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Unravelling the petroleum system by enhancing fluid migration paths in seismic data using a neural network based pattern recognition technique

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ABSTRACT

Understanding the hydrocarbon migration system in the sub-surface is a key aspect of oil and gas exploration. It is well known that conventional 3D seismic data contains information about hydrocarbon accumulations. Less known is the fact that 3D seismic data also contains information about hydrocarbon migration paths in the form of vertical noise trails. A method has been developed to highlight vertical noise trails in seismic data semi-automatically, using assemblies of directive multi-trace seismic attributes and neural network technology. The results of this detection method yield valuable information about the origin of hydrocarbons, about migration paths from source to prospect and about leakage or spillage from these prospects to shallow gas pockets or to the sea bed. Besides, the results reveal the sealing quality of faults, provide information on overpressure and whether prospects are charged or not. All these aspects are useful information for basin modelling studies and for an increased understanding of the petroleum system.

Key words: basin modelling, fault seal, fluid migration, hydrocarbons, seismic

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INTRODUCTION

Unravelling the petroleum system is the key to exploration success. Recently, Statoil explorationists introduced seismic chimney interpretation as a new tool to help unravel the petroleum system (Heggland 1998). Large fluid migration structures are often visible on seismic data, but they are quite difficult to map manually. More subtle features are often overlooked. The newly developed method for detecting fluid migration paths in seismic data uses a combination of seismic attributes, neural network technology and the interpreters' insight for the identification and enhancement of fluid migration structures (Meldahl *et al.* 1998; Meldahl *et al.* 2001). The method is used in conjunction with other geological and geophysical data, such as well logs, pressure data and other relevant information to confirm the observed structures.

METHOD

The workflow for the enhancement of fluid migration paths in seismic data starts with thorough analysis of all available data to gain a better understanding of the local and regional geology. Special attention is paid to seismic data to recognise features in the data that indicate present and/or past fluid migration. These include gas chimneys, pockmarks, mud volcanoes, carbonate build-ups that are related to hydrocarbon migration, shallow gas pockets and prospects (Hovland & Judd 1988; O'Brien & Woods 1995). Figure 1(A) is an example of a leaking anticlinal structure, above which intense fluid migration is observable just above its crest, breaking through hard rock formations and reaching shallow sediments. Fluid migration occurs predominantly along a large-scale fault.

The next step in the detection workflow is the selection of example locations representing fluid migration paths that will be used for the training phase of the neural network. These locations are manually picked by an interpreter (white picks, Fig. 1B). Only areas are selected that definitely indicate fluid migration, confirmed by other characteristics such as shallow gas pockets (palaeo-) mud volcanoes, and so on. In addition, example locations are selected that do not represent fluid migration (black picks, Fig. 1B). At these picked locations various seismic attributes are extracted. The parameters of these attributes are evaluated to find the optimal settings for enhancing fluid migration path characteristics. Typically, fluid migration paths exhibit a low energy and noisy (near-) vertical chaotic seismic response. Seismic attributes that pick up these characteristics are a/o: Energy, Similarity (Coherency-type of attribute), 3D-Curvature, Frequency, various dip/azimuth calculations. The final set of attributes with associated class indication serves as training set for the neural network, which will learn to distinguish between fluid migration paths and nonfluid features.

Artificial neural networks belong to a group of mathematical algorithms which in general are inspired by the 'brain metaphor', meaning that they try to emulate the internal processes of the human brain. They usually consist of many processing nodes that are connected by weights. Neural networks are used in many industries today to solve a range of problems, including pattern recognition, regression analysis and data clustering. In the oil industry, neural networks are now routinely used in seismic reservoir characterisation and seismic pattern analysis (Wong *et al.* 1995; Mohaghegh *et al.* 1996) and in general for solving complicated data problems. In our application, a fully connected multi-layer perceptron (MLP) neural network is used (Bishop 1995). MLPs are the most common type of neural network and are sometimes (mistakenly) referred to as 'back-propagation' networks after the popular training algorithm used in the learning process. MLPs are supervised neural networks, i.e. they learn by example. In this situation, the large database containing information on the seismic character of the fluid migration structures, expressed by various seismic attributes, is fed to the neural network. The neural network will train itself by scanning through the data many times, trying to recognise patterns in the data. At the end of the neural network training phase, the network has captured the relationship between the input (the seismic attributes) and the desired output (to which class it belongs).

