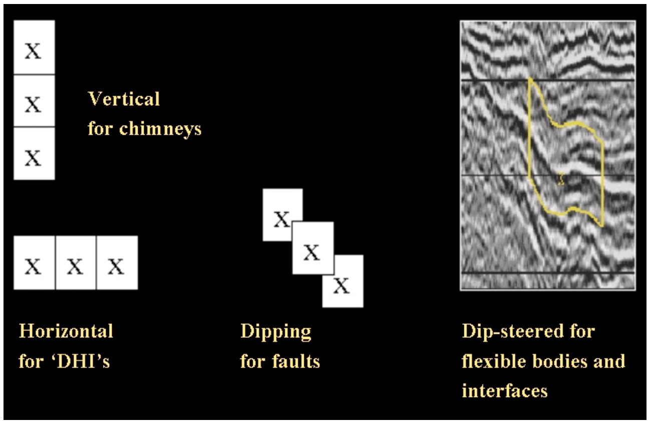

Figure 2. Size, direction, and shape of attribute extraction windows are chosen in relation to the object we wish to detect.

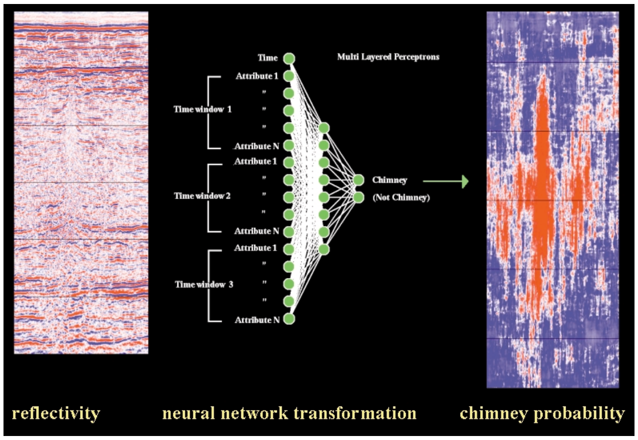

Figure 3. Seismic input section and corresponding section from the chimney cube. The network uses 16 attributes to classify each data point into chimney or nonchimney classes. Only the value for the "chimney" node is passed to produce the output cube. Warm (red) colors indicate high chimney probability.

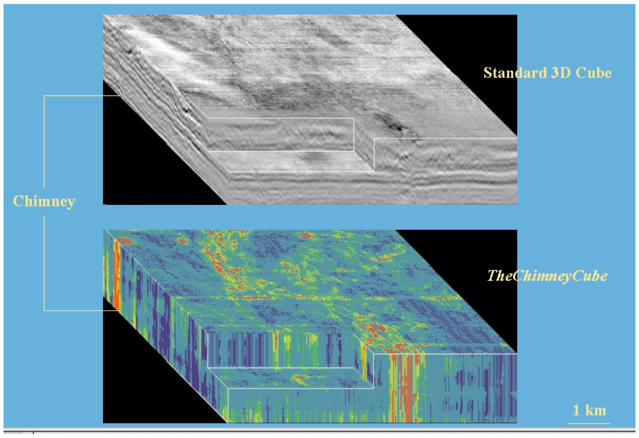

Figure 4. Seismic input cube and corresponding "chimney cube."

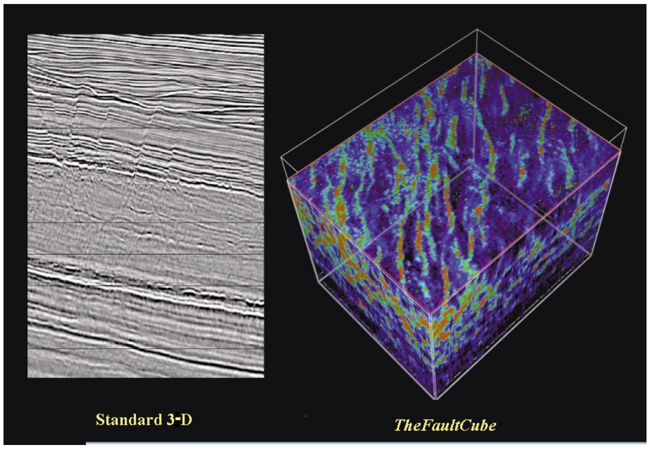

Figure 5. Seismic line (left) and fault cube image (right).

