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Detection of fluid migration pathways in seismic data: implications for fault seal analysis

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ABSTRACT

A new and efficient method for fault seal analysis using seismic data is presented. It uses multiple seismic attributes and neural networks to enhance fluid migration pathways, including subtle features that are not detectable using single attributes only. The method may be used as a first estimate of fault seal or to calibrate results from other techniques. The results provide information about which faults and fault segments are sealing or leaking. Fluid flow along individual faults appears to be focused along zones of weakness, and fault seal research should thus be focused on finding such weak locations within fault zones, a task that is best done using three-dimensional (3D) seismic data. Under certain conditions, it is suggested that fluids migrate along fault planes by a diapiric fluid flow mechanism. The results assist in calibrating the bulk hydraulic properties of faults and rock formations and can be used in basin modelling.

INTRODUCTION

Faults are the main conduits for fluids in many basins worldwide, especially in the deeper subsurface where more consolidated to completely lithified rocks are present. The analysis of the sealing quality of faults is, therefore, one of the most important focal points in the oil and gas industry. It provides important information on where hydrocarbons could have migrated or accumulated. Herein also lays a difficulty, because too much uncertainty still exists in existing fault seal evaluation methods. For example, Shale Gouge Ratio (SGR) analysis (Yielding *et al.*, 1997) and juxtaposition analysis using Allan diagrams (Allan, 1989) provide useful information on the possibilities for leakage along the fault planes and about possible interconnectivity between both sides of the faults (e.g. Losh *et al.*, 1999). However, the risk that the interpretation based on these techniques is incorrect or incomplete is often still too high because of all uncertainties involved (Yielding, 2002; Yielding *et al.*, 2003). Combining these methods with results that are generated by the approach presented in this paper can significantly increase the confidence level of the existing fault seal analysis methods (G. Yielding, pers. comm., 2004).

The workflow presented in this paper for elucidating the fluid migration pathways and faults on seismic data has been successfully applied to many different 2D and three-dimensional (3D) seismic data sets, in various basins, worldwide. Highlighting these fluid migration pathways provides a better insight in the spatial relationship between the various elements of the petroleum system. These include processes such as:

(1) Fluid activity in source rocks that may be related to active hydrocarbon expulsion (Ligtenberg & Thomsen, 2003).
(2) Gas chimneys and fluids migrating along faults and reaching potential reservoir formations, thereby providing information about whether a prospect is charged or not (Heggland *et al.*, 2000, 2001).
(3) Leakage from potential reservoirs, which may provide better insight in the lateral and top seal quality (Walraven *et al.*, 2004).
(4) Leakage from these potential reservoirs to shallower levels and charging shallow sands, thus indicating the presence of shallow gas drilling hazards (e.g. Heggland *et al.*, 2001; Aminzadeh *et al.*, 2002).
(5) Hydrocarbons reaching the seabed, creating mud volcanoes and pockmarks; the occurrence of such features is important, as they can affect the positioning of new offshore installations and pipelines (e.g. Hovland & Judd, 1988).

The same kind of analysis can also be used to better understand fluid flow characteristics along faults, highlighting small-scale features that are related to fluid flow that would not have been detected by any other method.

Results from fluid migration pathway detection on seismic data have successfully been used in basin modelling to constrain and populate the models, e.g. to locate zones of high fluid flux, to highlight zones of possible hydrocarbon expulsion, to indicate which faults or fault segments are leaking and to locate zones of overpressure (Ligtenberg & Thomsen, 2003). Furthermore, the resulting values could be fully integrated in the process of calibrating hydraulic properties of faults and formations (B. Wygrala, pers. comm., 2004).

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METHODOLOGY

In this study, fluid migration pathways in seismic data are detected by means of advanced seismic attributes, neural network pattern recognition technology and interpreter's insight (Heggland *et al.*, 1999; Meldahl *et al.*, 2001; Ligtenberg, 2003b). The approach for enhancing fluid migration pathways in seismic data starts with a thorough tectono-stratigraphic analysis of the seismic data. This provides a better understanding of the local and regional geology from a stratigraphic, structural and tectonic perspective. Special attention is paid to locating seismic features that indicate hydrocarbon presence. These leakage-related features range from expressions at the seabed, such as pockmarks and mud volcanoes, to gas chimneys and bright spots at deeper levels. The most important types will be described in more detail below.

The identified leakage-related features are used in the next phase of the workflow: when selecting representative training locations for the neural network. When such features are present, they may indicate that an active petroleum system exists in the basin under investigation, although the interpretation of leakage-related features is ambiguous and should be dealt with carefully. For example, when pockmarks are encountered on the seabed, it does not necessarily mean that a prospective reservoir is located directly below these pockmarks. Hydrocarbons may be because of biogenic methane expulsion and thermogenic hydrocarbons can migrate over long distances up to hundreds of kilometres (Trasher *et al.*, 1996; Evans & Hobbs, 2003) from deeper parts in the basin through permeable beds to shallower levels, reaching large structures such as salt or mud diapirs or major faults that can act as important leakage points. Fluids migrate upward along faults or along the flanks of diapirs, and along faults and fractures above diapirs, and may reach the seabed where pockmarks may form if fluid flux is sufficiently vigorous. This type of fluid flow is one of the most important migration and leakage mechanisms, for example, in the North Sea basin and the Gulf of Mexico (Trasher *et al.*, 1996).

The next phase in the workflow is the selection of representative training locations for the training of the neural network (Ligtenberg, 2003b). The locations are carefully picked within zones that are interpreted to represent fluid migration pathways (Fig. 1b). In addition, a set of example locations are selected that do not represent fluid migration, in order for the neural network to distinguish between fluid migration features and the background seismic signal. Generally, around 500–1500 training locations are selected in a 3D seismic data set of approximately 750 km^2, depending on the seismic quality and the seismic character of the fluid migration pathways present. At these training locations a whole set of advanced seismic attributes are extracted. The parameter settings of the applied seismic attributes have been set such that they are optimally suited to detect the fluid migration pathways in the seismic volume. Subsequently, the training locations and an assembly of seismic attribute definitions are given to the neural network. The type of neural network used in this methodology is a so-called supervised neural network that learns by the provided representative examples (e.g. Wong *et al.*, 1995; Meldahl *et al.*, 1999).