Application of the trained neural network yields a so-called chimney probability cube, i.e. a volume with values between approximately zero and one. High values in this cube represent a high 'probability' of belonging to the class

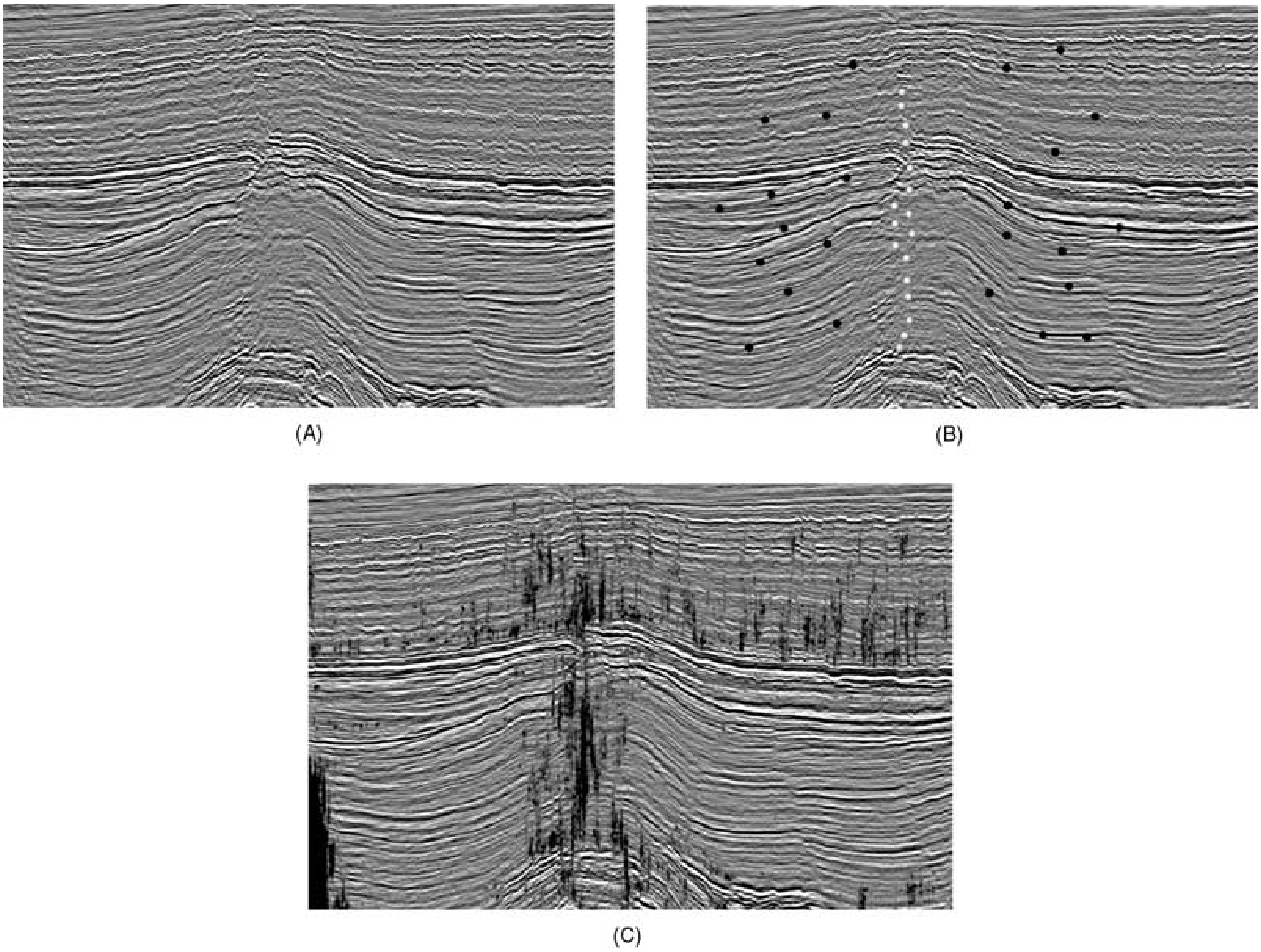


Fig. 1. Example of the fluid migration detection workflow: (A) the original seismic data, North Sea, (B) the selection of train locations representing fluid migration (white) and nonfluid migration (black) and (C) fluid migration path detection result after the application of the trained neural network. Cross-section 17 km, depth 1900 msec.

of seismic chimneys (or fluid migration paths). Figure 1(C) shows the result after application of the trained neural network to the seismic data, only enhancing the intense leakage along the faults above the anticlinal structure. In addition, the neural network has picked up the polygonal faults at shallow level that may have formed by dewatering in undercompacted clays.