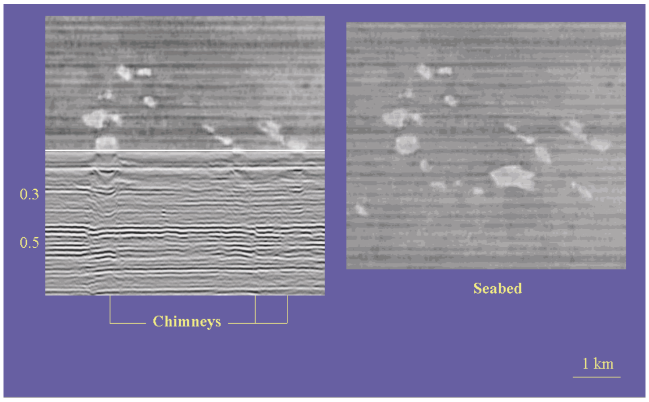

Figure 6. Composite display of 3-D seismic section and time slice at seabed (left), and the full time slice (right). Chimneys and buried craters on top of them are surrounding a deeper oil reservoir.

tion can be fed back to the process, either to increase the detection strength or to increase the resolution of highlighted objects. The method, in essence, is composed of the following:

1) Only one type of geologic object is targeted at the time.
2) A selection of attributes with the potential to enhance the objects is made.
3) A neural network is trained on attributes extracted at example object and nonobject positions selected by the interpreter.

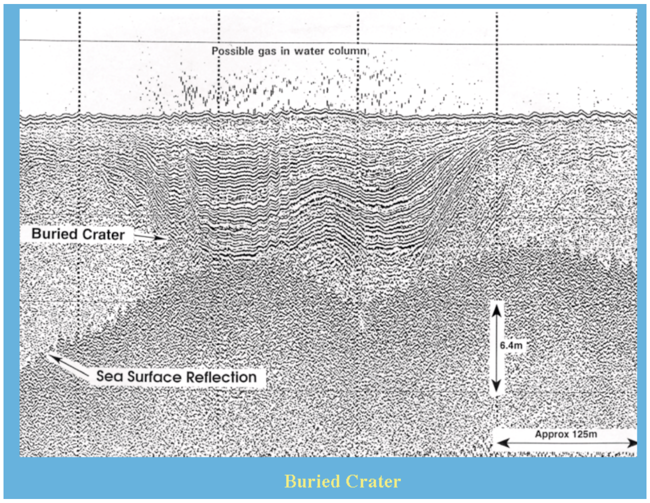

Figure 7. High-resolution sparker line through a buried crater. High reflectivity in the water column indicates gas escape above the crater.

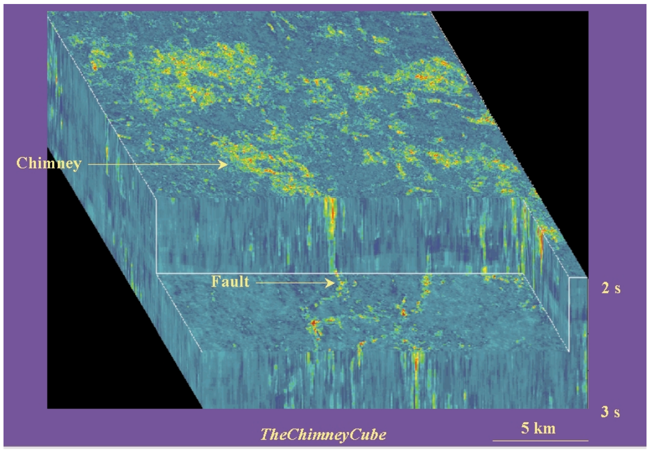

Figure 8. Chimney cube showing tie between chimneys and deeper faults.