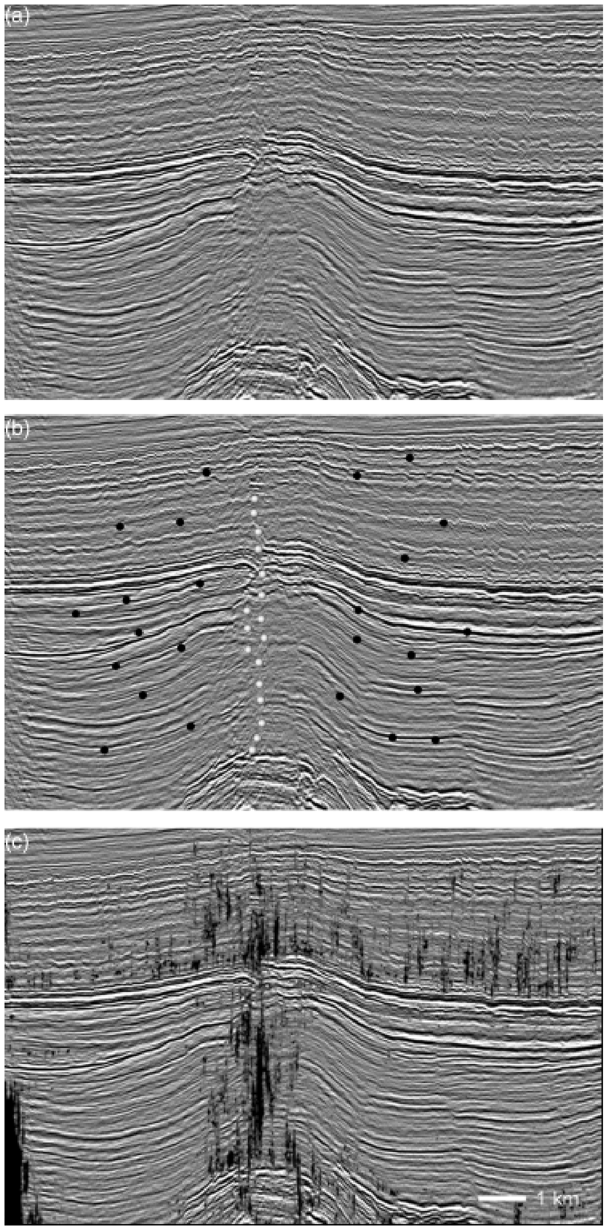


Fig. 1. Example of the fluid migration pathway detection workflow: (a) the original seismic data (North Sea), (b) the selection of train locations representing fluid migration pathways (white) and non-fluid migration pathways (black) and (c) fluid migration pathway detection result (chimney probability shown, 0.7–1.0) after the application of the trained neural network (vertical range displayed: approx. 1600 m).

The neural network will train itself by scanning through the data many times, trying to establish a relationship between the input (seismic attributes) and the output, based on the selected training locations. Application of the trained neural network yields a fluid migration probability cube, a so-called 'chimney cube' (Meldahl *et al.*, 1999;

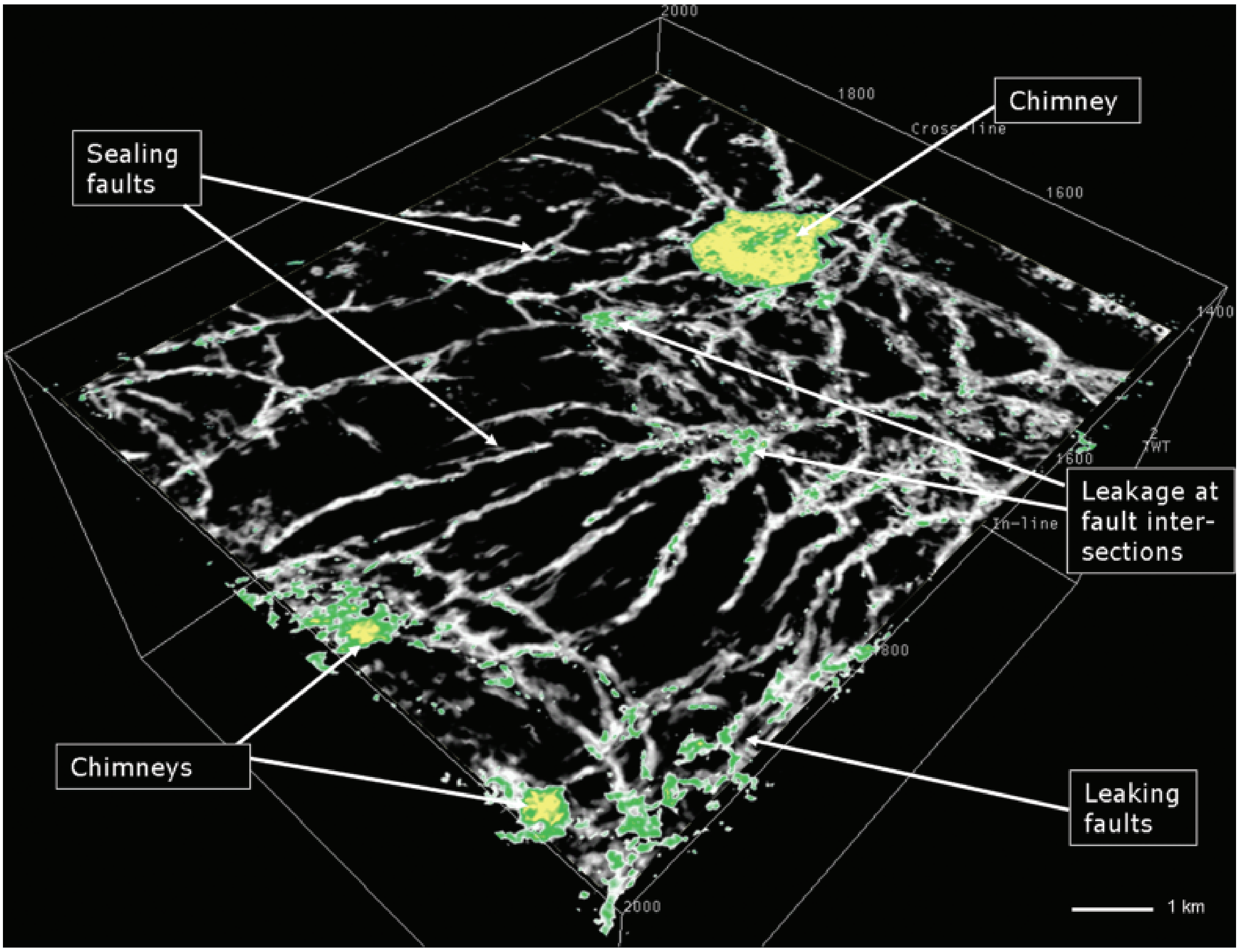


Fig. 2. Time-slice through a fault cube (grey), with an overlay of elucidated fluid migration pathways in yellow-green ('chimney' probability shown, 0.7–1.0). The yellow zones correspond with large gas chimneys with high fluid flux. The southernmost two chimneys are shown in cross-section in Fig. 6. Increased fluid activity is observed at fault intersections and along several faults, indicating leakage. Faults without enhanced fluid activity are interpreted to be sealing or having very low fluid flux. Data from West Africa.

Heggland *et al.*, 1999, 2000; Ligtenberg, 2003b), in which the resulting 'chimney-probability' values range between 0 and 1 (Fig. 1c). High values in the chimney cube designate data areas very similar to the training locations interpreted to represent fluid migration pathways. The described method, using an assembly of advanced seismic attributes in combination with a neural network and the interpreter's knowledge, is able to enhance features that otherwise would have been missed using single seismic attributes. Results in this paper will illustrate this conclusion and will emphasise the importance of using neural network technology above the independent use of single seismic attributes.

A similar approach is used to enhance faults present in the seismic data. Training points are selected in the centres of the faults, and the parameter settings of the attributes are optimised to enhance faults in the seismic data. Application of the trained neural network results in a so-called 'fault cube', which shows probability values of the fault prediction between 0 and 1. High values in this case designate likely fault zones.

Comparing fault cube results with the interpreted zones of enhanced fluid migration is a powerful method to quickly evaluate the sealing quality of faults. In general, the fault cube displays all of the faults present, whereas the chimney cube shows all (parts of) those faults that are associated with vertical fluid movement. Figure 2 displays a time-slice through a fault cube (in grey), with an overlay of fluid migration pathway detection results (in green-yellow). The bright yellow, circular areas on this time-slice correspond to large gas chimneys. Note the detected fluid activities along certain faults (as indicated in Fig. 2), indicating possible leaking faults and fault segments; in contrast to other faults without any detected fluid activity, representing possible sealing faults and fault segments. Furthermore, increased fluid activity at fault intersections can be observed in Fig. 2. Fault intersections are expected to play an important role as potential fluid migration pathways in many basins worldwide (Gartrell *et al.*, 2003), as is explained below.