All seismic attributes that go into the neural network contribute to the final outcome. A similar result cannot be achieved using single attributes. For example, based on the similarity attribute only, chimneys and nonchimneys cannot be separated (Fig. 2B), because a large overlap exists in the response (Fig. 3A). Figure 2(B) illustrates that all noisy features in the data are picked up when using the similarity attribute only, such as the low acoustic impedance zones at shallow level that are not related to the presence of hydrocarbon migration paths. The neural network result is clearly less noisy (Fig. 3B). Moreover, all migration structures with similar attribute response as the training set are detected. Figure 2(C) shows a large gas chimney, reaching the seabed and creating a mud volcano as surface expression. This feature was sampled to serve as training set. In the resulting chimney 'probability' cube, smaller gas chimneys running parallel to this large gas chimney are clearly visible. These

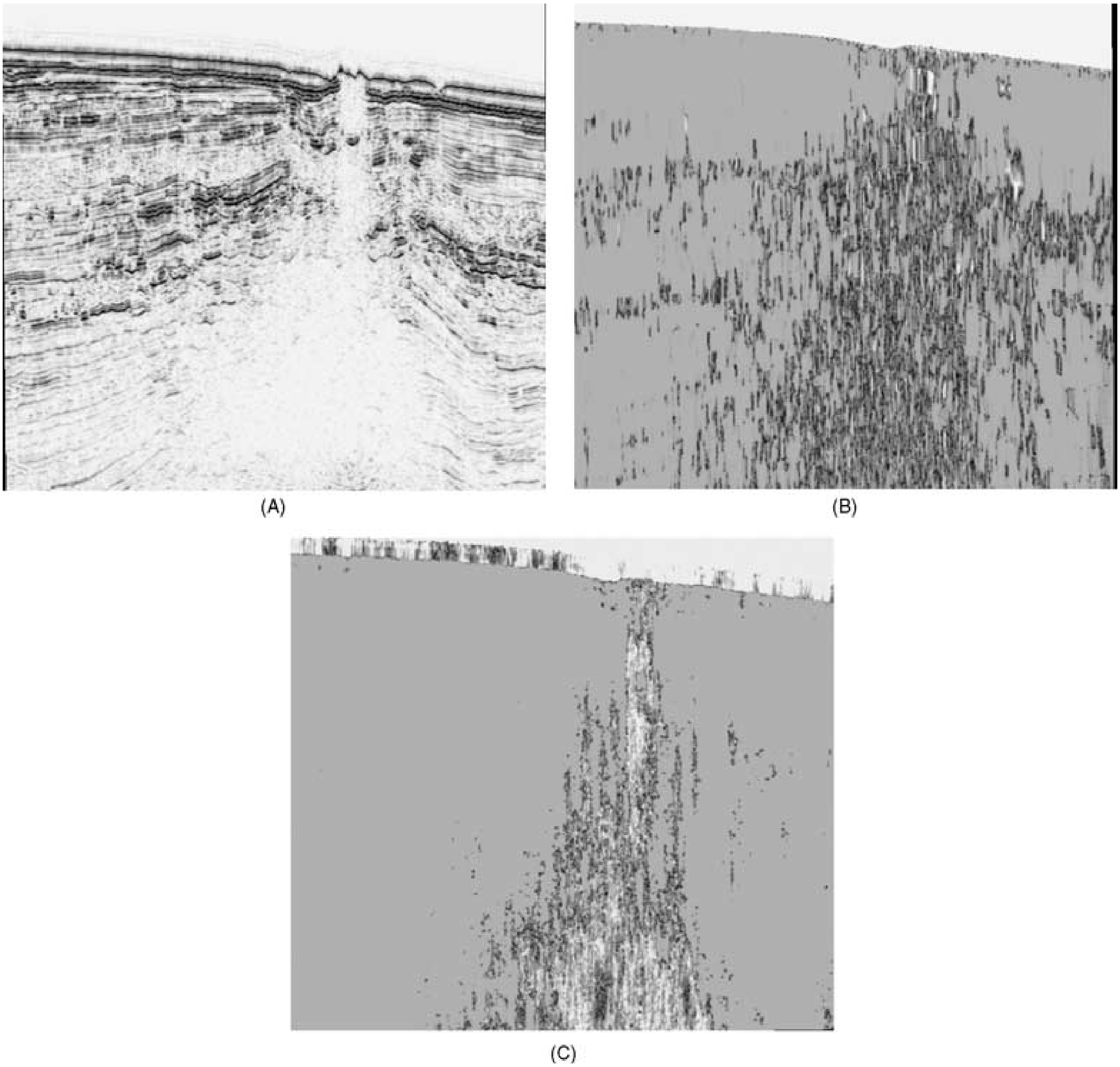