4) The trained network is applied to the entire seismic cube to produce a new cube with high values at positions where the object is recognized.
5) Optionally, image-processing techniques are applied to improve the neural network generated output cubes.
6) The sequence can be improved by iterating steps 1-5 using knowledge gained in the process.

The sequence is very intuitive. The interpreter targets a particular object (response) that should be highlighted. Then, the basic information is supplied in the form of examples and attributes. Default attribute sets exist for different types of bodies. The network takes over the role of the expert by combining the information in an optimal way. Networks are not very sensitive to redundant information, which means that a few additional attributes do not affect the end result. Application of the network to a small area surrounding an identified example body is an effective way to QC the network's performance.

A similar procedure has been developed for unsupervised neural networks. The output of this procedure is a clustered data volume. However, this unsupervised approach is beyond the scope of the current paper.

Seismic attributes play a key role in the method described above. In principle, single- and multitrace attributes are selected that have a potential to increase the contrast between

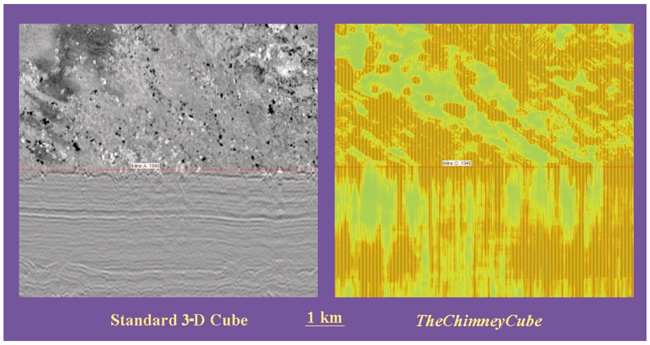

Figure 9. Composite display of standard seismic section and time slice (left) and corresponding chimney cube (right). Chimneys and faults below amplitude anomalies are detected by the chimney cube.

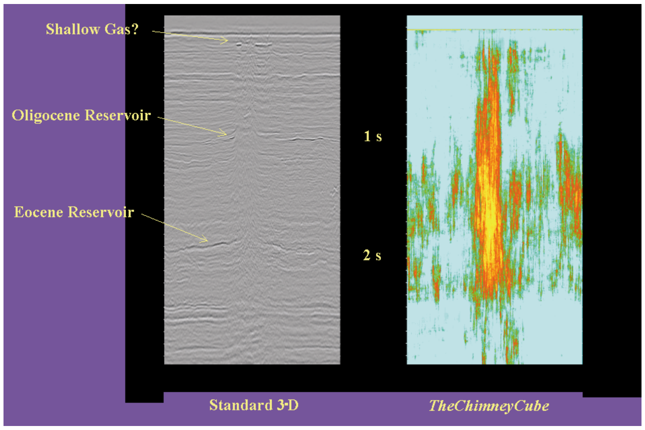

Figure 10. Standard seismic section and corresponding chimney cube section. Chimneys are passing through an Eocene and an Oligocene reservoir. Amplitude anomalies are at the top of the chimneys.

objects and their surroundings. The detection power of a combination of attributes is greatly improved if the extraction windows are designed to match the size, orientation, and extent of the targeted objects. If this is the case, we are mapping directive attributes. Directivity in attributes increases the signal-to-noise ratio, sometimes dramatically. Unlike similar procedures used in acquisition and processing (Meldahl, 1998), we do not need to limit the directivity strength to avoid smearing. We can focus on specific object types and positions. Windows for directive attributes can have fixed shapes and orientations, or they can have data adaptive shapes and orientations (Figure 2). In the latter case they follow the local dip and azimuth of the seismic object.