The combination of fault cube results and enhanced fluid migration pathways can also illustrate leakage through faults related to the regional stress regime (Fig. 3): local dilatational zones are formed along the faults planes with orientations parallel/sub-parallel to the main stress

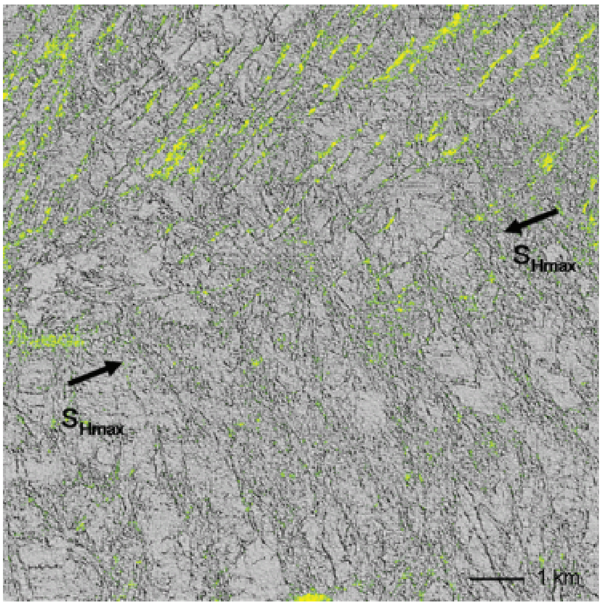


Fig. 3. Fluid migration pathway detection results (yellow) as overlay on fault structures, indicating leaking (ENE-WSW) and sealing faults (NNW-SSE) and its apparent relation to the regional stress regime. Local dilatational, leaking zones are formed parallel/sub-parallel to the main stress field (S_{Hmax}). Sealing faults are located normal to S_{Hmax} (example from the Mediterranean Sea).

field (S_{Hmax}), whereas sealing faults are oriented normal to S_{Hmax}. This fits well with observations in e.g. remote sensing data (O'Brien *et al.*, 2002). The direct correlation between the results from seismic attribute and neural network detection and the results from other fault seal analysis methods illustrates that the outlined methodology provides a very useful empirical measure of fault seal, and it is therefore recommended to form part of any fault seal analysis where seismic data are available.

SEISMIC EXPRESSIONS INDICATING FLUID MIGRATION

Locating good training locations for the neural network requires some knowledge of the different type of seismic features that are indications of fluid migration and seepage. Hydrocarbon leakage can often be recognised on seismic data, because it causes an acoustic, mechanical or diagenetic change in the geological sequences. Direct indications for fluid migration and seepage are expressed in characteristic seepage features both at seabed and in the subsurface. Expressions of fluid seepage at the seabed comprise features such as carbonate mounds, mud volcanoes and pockmarks that are often associated with hydrocarbon gas migration (Hovland & Judd, 1988). Dedicated seabed imagery or a good seabed reflection is necessary in order to study these features in detail. The subsurface contains different types of features that are direct and indirect indicators of fluid migration in general and hydrocarbon migration in particular. These include features such as

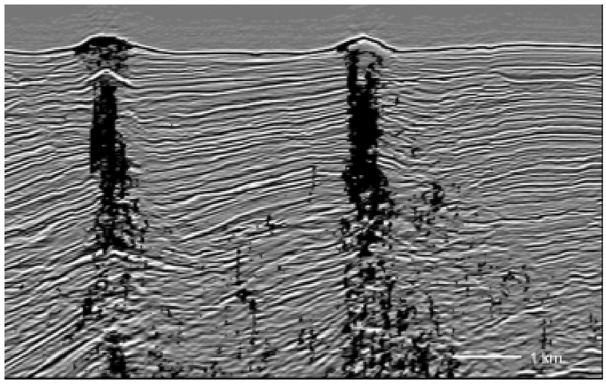


Fig. 4. Seismic cross-section from offshore West Africa with overlay of enhanced fluid migration paths, illustrating feeding of mud volcanoes by means of large-scale gas chimneys.

gas chimneys, mud diapirs, bright spots, acoustic turbidity zones and palaeo-surface expressions, such as buried mud volcanoes and pockmarks (e.g. Hovland & Judd, 1988). In the following, brief descriptions of the most important types for fluid migration analysis in seismic data are provided.

Mud volcanoes

Mud volcanoes are distinctive conical topographic structures and are therefore easily recognised on seismic data (Fig. 4). Mud flows that are expelled from volcanoes can also often be recognised and mapped out on seismic data (Fig. 5; Cooper, 2001). Palaeo-mud volcanoes, buried under thick continuous layers of sediments, are often encountered on seismic data (Fig. 5b). They are often located below active mud volcanoes at the present-day seabed. These are indications for long-term focused fluid migration and form important information for the construction of detailed basin models (Ligtenberg & Thomsen, 2003). Buried mud volcanoes separated by intervals of non-extruded sediments furthermore indicate that fluid expulsion has been episodic (Heggland, 1998; Xie *et al.*, 2003).

Mud volcanoes are often, but not always, formed in association with the release of gas from beneath the seabed. Mud volcanoes are encountered both onshore and offshore and have a wide variety of sizes, ranging from a few meters to several kilometres in basal diameter and up to 500 m in height (Hovland & Judd, 1988; Guliev, 1992). In contrast to pockmarks that only record fluid expulsion (Hovland & Judd, 1988; Cooper, 2001), mud volcanoes are related to high fluid and sediment flux. Mud volcanoes are found at many locations all over the world and are often associated with deeply buried, overpressured shales (Hedberg, 1980) or areas of tectonic compression where they are aligned along structural features such as faults or fold axes (Hovland & Judd, 1988; Deville *et al.*, 2001; Huguen *et al.*, 2001). Mud volcanoes are often found in basins that underwent rapid subsidence and high sedimentation rates, up to 1000 m Myr^{-1}, such as the South Caspian Basin (Guliev, 1992), in Azerbaijan (Guliev, 1992; Cooper, 2001), on the

