1. Fault displacement.
2. Water encroachment
3. Wall rock cementation
4. Spalling and borehole enlargement
5. Drilling rate
6. Accumulation of radioactive material

Fault Displacement in Horizontal Wells*:* In horizontal wells fault displacement is detectable by abrupt changes in openhole logs (Figure 3). Such abrupt changes can be observed only when the fault displacement is larger than the thickness of reservoir units and the reservoir units have dissimilar lithology. Since most fracture corridors do not have any displacement and many small faults have displacements smaller reservoir unit thickness, fault displacement has limited use in detection of fracture corridors. Moreover detecting a fault does not guarantee presence of a fracture corridor. Faults have fracture corridors only in brittle and friable layers. Faults through ductile shale or mudstones may not have any associated fractures.

Water Encroachment

One of the fundamental principles which aid fracture corridor identification is the water encroachment pattern. Injection water rises at a much faster rate within fracture corridors than in the matrix (Figure 4). The flood front advances as a wedge into matrix away from fracture corridors causing bottom up sweep. Water advances faster in high permeability layers creating thief zones and water overrides in reservoirs with no fracture corridors.

Horizontal wells through fracture corridors most likely have high water saturation (Sw) with no corresponding change in porosity in the vicinity of fracture corridors if the water level within fracture corridors has reached the well level (Figure 5). The key characteristic of water invasion is a rise in water saturation with no corresponding change in porosity. This guideline is especially useful for horizontal wells in homogeneous reservoir with little change in porosity. High Sw with no change in porosity may also indicate thief zones, highly permeable thin matrix layers. The water invasion in thief zones appears as wide bands in openhole logs in contrast to spiky appearance of fracture corridors. In many cases, the water invaded part of a thief zone is not far from a fracture corridor. Water override within many thief zones is facilitated by fracture corridors. Water rises up rapidly within fracture corridors and overrides into highly permeable layers. Short range water overshooting signifies fracture corridor intersection. In order to determine this it is necessary to construct flattop cross section to establish the relationship between borehole geometry, water saturation from openhole logs and reservoir geological cross section (Figure 6).

Diagenesis and Wall Rock Cementation

Fracture corridors and host rock often undergo diagenetic leaching or cementation several times (Figure7). Cementation of the host rock can be detected as a sharp increase in bulk density or sharp reduction in porosity. The density spike of the walls may have low density high water saturation spike in between corresponding to the conductive central zone of the fracture corridor (Figure 8). Wall rock cementation and water invasion of large conductive fractures cause spiky fluctuations of porosity and water saturation in horizontal wells which intersect large fracture corridors with several large conductive fractures (Figure 9&10). It would be possible without the aid of image logs to actually identify most of the fracture corridor and large conductive fractures from saturation and porosity spikes in this example, especially in combination with lost circulation data.

Spalling and Borehole Enlargement

One of the most common features of boreholes is borehole enlargement across faults and fracture corridors. Borehole enlargement is caused by spalling at the walls of large open fractures and fragmentation. Karstic zones and friable and incoherent rocks may also cause borehole enlargement. However, borehole enlargement is confined to a narrow interval and is very spiky across faults and fracture corridors. Borehole enlargement has degrading effect on density neutron and resistivity logs based on pad devices. Bulk density and porosity and resistivity spikes across borehole cavities therefore suggest possible fault/fracture corridor intersection (Figure 11&12).

High Permeability and Deep Mud Filtrate Invasion

Karstic zones with roof collapse fractures, or fracture corridors with large open fractures which are nearly perpendicular to the horizontal well trajectory may cause a sharp reduction in medium and deep resistivity because of deep invasion. In gas bearing reservoirs this results in an increase in neutron porosity with a conflicting increase in bulk density (Figure 13). Deep invasion through fracture or karstic intervals in gas or oil zones causes the deep resistivity drop to the levels of shallow resistivity indicating extremely high permeability.

In the presence of barite bearing mud, PEF log may indicate fracture corridors and large conductive fractures as a spike caused by infiltration of barite bearing mud (Figure 14). The heavy mud may also show as density spikes across fracture corridors and mega fractures.

Drilling Rate

Drilling rate is controlled by various factors including intense fracturing and fragmentation. In some cases, rate spikes correspond to major fault and fracture corridors (Figure 15), but drill rate is not the best indicator as drill rate is controlled by various other factors such as karstification, leaching, rock strength and ductility.

Gamma Ray Spikes

In some reservoirs, such as the Lower Cretaceous Shuaiba in Oman, fracture corridors and large conductive fractures are associated with gamma ray spikes (Figure16&17). The origin of the gamma ray anomaly is speculative. Organic matter residue, radioactive injection water or clay filling may cause gamma ray anomaly across fracture corridors. Clay filling may occur if fractures are exposed and in karstic areas. Since clay is conductive, it is not possible to differentiate fluid conductive and clay filled fracture corridors from image or openhole logs. It is always advisable and in this case necessary to have flowmeter logs to determine fluid conductivity of fracture corridors. If Gamma ray spikes are caused organic residue on the fracture walls, both cemented and open fractures may have gamma ray spikes, therefore without image logs, flow meter logs are needed to determine fluid conductivity of fracture corridors with Gamma Ray spikes. It is important to note that Gamma Ray spikes are not universal criteria. In many reservoirs, fracture corridors have no Gamma Ray response at all.