This philosophy can be applied to detect seismic chimneys. Chimneys are vertical disturbances in seismic data often characterized by low amplitudes and low trace-to-trace similarity (Figure 3). We use this knowledge by including energy and similarity as input attributes for the neural network. Knowledge about the vertical dimension is gained by extracting energy, similarity, and other attributes in three vertically aligned extraction windows. The final product is a cube in which chimneys are visible by high sample values (high probability) and the surrounding volume by low sample values (low probability, Figure 4). Restricting the detection criteria in a second iteration can further refine the results. The interpreter should be aware that the network enhances all vertical disturbances with similar seismic characteristics, like steep faults, fractures, diapir and channel edges, and merged data zones.

The same method can transform a seismic data cube into a fault cube (Figure 5). In the example shown, a neural network was trained on seismic attributes at selected fault and nonfault locations. Twenty-two total attributes were fed to the neural network. These were the reference time, dip (a multitrace attribute calculated by local, 3-D Fourier-Radon transformation), several dip-variance, energy, similarity, and amplitude calculations. The network made a classification of the entire data set into fault and nonfault samples. As before, high output values indicate a high probability of the object (fault) being present, while low values mean low object probability. The result of Figure 5 can be improved by iterating the detection process using information on the direction of faults as calculated from the first-pass result. Image processing techniques and special purpose extraction algorithms can then be applied to extract fault planes in a user-controlled way.

Examples of chimney interpretation. Seismic chimneys are vertical disturbances of the seismic response often associated with upward fluid migration. They can be expressions of hydrocarbon migration pathways between a source rock and a reservoir and between reservoirs at different depths. Chimney concentrations appear to be less distinct in North Sea areas with dry wells, although components of lateral migration may confuse the image. We also recognize that chimneys can be caused by gas released from upward moving water, due to pressure release. Chimneys frequently tie in with faults, which would be expected if hydrocarbon migration is taking place in the subsurface. Chimneys also tie in to features related to fluid or gas seepage, like pockmarks, mud volcanoes, and carbonate formations (Heggland 1998, 1999, 2000). Amplitude anomalies indicating shallow gas accumulations are often located near the top of chimneys. Due to their diffuse appearance, seismic chimneys are very difficult to map on conventional seismic images.

Shallow chimneys sometimes surround deeper, hydrocarbon-filled reservoirs (Heggland, 1998). Figure 6 shows an example from the Danish North Sea using standard 3-D seismic data. In this case, buried craters are located on top of the chimneys close to the seabed. This circular group of chimneys and buried craters are located around a Tertiary reservoir where an oil and gas discovery has been made. The craters have been formed during a period of sustained gas seepage and buried after the gas seepage has declined. A high-resolution sparker line through one of the craters shows high reflectivity in the water column above the buried crater, indicating active gas seepage (Figure 7). Features indicating periodic gas migration in this area are described in Heggland, 1998.

Making time slices through the chimney cube is a way to generate maps of chimneys. In the standard cube, chimneys are not visible on time slices. In this example, taken from the Norwegian North Sea in the vicinity of a major oil and gas field, isolated chimneys are observed as well as clusters of chimneys on top of a major fault trend (Figure 8). The base of these chimneys ties to the top of the fault system. This seismic evidence shows that deeper fluid migration takes place through the fault into shallower sediments where the migration is vertical up to the seabed. The chimneys are partly surrounding the deeper oil and gas field.

Within the Upper Tertiary sediments, vertical disturbances are visible below amplitude anomalies (Figure 9). The chimney cube reveals that these disturbances have different shapes and lateral extents than the amplitude anomalies. This makes it less likely that the disturbances are caused by the amplitude anomalies and more likely that they are actual chimneys. The high amplitudes on top of them are interpreted to be carbonate buildups above gas seepages to the Tertiary seabed. The distribution of chimneys is aligned with mid-Miocene faults over which chimneys appear. The chimney cube also reveals small faults in the Tertiary along chimney lineaments.