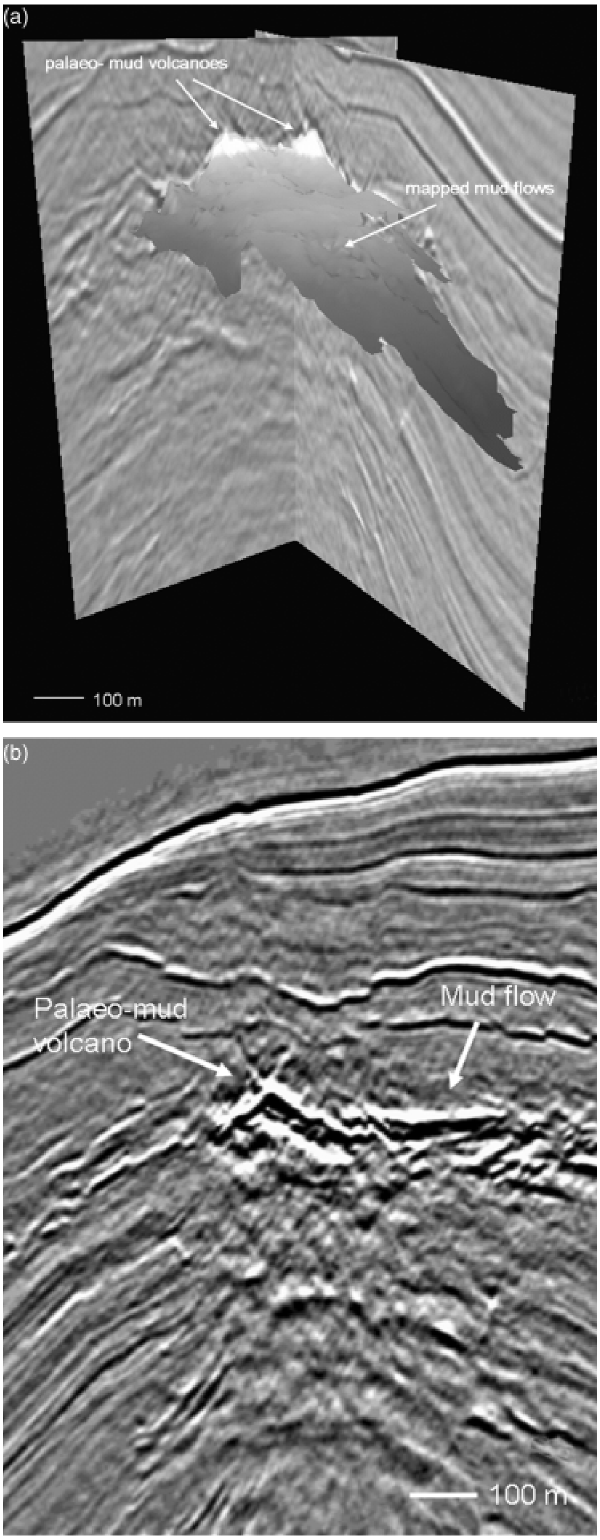


Fig. 5. (a) Two palaeo-mud volcanoes (white peaks, indicated by arrows) and mud flows mapped in seismic data (Gulf of Mexico). The right mud volcano corresponds with the buried palaeo-mud volcano shown in Fig. 4b (vertical range displayed: approx. 1000 m). (b) Buried palaeo-mud volcano and related mud flow, indicative for fluid flow in the past (Data from Gulf of Mexico; vertical range displayed: approx. 1000 m).

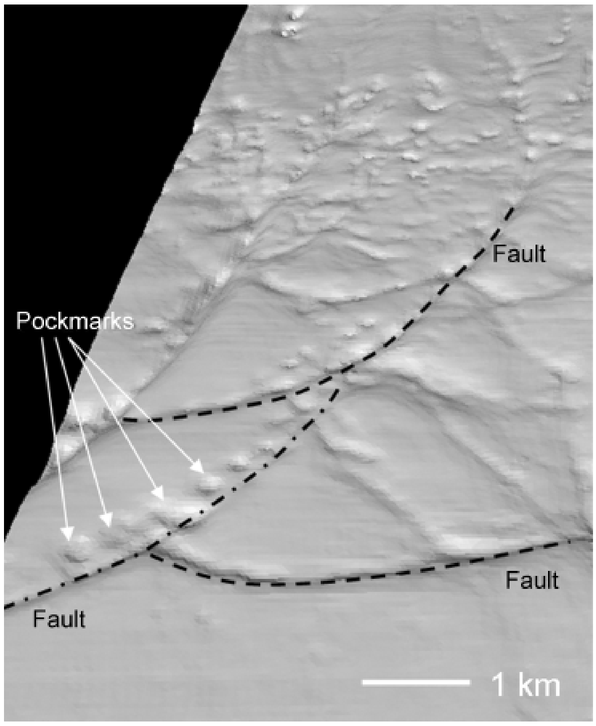


Fig. 6. Image of the seabed (offshore West Africa), showing pockmarks at regular spaced intervals above and along leaking faults. Note the slight offset of the pockmarks from the fault (see text for further explanation).

Nigerian continental slope (Graue, 2000; Heggland, 2003), and in the Nile delta (Mascle *et al.*, 2003). Mud volcanoes are furthermore encountered in active compressional tectonic regions, such as New Zealand, Trinidad and the Mediterranean, where the increased subsurface pressures are because of tectonic stresses which result in the formation of large mud volcanoes and mud diapirs (see overview by Graue, 2002).

Pockmarks

Pockmarks are crater-like depressions on the seabed that are related to focused fluid flow and are generally found in low permeability, fine-grained sediments. They vary in size from 1 to 700 meters in diameter and from 0.5 to 45 m in depth (Hovland & Judd, 1988; Cole *et al.*, 2000). Different types of pockmarks exist, including unit pockmarks, normal pockmarks, elongated pockmarks and eyed pockmarks, in which the difference mainly lies in size, location and internal character (Hovland *et al.*, 2002). Internally, bacterial mats and/or carbonate crusts can be encountered, as well as carbonate cemented sediments. This is assumed to be formed by the oxidation of biogenic or mixed biogenic/thermogenic methane gas (Hovland & Judd, 1988).

On seismic data, when the water is deep enough to allow a good seismic reflection from the seabed, and if the pockmarks are large enough (i.e. 50 m across or more), the pockmark craters can be clearly distinguished on the seabed reflection. They often occur in characteristic patterns. Normal pockmarks can be found along fault trends, which is a clear indication of fault leakage (Fig. 6). Pockmark groups can also be found in circular to semi-circular

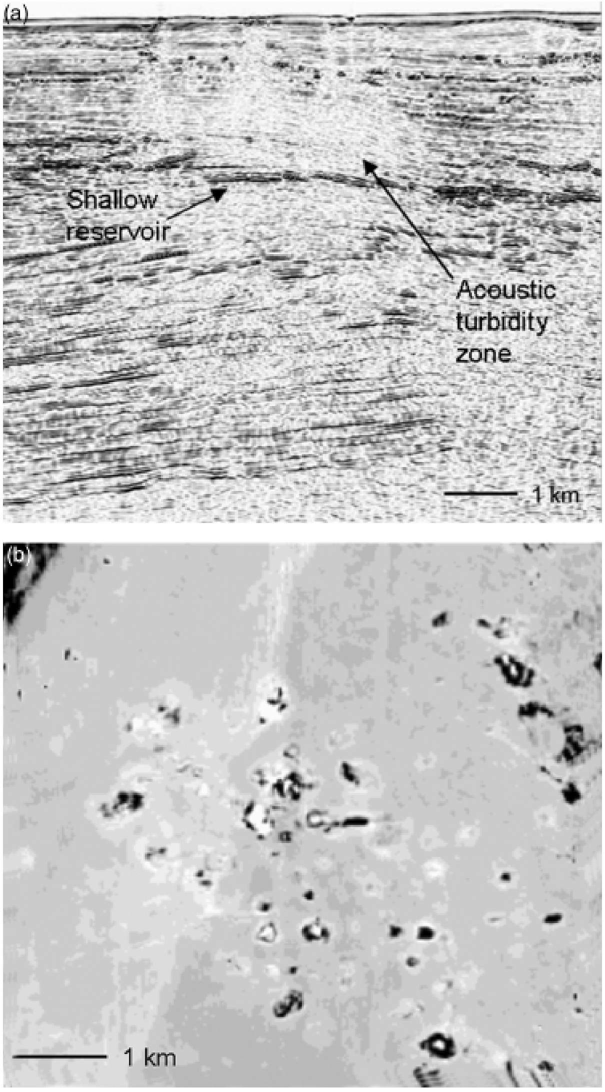


Fig. 7. (a) Leakage indications by acoustic turbidity zone above shallow reservoir, from which small-scale gas chimneys originate and migrate hydrocarbons to the seabed, where a pockmark field is created, as shown on the similarity timeslice (b) (data from offshore West Africa).

patterns, which is related to the diagenesis and cementation of the sediments into impermeable rocks directly above the fluid flow. Continued fluid flow will migrate around the impermeable rocks, leading to these groups of pockmarks in circular to semi-circular shape. They can also be found as strings, which follow sedimentary features in the deeper section, such as buried overpressured channels (Gay *et al.*, 2001a, b). In addition, buried palaeo-pockmarks are also clearly distinguishable on seismic data and are useful indicators of fluid flow in the past and of the possible presence of hydrocarbons in the deeper subsurface (Heggland, 1998).

