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Fault seal analysis by enhancing fluid flow paths and fault irregularities in seismic data

Summary

For detailed analysis of the sealing quality of faults it is recommended to focus on finding the weak locations in the fault zones. These weak zones in the fault zone are assumed to be the locations of dominant fluid flow along leaking faults. It is expected that faults are not leaking along its entire length, but that fluid flow is mainly concentrated at these weak locations and segments of faults. For example fault intersections, fault bends and step-over zones of faults can form zones with a high concentration of open fractures and/or generate dilation zones that may represent local zones of high fluid flux.

A seismic pattern recognition technique is used to enhance various seismic objects in the data and enables you to enhance small details of fluid flow and fault character that otherwise would have been missed. The detection method is using a set of advanced dip-steered attributes and neural network technology. The results enable you to distinguish between faults and fault segments that are leaking, and which faults and fault segments are sealing. A detailed study of the fluid migration paths on fault planes revealed columnar features that line up with regular spaced pockmarks on the seabed along the fault strike. This observation has led to the interpretation that fluids along the fault planes may migrate by a diapiritic mechanism. The detection method is also able to enhance small-scale fault irregularities and local zones of high fluid flux and is therefore recommended in fault seal studies.

Background

Faults are the dominant fluid migration pathways in many basins worldwide, especially in the deeper subsurface where more consolidated to completely lithified rocks are present. Fault seal analysis has therefore been an important research aspect in the oil and gas industry for many decades. Existing fault seal analysis techniques, such as the shale gouge ratio and Allan diagrams, are useful and are often the only way fault seal quality can be estimated. However, a high degree of uncertainty is involved (Yielding et al., 2003). The question rises if a different type of approach is required for fault seal analysis that can contribute to a higher degree of confidence of fault seal quality estimation.

The workflow that is being presented has proven its value in many basin studies worldwide, including the North Sea, Gulf of Mexico and offshore West-Africa. The method detects fluid migration paths and faults in seismic data. The combination of fault enhancement and fluid migration pathway detection provides information on fault seal quality. In general, highlighting fluid migration paths in seismic data provides better insight in the spatial relationship between the various elements of the petroleum system. This includes the detection of hydrocarbon expulsion at source rocks from seismic data (Ligtenberg & Thomsen, 2003); gas chimney detection and fault leakage (Ligtenberg, 2003-a, 2004); information on charge of prospects and the related entry points; leakage or spillage from reservoirs; understanding the relation with seeps at seabed (Aminzadeh et al., 2004); and more.

In addition, the experience from many studies has led to the insight that fluid migration through faults is most often concentrated to specific locations, i.e. the weak sections of the fault zone. Detailed structural analysis is therefore recommended. Seismic attribute analysis may assist in enhancing these weak locations in fault zones.

Methodology

Fluid migration pathways are enhanced from seismic data by means of a combination of various seismic attributes, neural network technology and interpreter's insight (Heggland et al., 2000; Aminzadeh et al, 2001; Meldahl et al., 2001; Ligtenberg, 2003-b). After detailed analysis of the seismic data, representative example locations are selected that represent vertical hydrocarbon migration paths. These are often vertical noise trails, in combination with other features that confirm the possible involvement of hydrocarbons. Examples of these features include direct hydrocarbon indicators like bright spots, seepage-related objects like mud volcanoes or pockmarks, information about hydrocarbon presence from well data, and so on. In addition, an example set is selected representing areas that are not related to fluid migration. This is a requirement for the neural network to be able to distinguish what is, and what is not a fluid migration path.

At these train locations a whole set of advanced seismic attributes are extracted. This information is subsequently fed to the neural network. The type of neural network used is a so-called supervised neural network (e.g. Wong et al., 1995), it learns by provided examples. The neural network will train itself on the provided examples to be able to distinguish fluid migration paths from the rest of the seismic data. This method, in which seismic attributes are combined with neural networks, highlights details and features that would otherwise have been missed using conventional techniques (Ligtenberg, 2004). The same approach is used to enhance faults in seismic data, but in that case attributes are optimized to detect fault character.

Combining results from fault detection with results from fluid migration pathway detection highlights faults and fault segments that are leaking. The leaking faults have a high fluid migration pathway probability, predicted by the neural network, compared to sealing faults, which have low fluid migration pathway probability. This method is a powerful method to quickly evaluate the sealing quality of faults and increases the confidence level of fault seal quality based on other techniques.

