Uncertainties associated with fault sealing analysis

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ABSTRACT: Recent advances in understanding how faults restrict fluid flow in sandstone reservoirs have led to improved models for reservoir simulation. Nevertheless, there are still many uncertainty factors that can render even the most detailed simulation model useless. On a detailed scale, these uncertainties include variations in lateral continuity of faults, properties and thickness of fault zones, and the influence of deformation bands within and outside damage zones. Subseismic features such as small-scale relay zones, drag features and frequency and distribution of small faults around the fault zone further decrease the confidence level of simulation modelling results. Detailed analyses of seismic and well data from the Gullfaks Field, Northern North Sea, have helped understand the detailed structural reservoir characteristics. The results from these analyses can, in many cases, be used as input to further enhance models for reservoir simulation in order to increase the validation of the models. Furthermore, the studies carried out on the Gullfaks Field demonstrate that a sound approach to knowledge management for increased oil recovery based on fault seal analysis requires sharing of gained knowledge from many oil and gas fields rather than monopolizing information that cannot be fully utilized by studies from a single field.

KEYWORDS: *Gullfaks Field, fault plane, uncertainty, sealing characteristic, reservoir communication*

INTRODUCTION

The last decade has seen rapid growth in our understanding of how faults affect fluid flow in oil and gas reservoirs (Allan 1989; Bouvier *et al.* 1989; Bentley & Barry 1991; Antonellini & Aydin 1994; Gibson 1994, 1998; Knott *et al.* 1996; Lopez & Smith 1996; Childs *et al.* 1997; Fristad *et al.* 1997; Fulljames *et al.* 1997; Knipe 1997; Lia *et al.* 1997; Yielding *et al.* 1997, 1999; Crawford 1998; Foxford *et al.* 1998; Knai & Knipe 1998; Manzocchi *et al.* 1998, 1999; Ottesen Ellevset *et al.* 1998; Walsh *et al.* 1998*a*, *b*; Fossen & Hesthammer 1998*b*; Hesthammer 1999*b*). These advances have helped to establish sound methods for calculating fault sealing potential as a function of rock properties and fault characteristics (Knipe 1997; Yielding *et al.* 1997; Manzocchi *et al.* 1999).

These methods may, however, fail if the reservoir characteristics are not fully understood. For example, known fault rock properties (Yielding *et al.* 1997; Manzocchi *et al.* 1999) can be combined with fault juxtaposition diagrams (Allan 1989; Knipe 1997) to evaluate the sealing capacity of faults. The input is generally based on displacement estimates from seismic interpretation, known rock properties and the general relationship between fault zone thickness and displacement. The effect of subseismic faults, local drag and width of damage zone (not fault zone; see Fig. 1) is not considered. These factors can drastically change the effects of fluid flow across the barriers and must be considered in a thorough investigation.

This paper focuses on how the already established methods for calculating fault sealing potential and modelling fluid flow can benefit from newly acquired knowledge based on studies of dipmeter data, core data and seismic data from the Gullfaks Field. This includes information on fault frequency and characteristics of drag zones and damage zones. This integrated approach should lead to a fuller and better understanding of how and to what extent fluid flow is restricted by faults.

ESTABLISHED METHOD AND UNCERTAINTIES

Several works have discussed how fault seal potential can be calculated when the lithologic reservoir properties and fault properties are known (Yielding *et al.* 1997; Knipe 1997). As a next logical step in understanding fluid flow, Manzocchi *et al.* (1999) introduced a method for using fault transmissibility multipliers for flow simulation, thereby allowing detailed investigations into the complex topic of reservoir simulation. The procedure is based on the recognition that a fault displaces reservoir units of various quality. In addition, the fault zone itself restricts fluid flow.

The displacement of flow units can be evaluated by creating fault juxtaposition diagrams along the fault (Bentley & Barry 1991; Knipe 1997). As the different stratigraphic units are associated with a variety of permeability, porosity and shale contents, the flow across the fault will vary. As such, permeability profiles can be constructed along the fault.

The permeability of the fault zone in sandstone reservoirs is mainly dependent on the shale content and fault zone thickness. Manzocchi *et al.* (1999) use the Shale Gouge Ratio (SGR) method established by Yielding *et al.* (1997) to determine the shale content of the faulted sequence. This method calculates the proportion of phyllosilicate that is displaced past a particular point on a fault. Since the lowest SGR value will have the

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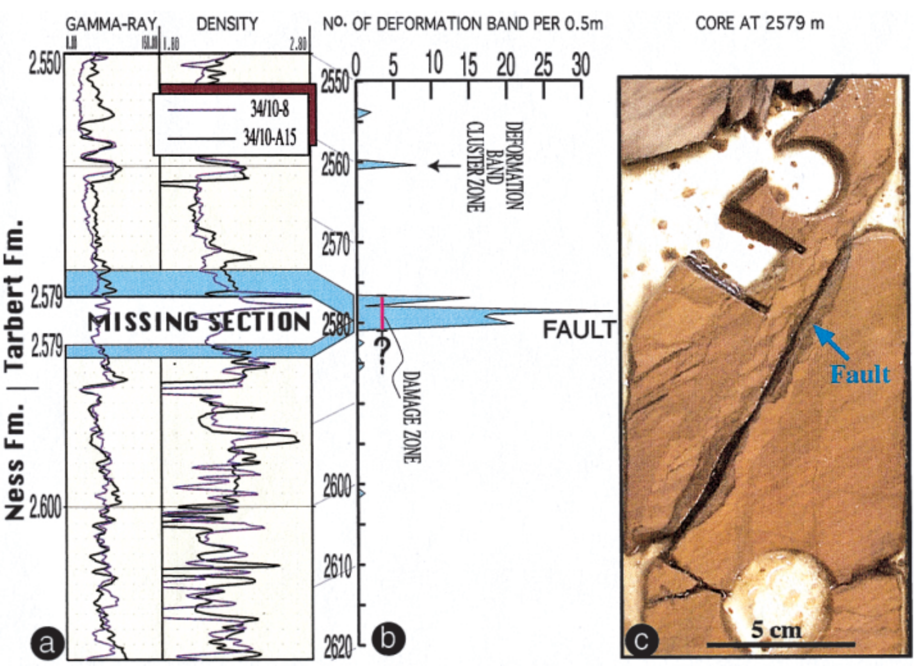