Gas chimneys

Gas chimneys seen in seismic data are vertical to near-vertical columns of noisy seismic character, here interpreted as scattered energy caused by zones of focused fluid flow.

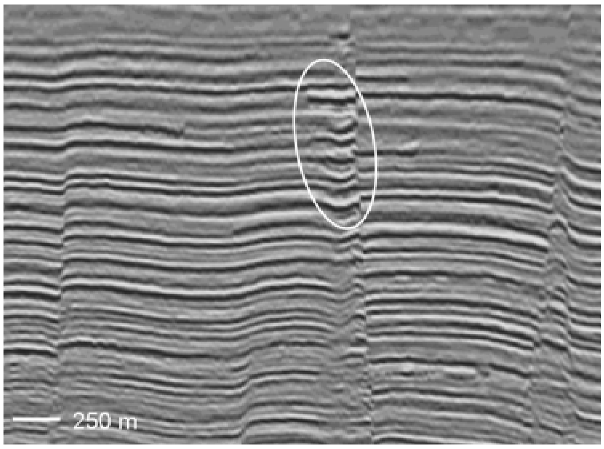


Fig. 8. Direct hydrocarbon indication by bright spots located along leaking fault (Data from Mediterranean Sea; vertical range displayed: approx. 300 m).

In seismic data, gas chimneys are characterised by low trace-to-trace coherency, low reflection amplitudes and highly variable dip- and azimuth of seismic reflections where they pass through the chimney (Fig. 7a). They are normally assumed to represent high fluid flux paths that are initiated by an overpressure regime. Hydrocarbons are often implicated in their formation, but pockmarks may also form because of pore water expulsion (e.g. Gay *et al.*, 2001a, b). Gas chimneys may feed mud volcanoes (Fig. 4) or pockmarks (Fig. 7) at the seabed, or they may charge shallow gas zones. In several basins worldwide it has proven crucial to map gas chimneys in order to avoid drilling hazards or are to be used in exploration as an indicator for an active hydrocarbon system (Heggland *et al.*, 2001; Aminzadeh *et al.*, 2002). Gas chimneys may be gradational with scatter zones that are inferred to indicate the presence of anomalous, but stationary fluids .

Acoustic turbidity zones

Acoustic turbidity zones are areas of chaotic seismic reflections that are related to the presence of fluids within the sediments, commonly gas in solution, causing scattering and absorption of the acoustic energy. In many cases, reflections show a 'pull-down effect' when entering this acoustic turbidity zone (Hovland & Judd, 1988). Acoustic turbidity zones occur in many basins worldwide, but are often overlooked and ignored as being some kind of seismic acquisition or processing artefact. However, in some cases a direct link with hydrocarbons is obvious. Figure 7a shows a shallow reservoir, overlain by an acoustic turbidity zone. From this zone, small-scale gas chimneys originate and reach the seabed where a large pockmark field is formed (Fig. 7b).

Direct hydrocarbon indicators

The most common direct hydrocarbon indicators on seismic data are bright spots, dim spots, flat spots and phase changes (Allen & Peddy, 1993). The most obvious and useful type in the described methodology is the bright spot.

Bright spots are defined as being high amplitude, negative phase anomalies that are related to a decrease in density/acoustic velocity, caused by a change in fluids in the rocks. Within hydrocarbon accumulations, a strong decrease in acoustic impedance is expected at the top, because of the transition from brine to hydrocarbons. On seismic data, these bright spots commonly occur as local, high amplitude zones near leaking faults (Fig. 8), within reservoirs, above leaking reservoirs, at shallow gas pockets and along gas chimneys.

Hydrocarbon-related diagenetic zones (HRDZ)

A different type of high amplitude reflection with positive phase is the hydrocarbon-related diagenetic zone (HRDZ) (O'Brien & Woods, 1995) and is another important seismic indicator for hydrocarbon migration. HRDZs form when hydrocarbons leak from deeper reservoirs, migrate upward, charge shallower sand formations and finally biodegrade. Biological oxidation of the hydrocarbons produces localised, intense carbonate cementation. This cementation produces sufficient increase in acoustic impedance for a strong seismic response (O'Brien & Woods, 1995; Cowley & O'Brien, 2000). HRDZs are often related to fault leakage and therefore have a linear expression; or can be related to point leakage, such as at fault intersections, forming a circular anomaly (O'Brien *et al.*, 2002).

FAULT CHARACTER ON A DETAILED LEVEL

From experience it is noticed that the main focus in fault seal analysis is generally on the large-scale faults bounding reservoirs, or on faults at target level, causing possible compartmentalisation of the reservoir. Faults are normally interpreted as being either completely sealing (non-conductive) or completely 'open' (conductive). It is, however, more realistic that fluid flow occurs along local, weak sections within the fault zone, as will be explained below. Therefore, it is stressed in this paper that the emphasis in fault seal analysis should be on detecting the weak points in the fault zones. Application of the presented fluid migration pathway detection on many seismic data sets worldwide shows that fluid migration very often occur at these weak fault zone sections (e.g. Figs 2 and 3).

In the assessment of the leaking quality of faults, the following should be kept in mind:

1. Fault complexity
2. Fault intersections
3. Fault plane irregularities

Fault complexity

Own structural and tectonic fieldwork and work by others (e.g. Price and Cosgrove, 1990; van der Zee, 2002; Koledoye *et al.*, 2003) have shown that large-scale faults normally represent very complex zones composed of many fault segments, multiple fault strands, Riedel shears, splay faults, dilatational jogs, relay ramps, et cetera. These individual fault elements may be sub-seismic and are therefore not automatically apparent on seismic data; however, they may be very relevant for the sealing quality of faults (Childs *et al.*, 2003; Walsh *et al.*, 2003; Gartrell *et al.*, 2004).

It is important to map these smaller scale faults and fault-related features, because they will often produce weak locations within the main fault. Weak zones may be produced at locations where these smaller fault structures are in contact with the main fault and at places where faults are stepping or bending. These are locations at which extensional, open structures are expected to form (Price & Cosgrove, 1990) that are more suitable for fluid flow than other sections of the fault zone.

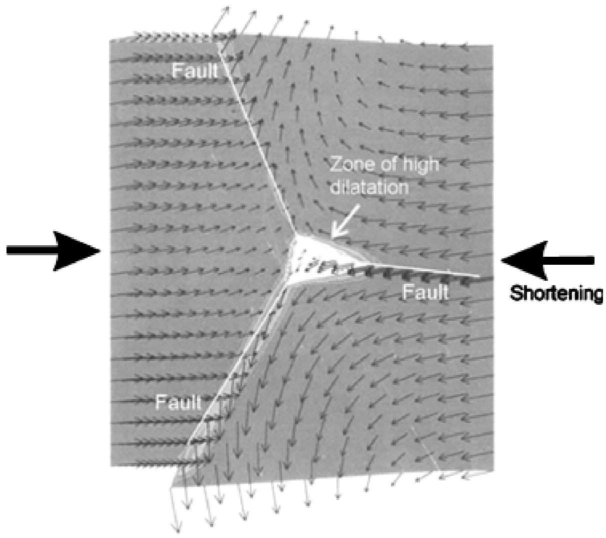


Fig. 9. 3D numerical modelling results on the mechanical behaviour of fault intersections, indicating the creation of a zone high dilatation at the centre. This will be an area with low shear strain and therefore low fault gouge production, making it an ideal location for high fluid flux (from Gartrell *et al.*, 2003).