Composites

In many horizontal wells, fracture corridors give rise to openhole logs spikes for more than one reason and it is not always possible to differentiate origin of a spike. A few examples are presented here to illustrate fracture corridors and associated ope hole log spikes in different log combinations. Fracture corridors are indicated by bulk density and neutron porosity spikes in Figure 18. These spikes are probably related to borehole enlargement across fracture corridors (Figure 19). The induction log shows sharp decline in resistivity at the fracture corridors suggesting water invasion. Fracture corridors are evidenced by bulk density spikes in Figure 20. The spikes are probably related to borehole enlargement (Figure 21). Gamma ray spikes are also associated with fracture corridors in this well.

Statistical Approach

Fracture corridors are not always detectible by openhole logs, especially in case the openhole logs is already spiky due to reservoir heterogeneity. Figure 22 shows such a case. There is a major fracture corridor near the purple unit, as also indicated by the flowmeter profile. Unfortunately, it is not possible to identify this fracture corridor from openhole logs. The fracture corridor may have spikes but because the logs are already very spiky, it would not be possible to detect the fracture corridors without the help of image or flowmeter logs.

Fracture corridor size is an important factor. Usually large fracture corridors are more likely to cause disruptions in openhole logs. The lowermost fracture corridor in Figure 18 is relatively small and has no openhole log manifestation.

It is often difficult to decide why openhole logs reveal some fracture corridors and do not have any indications of others. Many of the fracture corridors in Figure14 (for example fracture corridors, 3 and 11) have no openhole log expression. If it is not possible to determine why some corridors are not apparent, it may be necessary to run statistical analysis to determine the percent of spikes and overlapping spikes which correspond to fracture corridors from borehole images and openhole logs.

If there are a sufficient number of image logs from horizontal wells with fracture corridors, it is possible to correlate spikes with actual fracture corridors and calculate the correlation coefficient (Figure 23). The correlation can be calculated for different openhole log curves or a multiple regression analysis may be performed to find out how fracture corridors are correlated to a multiple set of curves.

It is also possible to estimate the conditional probability, P, of having a fracture corridor (F) given an openhole log spike (Slog):

P(F/Slog)= number of log spikes corresponding to a fracture corridors/total spikes)

If a suite of openhole log curves are available, one can calculate the probability of having a fracture corridor when at least one or two or three logs have spikes:

P(F/Slog1 or Slog2 or Slog 3..)=number of fracture corridors/number of logs 1 2 or 3 with a corresponding spike)

Once determined the conditional probably values are used to determine the probability of predicting a fracture corridor from openhole logs.

CONCLUSION

Openhole logs in horizontal wells can be extremely useful in detecting fracture corridor and faults especially in combination with lost circulation data. Fracture corridors appear as log spikes, which are caused mainly by wall rock cementation, borehole enlargement and water encroachment. It is necessary to correlate openhole log spikes and lost circulation zones with image logs first because the predictive ability of openhole logs vary considerable form field to field and for different reservoirs. If there are sufficient number of image logs with fracture corridors, the best approach is to calculate the probability of predict a fracture corridor from single or a combination of openhole log spikes.

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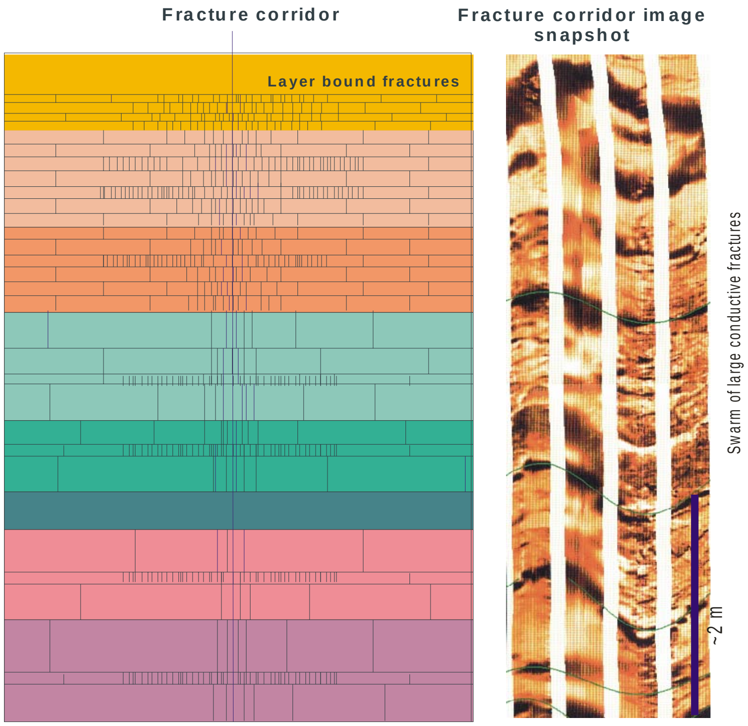

Fig. 1 *Two major fracture types are recognized in many Middle East Fields. These are fault related fracture corridors and layer-bound fractures. Fracture corridors are tabular sub-vertical fracture swarmswhich intersects the entire reservoir and extend laterally for hundreds of meters. Layer bound fractures are pervasive and their fracture spacing is controlled mainly by bed thickness and porosity.*