Chimneys over the top of faults are demonstrated on Figure 10, a comparison of a standard seismic section with the corresponding section from the chimney cube. Jurassic-age faults are passing through an Eocene and an Oligocene reservoir, in this example. Both these reservoirs contain oil and gas, proven by two wells. Figure 11 shows four maps at different levels through these events. The lower left is a time slice at 3 s TWT from the chimney cube. The base of the chimneys align with the top of Jurassic faults. The next figure is a time map of the top of the Eocene reservoir at approximately 2 s TWT, in which the two wells are displayed. The third map is a time slice through the chimney cube at 1 s TWT. It shows chimney distribution above the Eocene reservoir. A comparison with the top Eocene surface reveals a high correlation between reservoir closure and chimney distribution.

The chimneys are interpreted to represent hydrocarbon migration from the top of Jurassic faults, charging the Eocene and the Oligocene reservoirs. The upper right figure is a volume amplitude map from the standard seismic cube, showing amplitude anomalies at 250 ms above the chimneys. The amplitude anomalies may represent shallow gas accumulations, at approximately 100 m below seabed, caused by the hydrocarbon migration from a deeper source. Alternatively, they may represent ancient carbonate formations generated on top of the gas seeps.

Figure 12 is a 3-D visualization. Chimneys are yellow and the background is transparent. The Jurassic faults are visible on an interpreted base Cretaceous surface displayed in blue. The green surface is the time map corresponding to the top of the Eocene reservoir. Amplitude anomalies from the standard seismic cube are red, and lower amplitudes are transparent. The well in the right-hand corner, where no chimneys are present, was dry.

Other examples from the Norwegian North Sea show similar correlations. Chimneys have been observed near dry wells in some cases; however, these are shallower than the drilled reservoirs and may arise at this level as a result of shallow lateral fluid migration. We realize that chimneys also may be caused by gas released from upward-moving water, due to pressure release, as well as gas released from upward-migrating oil or free gas.

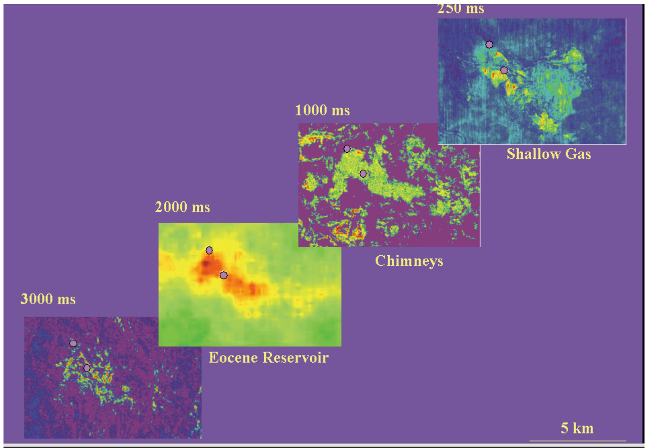

Figure 11. Composite display comparing Jurassic faults (lower left), top of an Eocene reservoir (middle left), chimney distribution at 1 s TWT (middle right), and amplitude anomalies at the top (upper right).