Fault intersections

Fault intersections have received little attention in research and in the oil and gas industry, but they may actually be one of the most important pathways for fluids in a basin (Gartrell *et al.*, 2003). For example, offshore north-west Australia, reactivation of faults and fault intersections play a dominant role in vertical fluid flow (e.g. O'Brien *et al.*, 2002).

Gartrell *et al.* (2003) have analysed the mechanical behaviour of faults and fault intersections by numerical modelling. At fault intersections, a dilatation zone is formed (Fig. 9) with a high concentration of small-scale, open faults and fractures. The shear strain at these fault intersections is very low, in contrast to the shear strain at the fault planes involved. Normally, high shear strain at fault planes results in a high production of fault gouge. At fault intersections, the shear strain is reduced, yielding reduced fault gouge

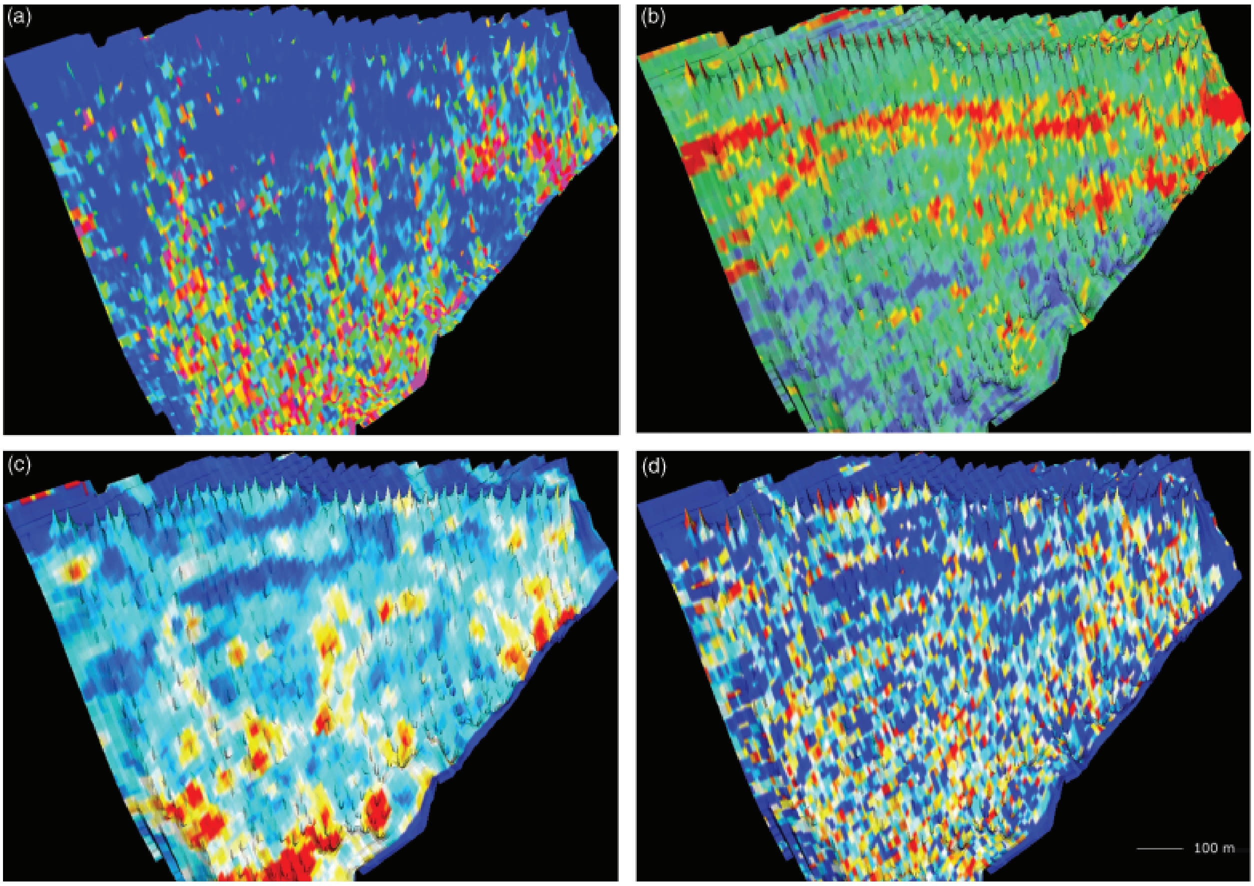


Fig. 10. 3D display of neural network analysis and single attribute application on a fault dipping approximately 70° towards viewer: (a) neural network detection results (chimney probability green to purple, 0.6–1.0), enhancing localised columnar fluid flow along fault, which is not detectable by single seismic attributes only: such as (b) Energy (red means high energy), (c) variance in local dip (red means high dip variance) or (d) similarity (coherency-type; red means low similarity). The same columnar fluid flow patterns are shown in 3D in Fig. 11, and line up with pockmarks on the seabed (Fig. 12), confirming that the observed features are not seismic artefacts but are related to hydrocarbon migration (West Africa; maximum vertical section of fault is approx. 1000 m).

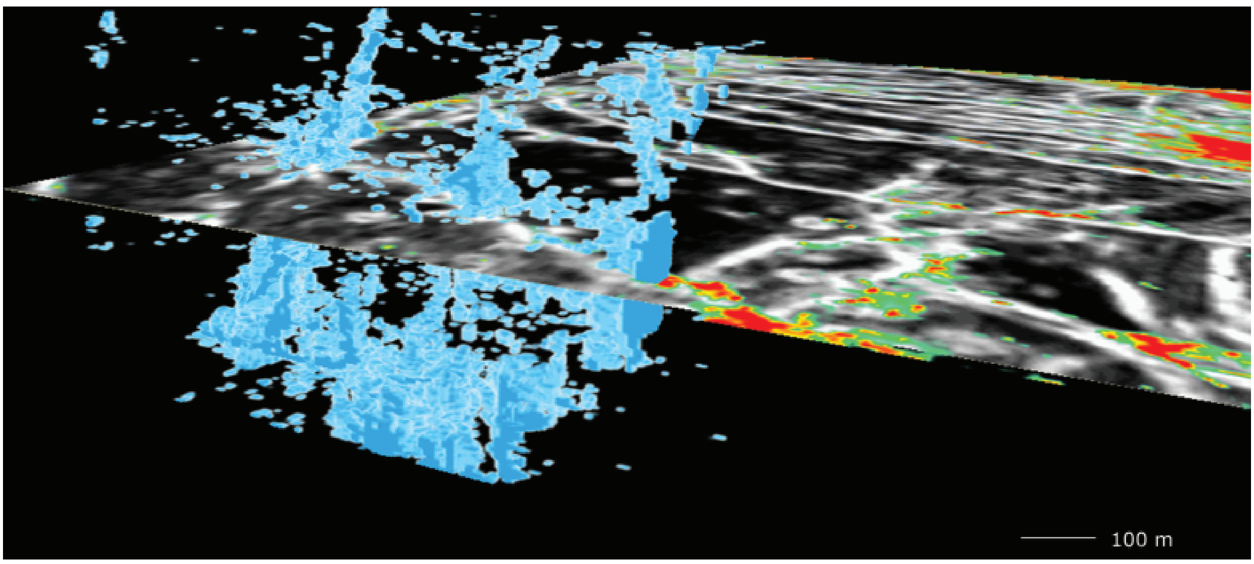


Fig. 11. 3D display of localised columnar fluid flow paths (blue) along a fault plane offshore West Africa. The time-slice displays results from the faultcube (grey-scales) and fluid migration pathway detection results (green to red; 'chimney' probability values shown, 0.7–1.0). The columns of fluid flow line up with pockmarks on the seabed (not visible). Note the regular-spaced interval of columns that is assumed to be related to diapiric fluid flow (see text and Fig. 13; vertical distance of columnar fluid flow paths is approx. 1000 m).