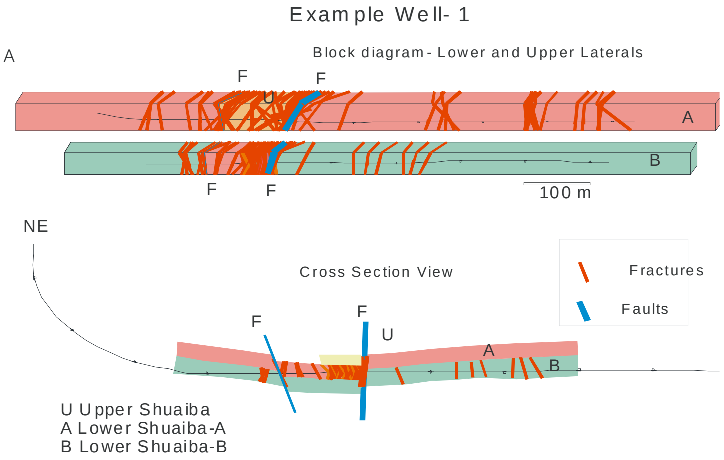

Fig. 2 *Faults are mostly associated with fracture corridors as illustrated by this example well. The degree of fracturing along a fault depends on rock mechanical properties of the host rock. There are however many fracture corridors which do not have any detectable fault displacement. Hence the relationship between faults and fracture corridors is not one to one.*

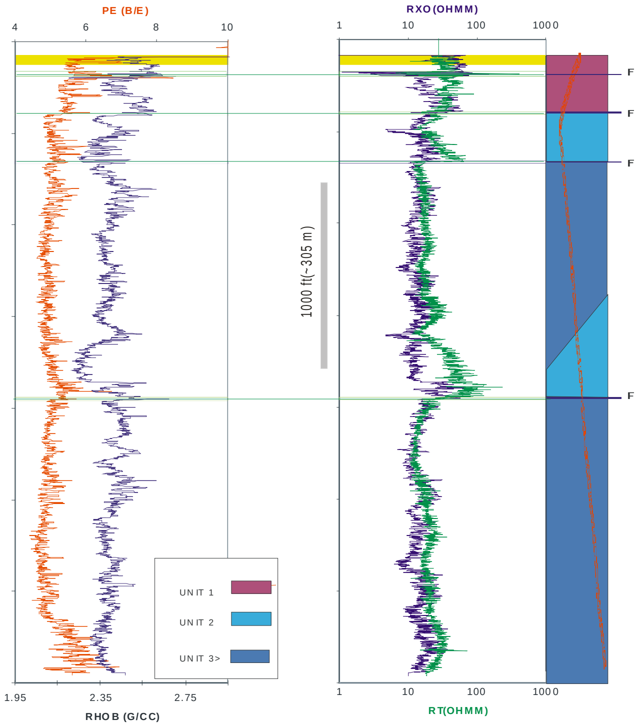

Fig. 3 Faults can be detected by abrupt changes in openhole log responses when the fault displacement is larger than the thickness of displaced units.

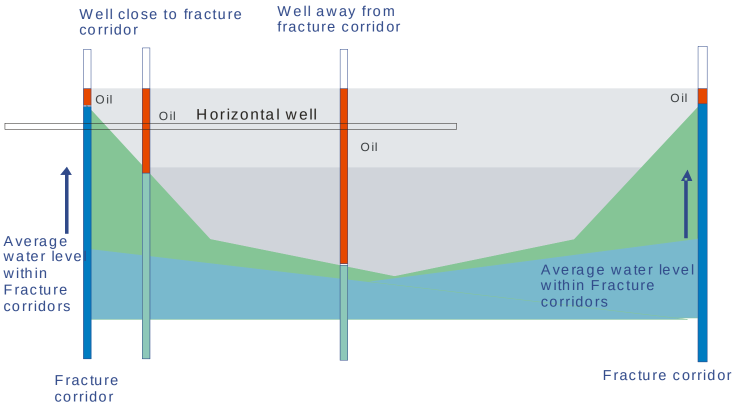

Fig. 4 *Water level rises at a faster rate in fracture corridors than in matrix in reservoirs with fracture corridors and water injection. Flood front moves as a wedge from fracture corridors into the matrix. A horizontal well through fracture corridors has high water saturation with no corresponding*

change in porosity in the vicinity of the fracture corridor, which appears as a water saturation spike in openhole logs.

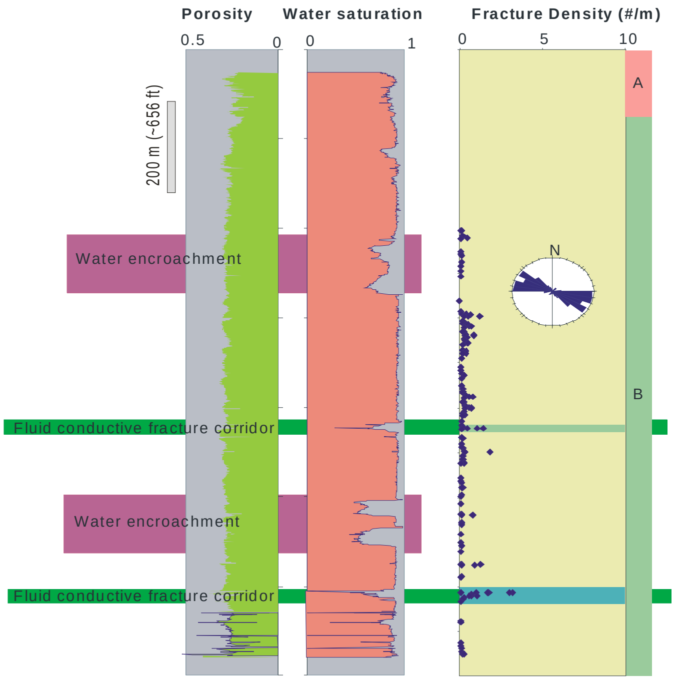

Fig. 5 *Saturation spikes with no corresponding change in porosity are good indicators of fracture corridors. The wide water fingers are interpreted as matrix related, but such water overrides often signify a nearby conductive fracture corridor.*