Fig. 2. Comparison between similarity and neural network technology for the enhancement of fluid migration paths on seismic data. (A) Original seismic data, West Africa, (B) single attribute analysis 'similarity', and (C) neural network detection method. Cross-section 13 km, distance from seabed to base of image approximately 4000 msec.

smaller features seem to charge shallow gas pockets, which constitute a geo-hazard.

INTERPRETATION OF RESULTS

The detection method provides additional information on fluid migration in the sub-surface and gives a better insight in all aspects of the petroleum system in basins, ranging from the origin of hydrocarbons, migration paths, sealing quality of faults to indications on charge of and leakage from prospects, as well as indications for overpressure and geo-hazards.

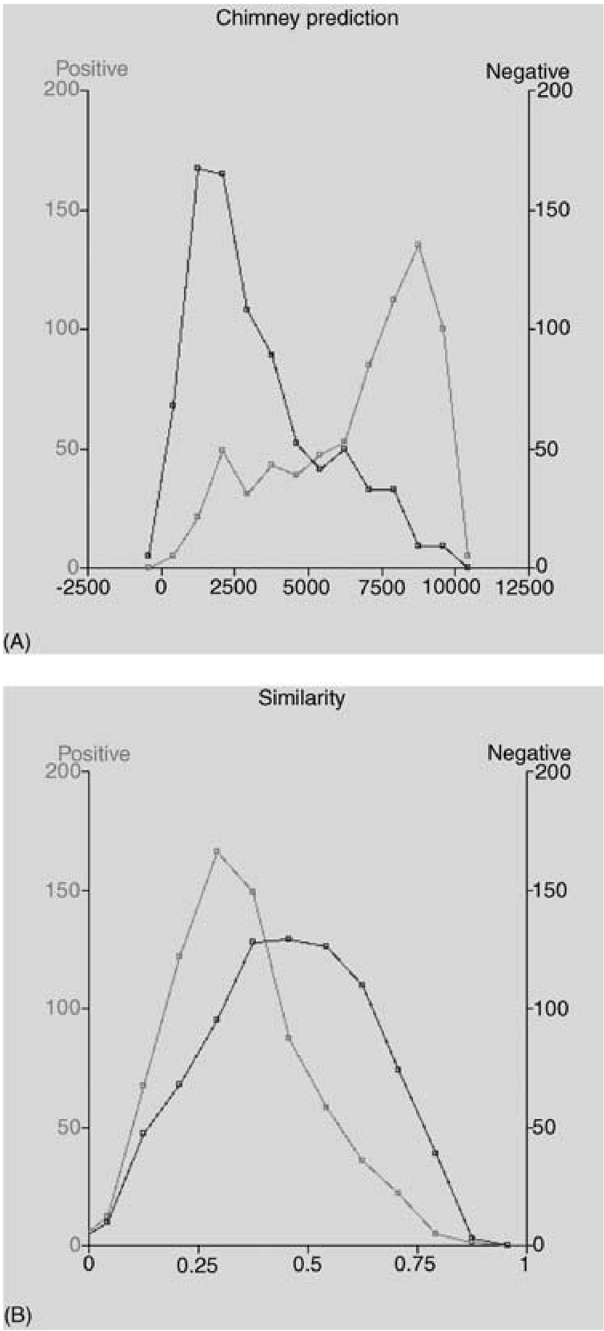


Fig. 3. (A) Similarity values for positive (fluid migration) and negative (nonfluid migration) picks (based on data in Fig. 2), showing impossibility of signal separation, in contrast to neural network technology (B) in which clear separation between fluid migration paths and other noise is visible.