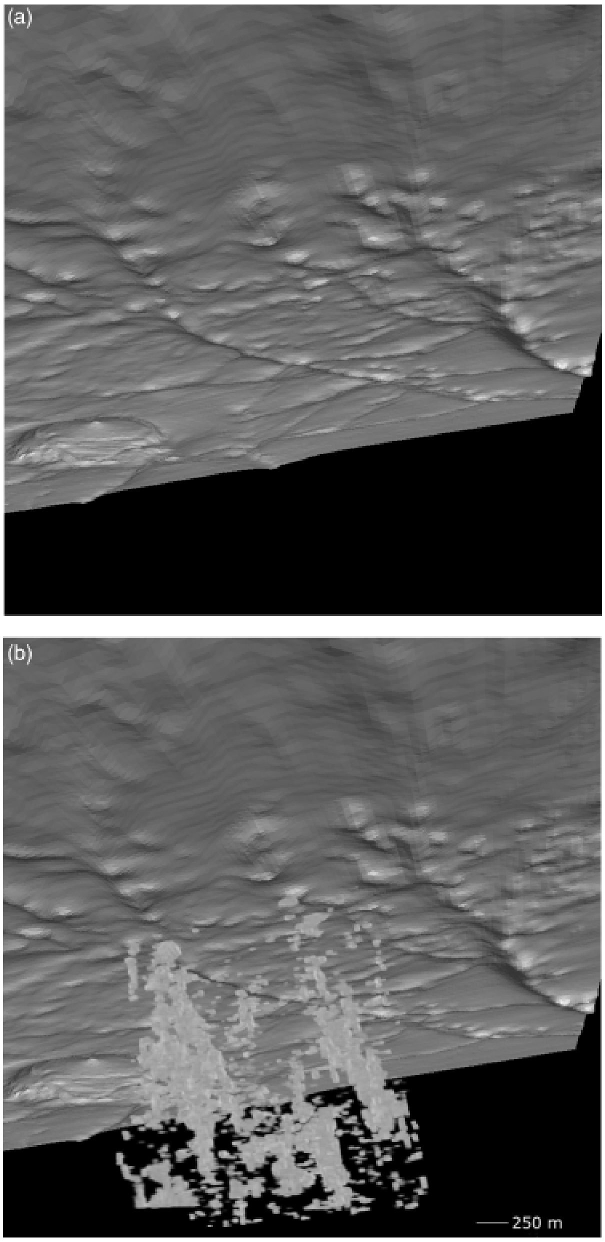


Fig. 12. (a) Mapped sea surface with faults and pockmarks (view from below). (b) Detected columns of fluid flow, lining up with pockmarks on the seabed, compare with (a), offshore West Africa (chimney probability shown, 0.7–1.0).

production and creating a sub-vertical, relatively open zone which is prone to high fluid flux (Gartrell *et al.*, 2004).

Indications of high fluid flow, predominantly at fault intersections, are observed on seismic data from various regions (e.g. NW shelf of Australia, West Africa (Fig. 2), Gulf of Mexico and the North Sea) using the described fluid migration pathway detection approach.

Fault plane irregularities

Fault planes also contain many irregularities themselves. For example, field analysis along a short fault-strike section of only 50 m (in seismic this is normally equal to only 2–4 traces), showed a high variation in plane-orientation with respect to strike and dip, defined as the 'roughness' of the fault profile (van der Zee, 2002). These minor variations either will not, or barely, be resolved on seismic data, and yet they may be very relevant as locations of concentrated fluid flow. The roughness of the fault profile is important, because it affects its shear strength, and thus fault gouge production. Therefore, fault profile irregularities may also influence the development of weak locations in fault zones.

FLUID FLOW BEHAVIOUR ALONG FAULTS

The presented method to enhance fluid migration pathways in seismic data by means of seismic attributes and neural networks is able to enhance very subtle features that otherwise would be missed when using only single seismic attributes. A recent study revealed small-scale fluid flow structures in a fault zone (Ligtenberg, 2003a; Fig. 10a), which are not picked up when only single seismic attributes are applied (Figs 10b–d). The prediction results from the 'trained' neural network shows very local concentrations of high fluid flow probability. The fluids appear to migrate along the fault zone in columnar flow patterns (Figs 10a, 11). These columnar structures appear to indicate concentrated flow along fault planes, instead of faults leaking along its entire length as a 'curtain' of fluids (Ligtenberg, 2003a). When these detected fluid columns are followed to shallower levels, they are lining up exactly with pockmarks on the seabed (Fig. 12; note that whilst this relation is easily seen in 3D, it is difficult to visualise in the 2D image shown here). This direct link with pockmarks on the seabed is proof that the enhanced columnar flow structures along the fault plane are indeed related to fluid flow, rather than being seismic artefacts. Previously, such sub-vertical features might have been dismissed as seismic artefacts. However, when these detected flow patterns do not match with acquisition line orientations, but follow the discrete fault orientations (e.g. Fig. 2); when they are not continuous 'along-fault-strike' noise zones below the fault (possible seismic fault shadows), but have circular 'pockmarked' patterns along fault-strike (as can be observed at individual faults in Fig. 3); and when they line up with pockmarks and/or HRDZs (Fig. 12), it is very likely they are real features.

Some of the detected fluid columns correlate with fault intersections; others are located in the central part of the fault plane and may be related to weak locations within the fault zone. These weak locations are expected to have a higher concentration of fractures and irregularities. They may be related to small fault bends, to changes in the dip of the faults, to sub-seismic stepping of faults, or they may be indirectly related to a diapiric fluid flow, which may contribute by local high pressure build-ups to the initiation and development of these weak and fractured locations within fault zones.

An interesting observation regarding leaking or conducting faults is the very regularly spaced interval of pockmarks