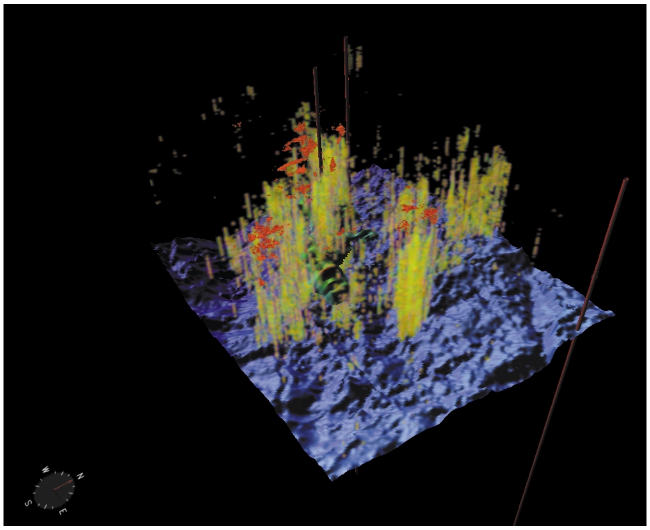

Figure 12. 3-D visualization of an interpreted base Cretaceous surface (blue) revealing top of Jurassic faults, interpreted top of an Eocene reservoir (green), chimneys from the chimney cube (yellow), and amplitude anomalies (red) from standard seismic volume. The two wells within the chimney area encountered oil and gas in the Eocene reservoir as well as in an Oligocene reservoir (not shown). The well to the right, where no chimneys are present, was dry.

Gulf of Mexico example. The final area of study is the deep-water slope of Green Canyon in the Gulf of Mexico in a water depth of about 2000 m. A 3-D seismic cube covering approximately 18 miles^2 was transformed into a chimney cube. The standard seismic cube and the chimney cube were used in combination, along with mapped horizons, to evaluate possible hydrocarbon migration. Figure 13 compares a standard seismic section (left), a single-attribute similarity section (middle), and the chimney probability section (right). It demonstrates that a single-attribute approach (similarity, which is a type of coherency) is inferior to the multiattribute neural network approach when the goal is to detect a certain kind of object and not just any object with a similar attribute characteristic.

Figure 14 shows a 3-D visualization of the chimney cube, the standard seismic cube, and two mapped surfaces. The two mapped surfaces are time maps—the upper one representing the seabed and the lower one approximately 1320-ft subseabed. From the standard seismic cube, only the highest amplitudes are displayed in red. Lower amplitudes are transparent in this display. Chimneys from the chimney cube are yellow. These correspond to the high values in the cube (meaning high chimney probability). Lower values are transparent. The deeper cloud of high amplitudes corresponds to the outline of a salt dome, while the shallow cloud of high amplitudes is interpreted to represent a hydrocarbon-charged reservoir.

Chimneys surrounding the salt dome indicate upward fluid migration from a deeper reservoir. The high density of shallower chimneys indicates charging of the shallow reservoir. The subseabed surface exhibits a radial fault pattern caused by the upward movement of the salt dome. Chimneys are visible up to the seabed, and a small mound is present at the seabed close to the top of the shallowest chimney on

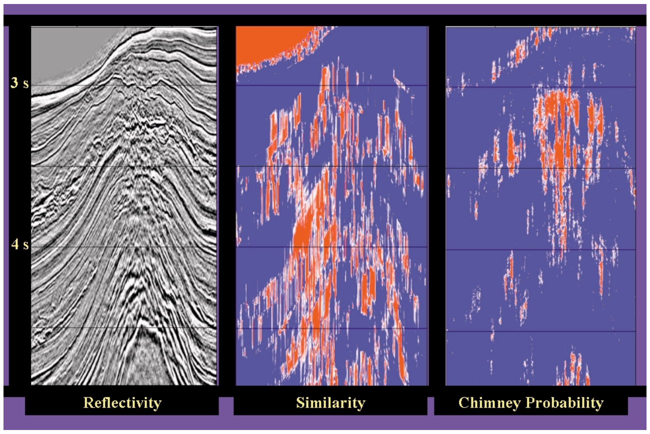

Figure 13. Comparison of a seismic section (left) with a single-attribute similarity section (middle) and a multiattribute neural-network-generated chimney probability section (right).

the right side. This may be a small mud volcano generated by the transport of sediments, fluid, and/or gas to the seabed.

The presence and distribution of the chimneys mapped in this area make the presence of a deep and a shallow hydrocarbon-charged reservoir more likely. A manual mapping of chimneys would have been difficult, less precise, and more time-consuming. The chimney cube helped to visualize and efficiently evaluate the possible hydrocarbon migration.