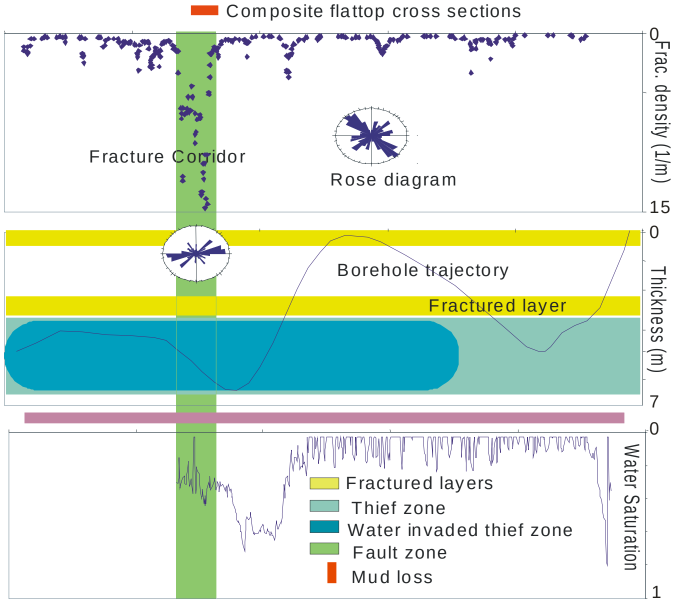

Fig. 6 *Water override within thief zones is facilitated by fracture corridors. Water rises up rapidly within fracture corridors and overrides into highly permeable layers. Short range water overshooting signifies fracture corridor intersection. In order to determine this it is necessary to construct flattop cross section to establish the relationship between borehole geometry, water saturation from openhole logs and reservoir geological cross section.*

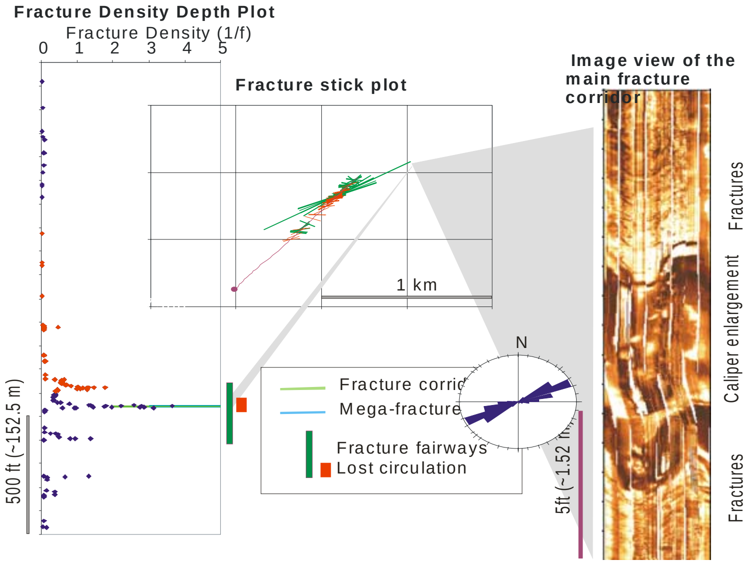

Fig. 7 This is an example of a fracture corridor with wall rock cementation. Fractures at the core are conductive but fractures at the fringes are cement filled. The map view and density depth diagram shows the orientation and distribution of conductive and cemented fractures. The image log shows the conductive core and cemented host rock.

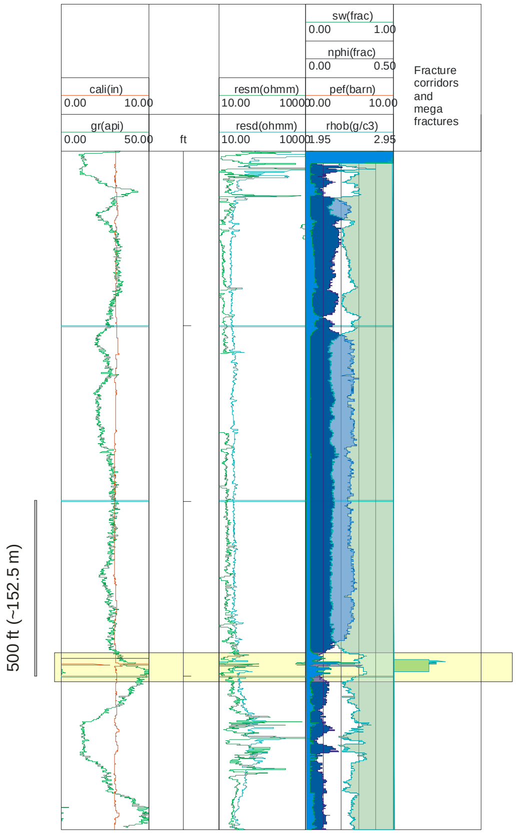

Fig. 8 *The fracture corridor is characterized by dense walls and a low density-high water saturation spike at the core. Logs: cali: Caliper, gr: Gamma Ray, resm: Medium resistivity, resd: Deep resistivity, Sw: Water saturation, rhob: Bulk density, nphi: Neutron density, pef: Photoelectric index.*