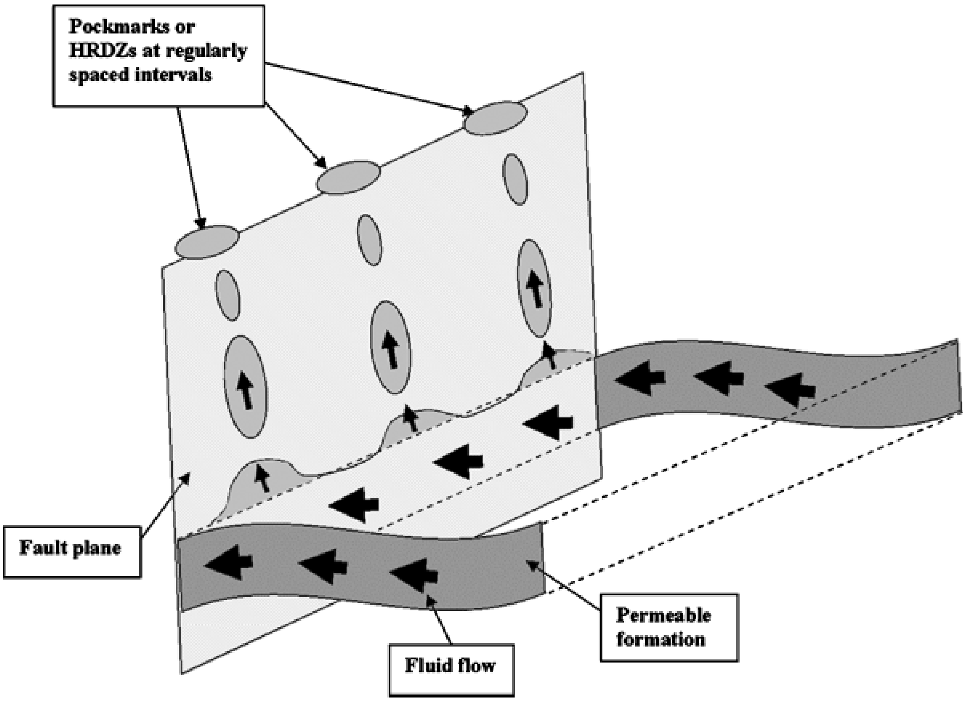
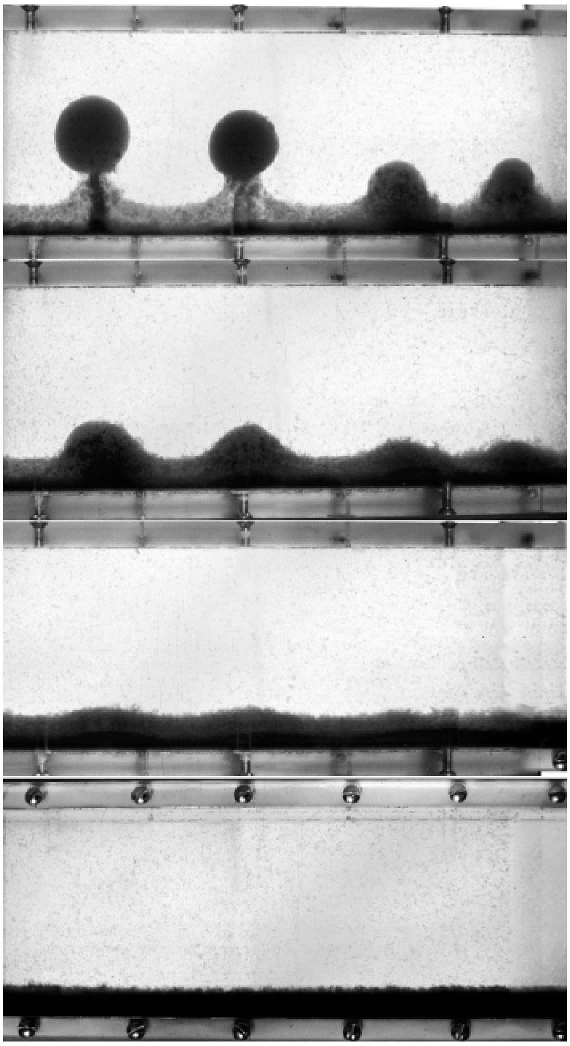


Fig. 13. Schematic illustration of diapiric fluid flow along faults: fluids (e.g. gas in solution) migrate through a permeable formation towards the fault zone. Differences in fluid character (such as viscosity and density) results in diapiric fluid migration, causing pulses of fluid flow and creating pockmarks or hydrocarbon-related diagenetic zones (HRDZs) at regular spaced intervals along the fault strike (see text).



on the seabed (Fig. 6). At deeper levels, the same kind of regularly spaced pockmarked character is seen in the fluid migration detection results from neural networks. This pattern of approximately constant distances between pockmarks above a leaking fault seems to indicate that a special mode of fluid flow occurs at these faults. It is here suggested that fluid flow may occur in a diapiric manner, because this mechanism could explain the regularly spaced intervals between pockmarks (or HRDZs) often found at the seabed and the observed regular spacing of fluid flow columns at deeper levels in the seismic data (Ligtenberg, 2003a). It might also help explain the occurrence of episodic fluid flow along fault planes and at pockmarks (Heggland, 1998; Xie *et al.*, 2003). Figure 13 illustrates the principles of the diapiric flow mechanism. Fluids, e.g. gas in solution, migrate through a permeable and overpressured formation towards the fault zone. At this fault zone, all other things being equal, the differences in viscosity and density between the hydrocarbon fluid and the formation water may cause the hydrocarbon fluid to move upward in a diapiric manner, perhaps leading to focused pressure build-ups (because of buoyancy) and may initiate or enhance local fracture development. With time, the irregular advance of the fluid front may lead to the formation of local, thin 'diapirs' of lighter fluids that migrate relatively rapidly along the fault zone. Diapirism as a

Fig. 14. Lab experiment in which diapiric fluid flow is initiated by differences in viscosity and density (base fluid: oil; top fluid: honey) (from Philpotts, 1990). The five pictures in this figure show the development in time of oil diapirs within the host medium (honey). Note the onset of one diapir (most left) and the withdrawal of the fluids nearby that seem to stimulate the development of the next diapirs.

mechanism of fluid flow is well known from other (geo-) scientific fields, dealing with systems where fluid flow is predominantly related to differences in viscosity. These include:

1. Meteorology, e.g. thunder clouds and fall-streak clouds.
2. Mining, e.g. in gold, lead and zinc.
3. Magmatic processes and volcanism, e.g. the occurrence of regularly spaced volcanoes in the Andes and along many island arcs, often 70 km apart (Marsh & Carmichael, 1974).
4. Salt movement, developing salt diapirs at regularly spaced intervals (e.g. in west Iran).
5. Laboratory experiments (Fig. 14, Philpotts, 1990).

The mechanism behind diapirism is predominantly related to viscosity and density differences between the diapiric and the overlying fluids or materials. For example, Philpotts (1990) has illustrated this by two-layer laboratory experiments (Fig. 14), in which oil was the basal fluid and was covered by a layer of honey. Note that the onset of one diapir (most left), and the withdrawal of the fluids nearby, stimulates the development of the next diapir. A weak spot in a fault zone, for example small-scale irregularities, can be a first seed point for the onset of diapirism. The occurrence of diapiric features in many other (geo-) scientific fields, like in meteorology and magmatic processes, underlines that it is a heterogenic mechanism and is therefore presented as a plausible mechanism for fluid flow along faults. Further research and fluid flow modelling is required to confirm these observations.

One may have noticed that the pockmarks along the strike of leaking faults are located at a small distance from the faults (Fig. 6). This observation suggests that the upward migrating fluids are being held within the fault by means of pressure differences and sealing quality of the overburden, and the fault is the only relatively open pathway for migration of fluids. At a certain point the depth is reached where the sediments are less cohesive and more permeable. The pressure of the migrating fluids inside the fault is high enough, relative to the rock strength, to break through and migrate vertically to the seabed.

CONCLUSIONS

A method has been presented which is capable of enhancing patterns in the seismic data that are related to fluid migration. The method combines a set of advanced seismic attributes with neural network technology and is able to highlight even very subtle fluid flow features that remain hidden when only single seismic attributes are used.

The results provide new insight into fluid flow behaviour, especially fluid migration along faults. Subtle columnar fluid flow patterns along fault planes are detected that line up with regularly spaced pockmarks on the seabed. It is suggested that the columnar flow zones are related to a diapiric fluid flow mechanism, although further research is required to confirm this hypothesis.

The results also highlight the significance of weak zones along the faults, thereby stressing the importance of focusing fault seal research on finding the weak locations in fault zones. These weak locations, such as fault intersections, appear to be the main migration pathways for fluids.

The fluid migration pathway detection results will enhance how different elements of the petroleum system are connected together, and will thus lead to an improved understanding of the petroleum system in basins. The methodology has proven to be very successful for many different applications that are related to an increased understanding of hydrocarbon migration in basins and for its use in prospect ranking. These include: highlighting zones of possible hydrocarbon expulsion, providing information about charge of prospects, using the results for lateral and top seal investigations of potential reservoirs and in fault seal analysis where they can increase the confidence level of other fault seal analysis techniques.

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