To further advance this technology, Statoil, dGB, and the Norwegian visualization specialists GeoCap are currently developing d-Tect, a seismic object detection system in which directive attributes, neural networks, and image processing techniques are combined with modern visualization techniques for flexible, interactive experimentation, processing, and interpretation of seismic data. It is believed that the technology has the potential to improve the standard interpretation workflow by reducing cycle times and producing more accurate results. d-Tect is sponsored by the Dutch government and six major E&P companies.

Conclusions. Seismic attributes and a supervised neural network can transform seismic input data into a new 3-D data cube in which one type of object is highlighted. This approach has been successful in detecting chimneys and faults, but the method has general applicability for detecting many different types of seismic objects. Other examples are reflectors, hydrocarbon indicators, and 4-D time-lapse differences. Application of the method on chimney detection has great potential within fluid-flow research, shallow gas detection, and prospect evaluations. It allows quantitative comparisons of chimneys and their distributions in different areas. The method is currently being used in research projects, as well as in prospect evaluations as a risk reduction tool and in the ranking of prospects. In the North Sea, in general, a high correlation has been observed between chimneys and the presence of oil and gas fields.

Suggested reading. “Gas Seepage as an indicator of deeper prospective reservoirs: A study based on exploration 3-D seismic data” by Heggland (*Marine and Petroleum Geology*, 1998). “The chimney cube, an example of semiautomated detection of seismic objects by directive attributes and neural networks: Part II; Interpretation” by Heggland et al. (SEG 1999 *Expanded Abstracts*). “Seismic chimney interpretation examples from the North Sea and the Gulf of Mexico” by Heggland et al. (*The American Oil and Gas Reporter*, 2000). “The chimney cube, an example of semiautomated detection of seismic objects by directive attributes and neural networks: Part I: Methodology” by Meldhal et al. (SEG 1999 *Expanded Abstracts*). “Survey evaluation and design: Prediction of resolution versus line interval” by Meldahl (*TLE*, 1998). E

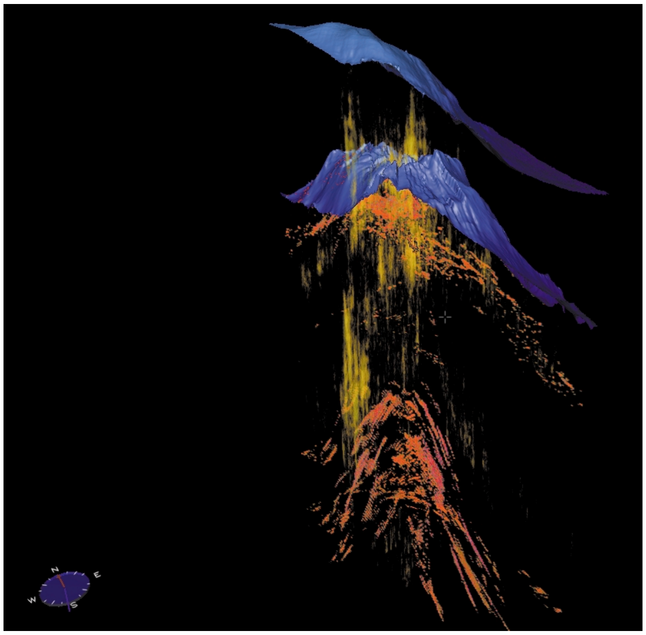

Figure 14. 3-D visualization of chimneys, amplitude anomalies, and mapped surfaces from a Gulf of Mexico data set. Chimneys indicate leakage from a reservoir trap against the flank of a salt dome (deep red cloud), feeding other reservoirs with associated amplitude anomalies above the salt dome (deep blue surface and shallow red cloud). From there, they spill to the surface, forming a mud volcano at the sea bottom (upper blue surface).

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