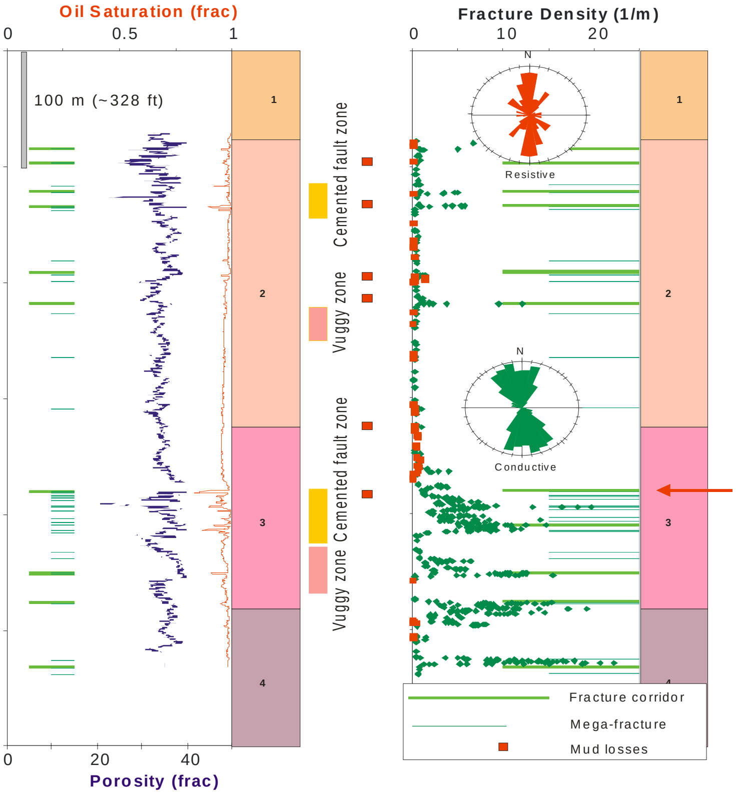

Fig. 9 *Fracture corridors, conductive large fractures and their openhole log response in carbonate units.*

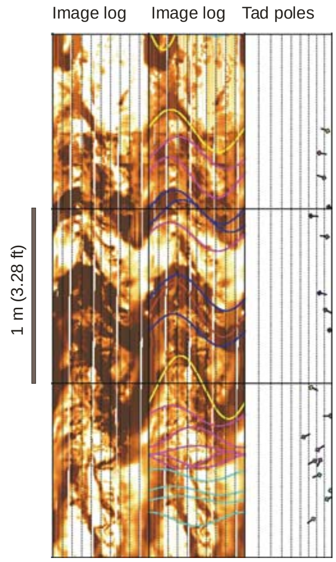

Fig. 10 *Snapshot of fracture corridor indicated by red arrow in the previous figure. Large conductive fractures and cemented wall rock create sharp density and resistivity contrast and create spiky openhole log response across fracture corridors.*

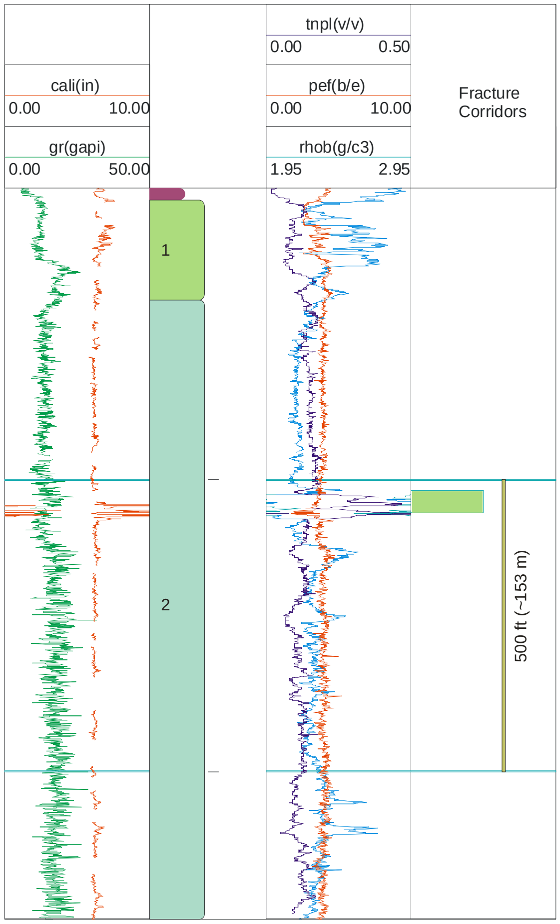

Fig. 11 *The fracture corridor is evidenced by caliper enlargement and consequent density and porosit spikes in this example well.*

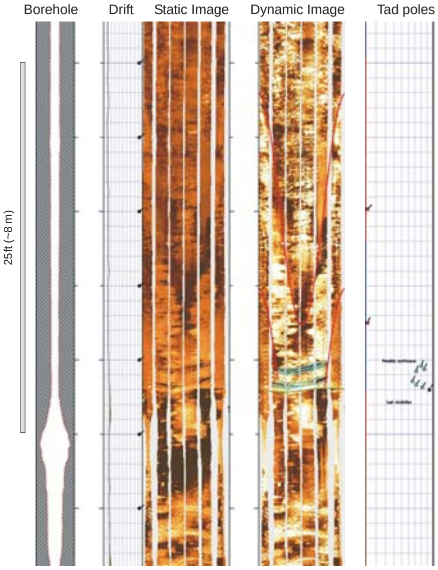

Fig. 12 *Image snapshot of the fracture corridors with density and porosity spikes and borehole enlargement.*