It should be realised that the described detection method in essence is a pattern recognition technique. It facilitates the interpretation of seismic features that exhibit a similar response as the response in the training set for the neural network. Whether or not high-valued events in the chimney probability cube are indeed reflecting fluid migration paths remains a question of interpretation. Vertical noise trails caused by acquisition and processing artefacts and seismic merge zones often show up in chimney cubes and must not be confused with real fluid migration paths. The interpretation centres on event recognition and spatial relationships between different types of seismic events (e.g. faults, anomalies) and other sources of information, such as well information, pressure regime, basin models and structure maps.

Hydrocarbon generation

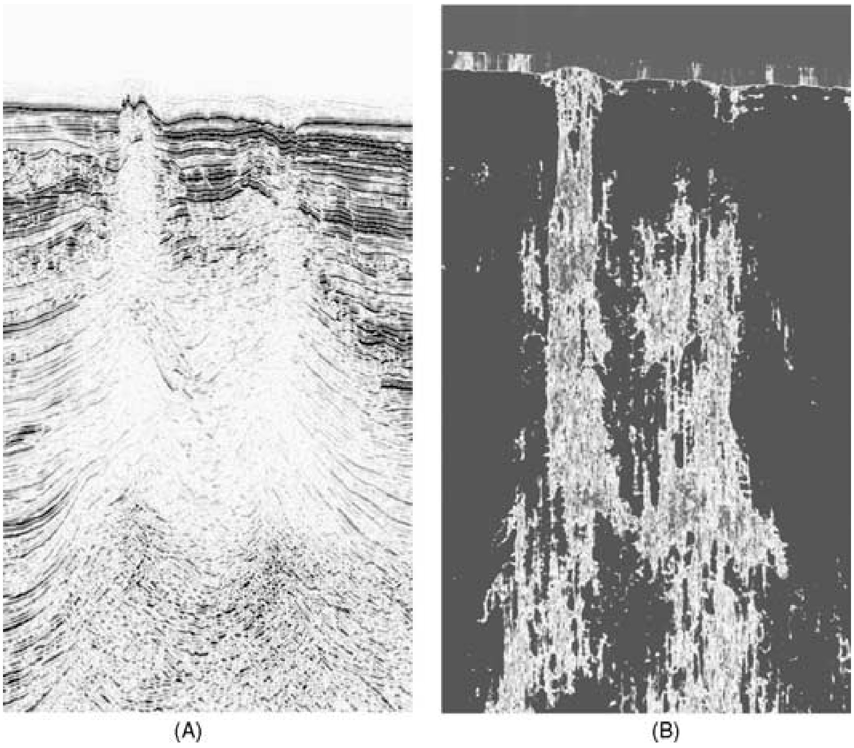
The described fluid migration detection method highlights where hydrocarbons originate by enhancing fluid activity in source rocks that are assumed to be related to active or past hydrocarbon expulsion. A recent study revealed very local activity in the source rock that could be correlated with the exact outlines of the known hydrocarbon maturation area (Fig. 4; Ligtenberg & Thomsen 2003). The information confirmed the outline of the modelled maturation cells and pointed in the direction of a possible second kitchen that was not recognised before. Further investigations are being carried out to confirm the observations with respect to active hydrocarbon expulsion. The detected fluid activity in the source rocks can confirm the observations that are made in the basin model, which is normally a problem in such studies. It can also provide indications that updates are required for the various elements in the model and for their hydraulic parameters (Ligtenberg & Thomsen 2003).

Chimneys

Fluid migration paths often appear as chimneys. Chimneys are vertical zones of fluid flux. They are related to variations in pressure systems by which fluids migrate to shallower levels (water or hydrocarbons). When these chimneys reach the seabed, mud volcanoes or pockmarks are formed, depending on the intensity of fluid flux and pressure.

Large-scale chimneys observable in seismic data as shown in Fig. 5 are most often gas chimneys, because gas is the only fluid that is able to break through the capillary pressures of overlying sediments. Oil and water generally use permeable formations, faults and fractures to migrate. Although its location is quite obvious, the exact outline of such a large-scale

Fig. 4. Fluid migration detection result on seismic data, North Sea, enhancing fluid activity in source rock (indicated by arrow) that is assumed to be related to hydrocarbon expulsion, along other fluid migration features. Cross-section 13.7 km, depth 1800 msec.