Fault character

Faults are often interpreted as either completely sealing or leaking. It is however more realistic that fluid flow in leaking faults predominantly occur through weak sections of the fault zone. Emphasis should therefore be on detecting the weak locations in the faults. Faults should be dealt with as complex zones, not as a single fault plane. They often consist of multiple fault strands and contain many segments that are linked together via Riedel shears and other small-scale fault structures. Irregularities in fault zones, such as step-overs between the fault segments, fault intersections and bends in fault zones are expected to be weak locations in fault zones and are assumed to be crucial in fluid migration (Ligtenberg, 2004). These locations are often zones with many small-scale open fractures and are prone to high fluid flux.

Structural analysis of fault zones can already provide information on extensional sections of fault zones, for example where faults are stepping or bending. These are locations where extensional structures are expected to form: open zones and prone to high fluid flux. Fault intersections also play a major role in fluid migration. Gartrell *et al.* (2003) have studied fault branch lines in detail and discovered that they are zones of high dilation, in which many open fractures are present and with only minor fault gouge production, and therefore important areas for fluid migration. Seismic attribute analysis can also assist to highlight very subtle variations in fault zones, e.g. by detecting locally more intensely fractured zones within major fault zones or by enhancing minor changes in fault plane orientation that may indicate local weak sections of the fault zone.

Fluid flow behaviour along faults

The described fluid migration pathway detection method is able to enhance very subtle features that otherwise would be missed when using single seismic attributes. A recent study revealed columnar fluid flow patterns along a leaking fault (figure 1). These patterns are not picked up when only single seismic attributes are applied. The detected columnar fluid patterns indicate concentrated fluid flow along fault planes, instead of faults leaking along its entire length. They line up exactly with pockmarks on the seabed, proving that the observed structures are indeed fluid migration paths and not a seismic artifact. The concentrated fluid flow also seems to suggest leakage at weak fault locations: some of these patterns are related to fault intersections, some with bends in the faults and some occur in the central part of a fault zone. The latter may be related to diapiritic fluid flow, which may contribute to the development of weak locations in fault zones.

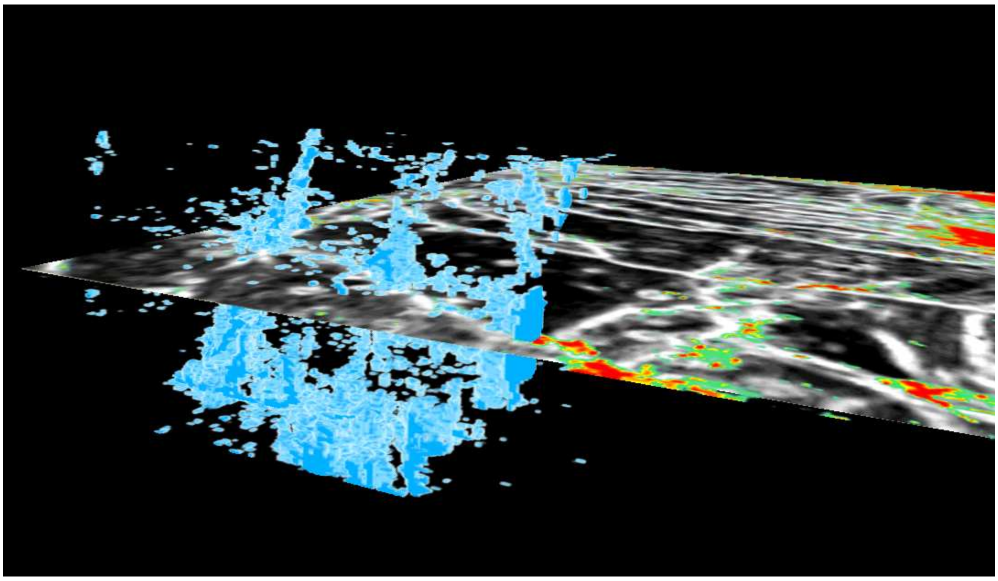

Figure 1. Fluid migration pathway detection results, highlighting columnar fluid flow patterns within a leaking fault and suggesting a diapiritic fluid flow mechanism. The columnar patterns line up with pockmarks on the seabed.