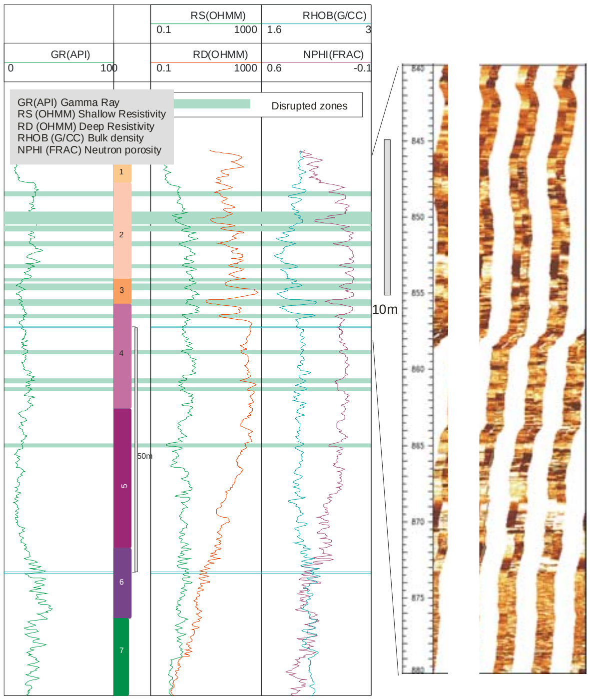

Fig. 13 *This figure shows the karstic disrupted and fractured zones identified from cores and their openhole log and image characteristics.*

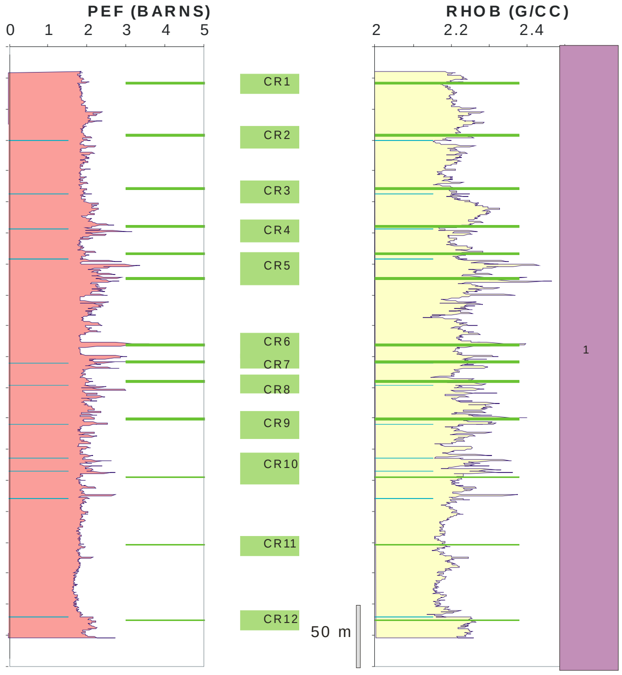

Fig. 14 *Both PEF and bulk density logs have spikes at fracture corridors and some large conductive fractures in a clastic reservoir.*

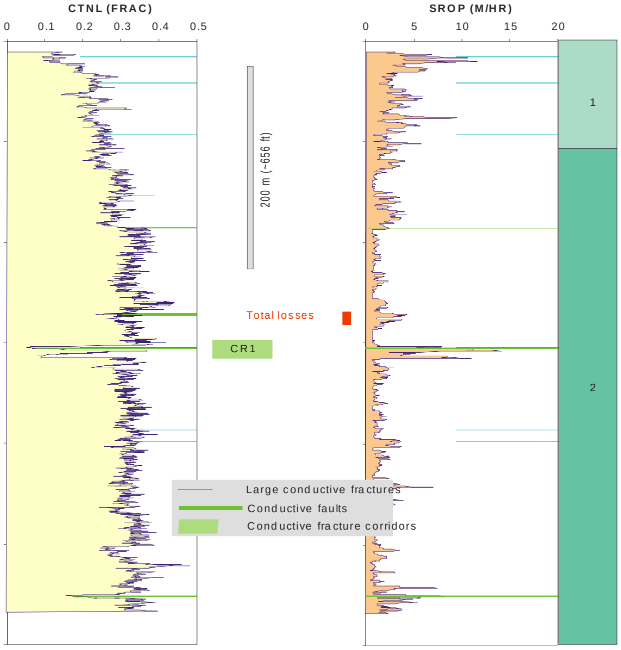

Fig. 15 *Heterogeneous clastic reservoirs make detection of fracture corridors and large fractures very difficult from openhole logs. Some logs are more effective in detection of fracture corridors, such as rate of drilling in this example.*

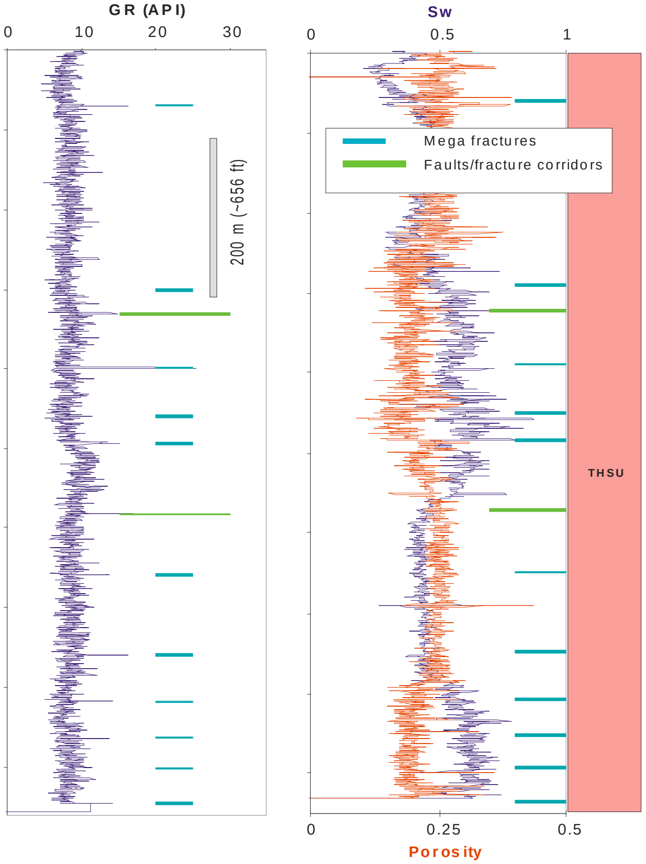

Fig. 16 *Large conductive fractures and fracture corridors have a strong Gamma Ray expression in this well, but porosity and water saturation logs fail to provide conclusive evidence on the fracture fluid conductivity. While a few mega fractures correspond to Sw spikes, many other Sw spikes do not correspond to large fractures or fracture corridors. The porosity spikes are actually borehole cavities caused by drilling activity.*