(A) (B)

Fig. 5. Example of large-scale gas chimneys in seismic data, West Africa (A), and the neural network fluid path detection result (B). Cross-section 7.5 km, distance from seabed to base of image approximately 4000 msec.

chimney is quite difficult to determine. Besides, small-scale vertical fluid migration features are most often not directly observable in seismic data and are often overlooked. The chimney detection method is capable of picking up these features that are hardly visible, and it increases the contrast between the chimney and other data by which the outlines of chimneys are better recognisable (Figs 1, 2 and 7).

The relation between closure, seal strength and buoyancy provides an important control on the amount of oil and gas present in reservoirs, as well as its hydrocarbon type in multiphase petroleum systems (Sales 1997). Important in this type of analysis is the knowledge of the local and regional geology for correct interpretations. Chimney detection provides important information on the quality of seals and charge and thus fills the information gaps that exist on charge, seal and leakage, which are all important aspects of determining the quality of prospects.

Faults

Seepage-related features such as carbonate build-ups and pockmarks in the vicinity of faults indicate present or past fluid

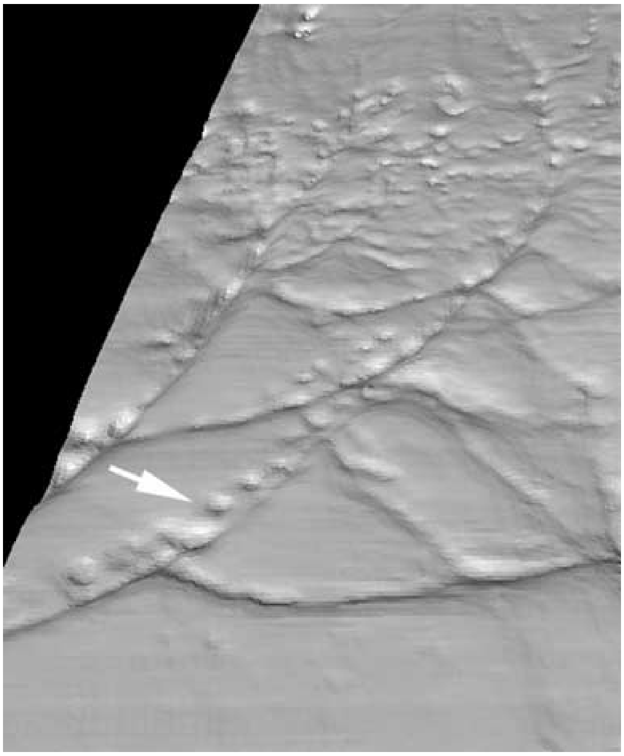


Fig. 6. Image of the seabed (West Africa), showing pockmarks along fault trends, indicative for fluid migration along these faults. Approximately 2.8 × 6.6 km.

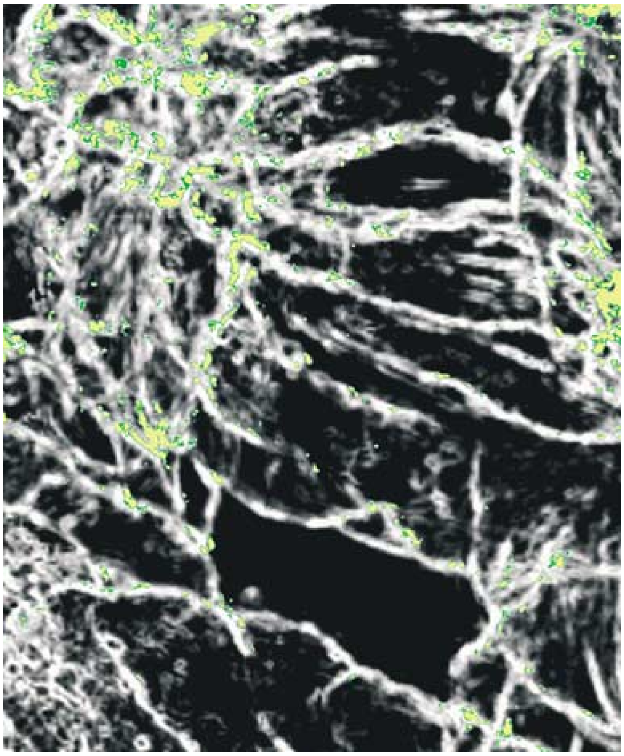


Fig. 8. Time slice through a Faultcube (West Africa), with an overlay of fluid migration detection results in yellow, indicating sealing and leaking fault segments. Approximately 4.5 × 6.3 km.