Pockmarks on the seabed along the strike of a leaking fault occur at very regular spaced intervals. The same regular spaced interval you find in the detected columnar fluid flow patterns. It is therefore suggested that fluid flow through these faults may occur by a diapiritic mechanism (figure 2)

(Ligtenberg, 2003-a, 2004). Fluid flow by means of diapirism may also clarify the occurrence of episodic fluid flow along fault planes (Xie et al., 2003).

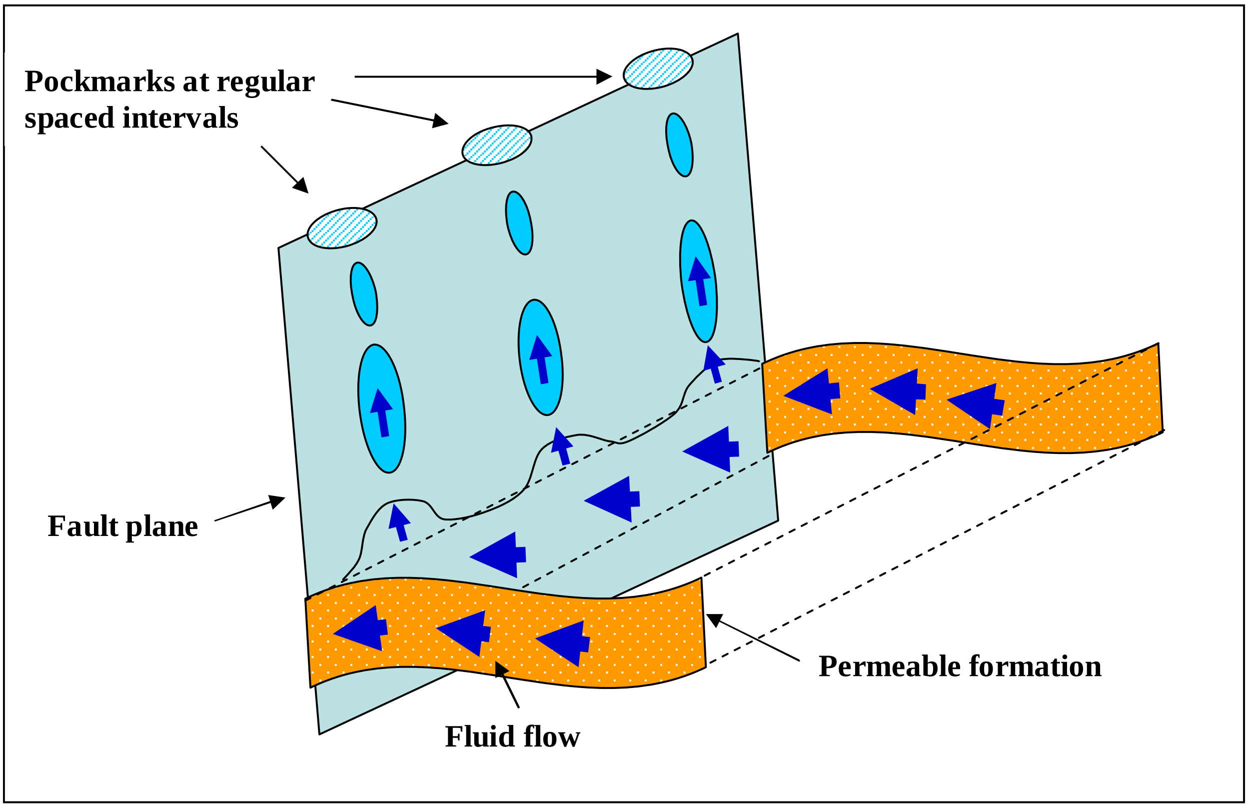

Figure 2. Schematic illustration of diapiritic fluid flow along faults: fluids migrate through a permeable formation towards the fault, at which fluids migrate upwards by means of a diapiritic mechanism. This would explain pulses of fluid flow and occurrence of pockmarks at regular spaced intervals.

Conclusions

The described method is able to enhance fluid flow and fault features that otherwise would be missed when using conventional methods. Observations provide new insight in fluid flow behaviour along faults and require a new approach in fault seal research. Combining fluid migration detection results with structural analysis and fault detection results provides information on the weak locations in fault zones and on the sealing behaviour of faults. Results will therefore provide crucial information for fault seal analysis and may also contribute in increasing the confidence level of fault seal quality determined by other fault seal analysis methods.

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