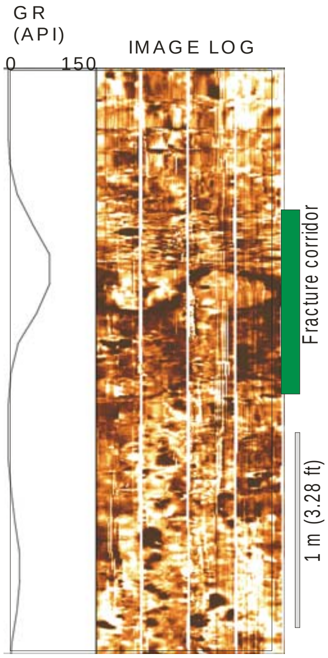

Fig. 17 *An overwhelming majority of the large conductive fractures and fracture corridors are associated with GR anomaly in many Shuaiba reservoirs in Oman. The offset is caused by slight depth shift.*

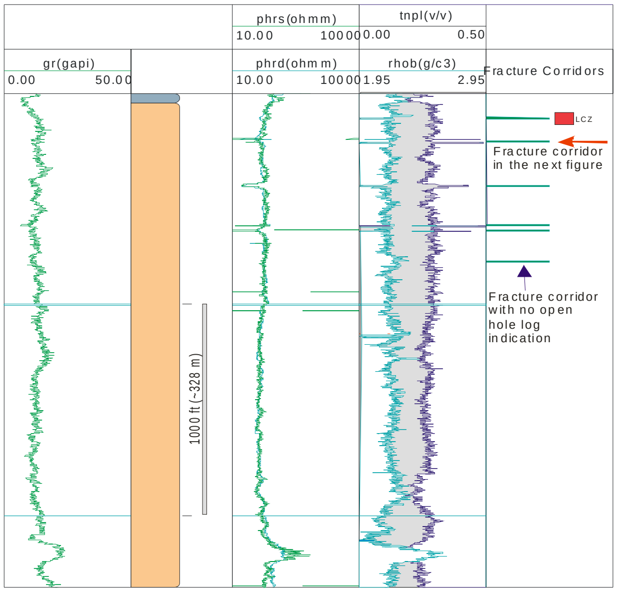

Fig. 18 *In many horizontal wells fracture corridors appear as spikes in different logs for different reasons. In this example, fracture corridors cause density and porosity spikes most probably because of borehole enlargement. Resistivity spikes may be related to water encroachment or mud filtrate invasion.*

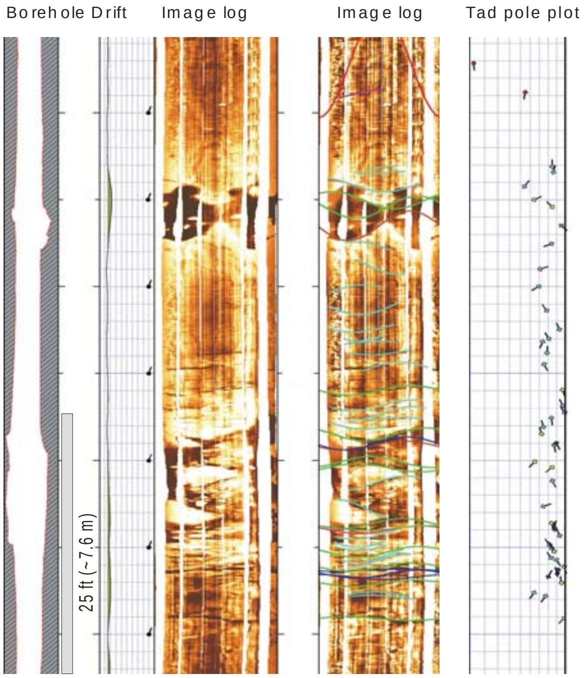

Fig. 19 *This image snapshot shows the fracture corridor indicated by red arrow in Figure 18.*

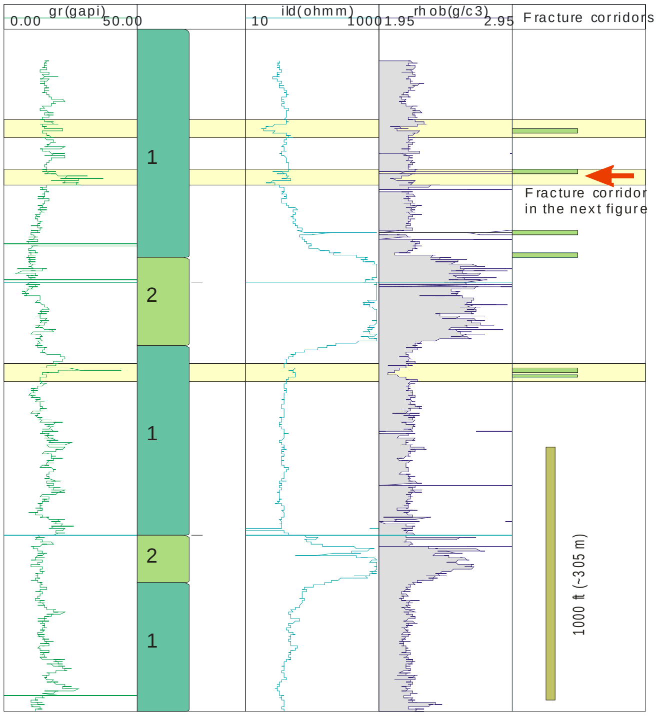

Fig. 20 *In this well, fracture corridors appear as density spikes due to borehole enlargement. Fracture corridors also cause gamma ray spikes. This may be related to organic matter residue or injection of slightly radioactive sea water.*