migration along the faults (Fig. 6; Hovland & Judd 1988). Fluid migration path analysis can also assist in the evaluation of the sealing quality of faults (Ligtenberg 2003). In many case studies, it is observed that different fault systems exhibit different signatures in seismic chimney cubes. Some faults are not visible at all. For others only segments of the faults are picked up. These faults without detected fluid migration are assumed to be sealing or having only low-fluid flux.

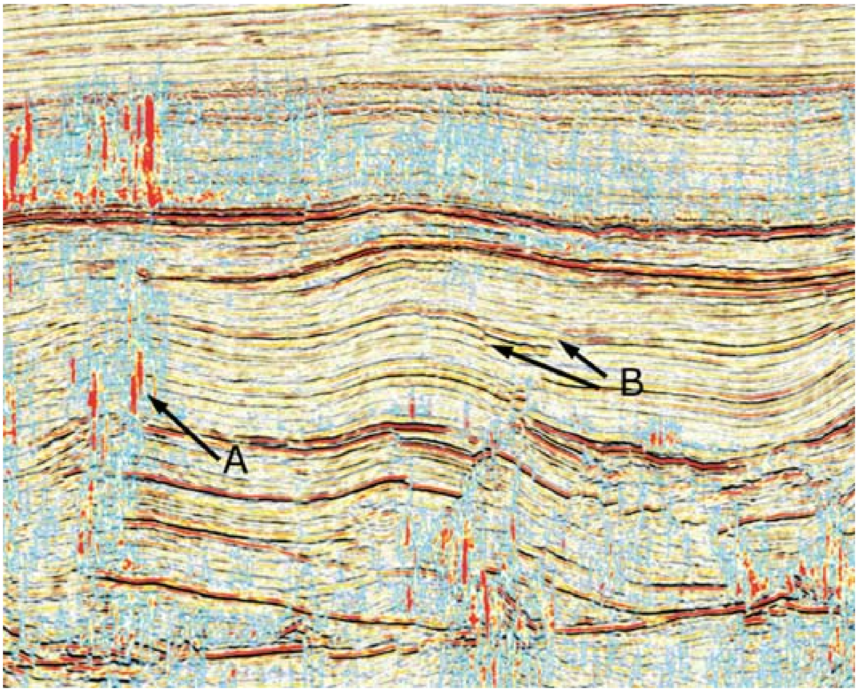


Fig. 7. Seismic line (North Sea) with overlay of fluid migration detection. Arrow A indicates faults with high-fluid flux, in contrast to the faults indicated by arrow B without or only minor fluid flux. Cross-section 20 km, depth 3450 msec.

Figure 7 contains a seismic line with an overlay of the fluid migration detection and shows active fluid migration along the large-scale faults on the left, with shallow gas zones in the clastic formation above. In contrast, the faults that are present in the central parts show no fluid migration structures and are assumed to be sealing or having low-fluid flux only. Figure 8 is an example from West Africa and shows a time-slice through a fault cube with an overlay from the chimney cube. This type of visualisation quickly enhances which faults or fault segments are leaking and which parts are sealing. In this case it illustrates that only segments of the larger faults appear to act as fluid migration paths. This segmentation in leakage intensity along faults may be related to variations in lithology along the fault or to variations in the pressure regime. It should be emphasised that all observations in fluid migration detection should be studied in conjunction with all other data available, such as well logs, reservoir information, pressure data and basin modelling results to confirm the observations.

CONCLUSIONS

Seismic fluid migration path detection has proven to be a useful supplementary tool for studying petroleum systems. The method may enhance areas of hydrocarbon expulsion, assist in evaluating the sealing quality of faults and can provide information on charge, leakage and spillage from reservoirs. In summary, it provides better insight in all elements of the petroleum system with respect to fluid flow.

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