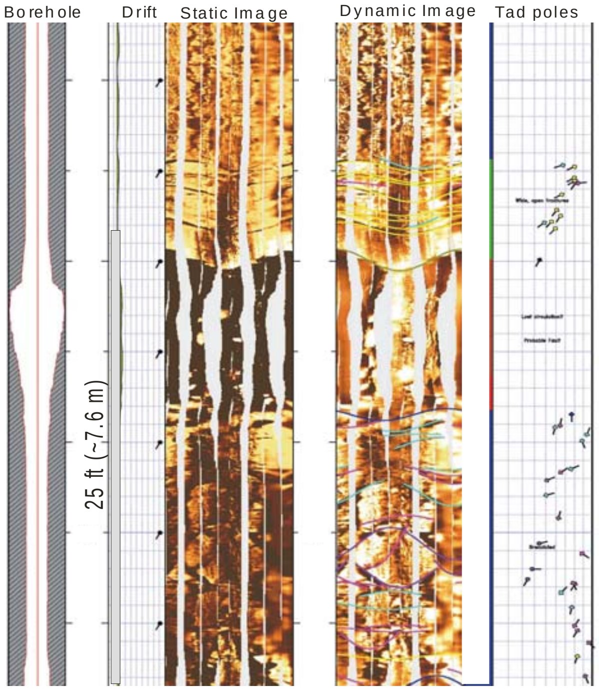

Fig. 21 *This is the image view of one of the fracture corridors in Figure 20 indicated by red arrow.*

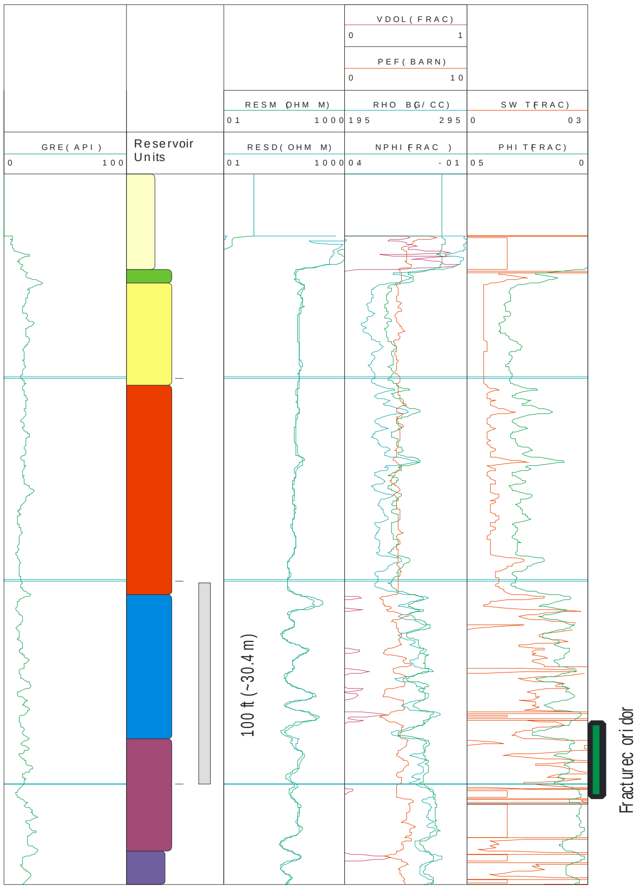

Fig. 22 *Openhole logs are not always helpful in fracture corridor identification. It is particularly difficult to identify spikes that correspond to fracture corridors in heterogenous reservoirs.*

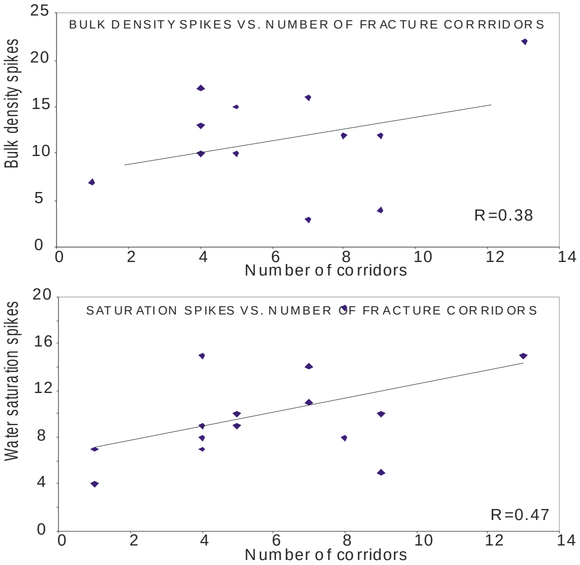

Fig. 23 *Cross plots of spikes and actual corridors acture corridors from spikes of different log types. Water saturation spikes are more effective than bulk density in this example.*

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