Fig. 1. (**a**) Well log correlation diagram showing the location of a fault associated with 6 m of missing section in well 34/10-A-15. (**b**) Fracture frequency diagram from well 34/10-A-15. A damage zone with abundant deformation bands is associated with the 6 m fault identified from well log correlation data. (**c**) Core photograph from the interval around the 6 m large fault. The thin fault zone is clearly identified, as are abundant deformation bands near the fault zone.

lowest capillary entry pressure, the method can be used to identify which points are likely to leak fluids and which points will represent barriers to fluid flow. Generally, a SGR greater than 15–20% results in a membrane seal (Watts 1987). The fault zone thickness is mainly dependent upon the displacement along the fault (Robertson 1983; Hull 1988; Childs *et al.* 1997; Walsh *et al.* 1998*a*; Manzocchi *et al.* 1999), although some studies also indicate a relationship between fault zone thickness and lithology (Childs *et al.* 1997; Knott *et al.* 1996). As such, a simple relationship between fault zone thickness and displacement may be used as input in modelling studies.

Manzocchi *et al.* (1999) aimed to predict fault zone properties by the use of a simple algorithm. They recognized that the method depends on several assumptions and approximations and clearly state that the model needs calibration against dynamic reservoir data, although considerable uncertainty will always be associated with the fault transmissibility simply due to the natural unpredictability of fault zone structure and shale content. For instance, Foxford *et al.* (1998) concluded from studies of the Moab Fault in Utah that the fault structure cannot be predicted over distances greater than ten metres. Lia *et al.* (1997) considered the fault transmissibility to be the largest factor of uncertainty related to reserves estimated for the Veslefrikk Field (located along the eastern flank of the Viking Graben). Based on the uncertainties related to fault zone properties and thickness, Manzocchi *et al.* (1999) expect at least two orders of magnitude variation in fault permeability at any particular SGR.

The uncertainty factors related to estimates of restrictions on fluid flow across faults can be summarized as follows.

(1) The rapid spatial changes in continuity and geometry along faults are difficult or impossible to predict and will greatly affect the predictions of fluid flow in a faulted reservoir.
(2) Faulted rock can have many different characteristics, such as fault gouge, clay smear, breccia, cement, lenses of undeformed rock and deformation bands. The different types of fault rock determine to a large extent how effectively the fault will restrict fluid flow. Diagenetic processes (for instance related to burial depth) may greatly affect the fault rock properties.
(3) Although a simple general relationship may be established for fault zone thickness estimates, huge variations will exist depending on deformation mechanism and rheology. For instance, the dip of the fault surface, shale content of reservoir rocks and the degree of consolidation at the time of deformation can greatly affect the resulting fault zone thickness.
(4) Shale content within a fault zone is a function of the rheology (‘ductility’) of the shale which is dependent on water content and porosity (a function of overburden) at the time of deformation.
(5) Deformation around faults in sandstones is not only related to the fault zone itself. Abundant deformation bands exist in a damage zone outside the fault zone. Deformation bands can drastically restrict fluid flow and must be considered in reservoir simulation and estimates of fluid flow restriction across faults.
(6) Deformation bands exist sporadically outside damage zones and will affect fluid flow patterns depending on their geometry and how much they reduce permeability. They should, therefore, be incorporated into simulation models.
(7) Relay structures on a subseismic scale can cause pathways for fluid flow across a fault that would otherwise be considered sealing.
(8) Seismic resolution is generally too poor to define whether a seismically interpreted fault is a single structure or consists of numerous smaller faults. This uncertainty may enhance or reduce estimates of fluid flow across fault barriers and can cause large errors in the prediction of fault sealing capacity.
(9) Many faults are associated with drag on a subseismic scale. The effect is somewhat similar to having several small faults rather than one large structure in that fault juxtaposition diagrams based on seismic interpretation will be wrong. However, whereas many small faults will represent several barriers, a drag zone – where the deformation mechanism is by reorganization of individual grains (common in loosely consolidated sandstones) – will only cause a minor decrease in porosity and permeability.

In general, lateral discontinuities (1) will always represent a serious uncertainty for simulation of fluid flow in reservoirs. The uncertainties related to fault rock properties (2), average fault zone thickness (3), shale ‘rheology’ (4) and damage zones (5) can be reduced by examining any available core data (see below). The geometry of isolated deformation bands outside damage zones (6) can only be partially extracted from core data. The lateral geometries (interaction with other deformation bands and length–displacement relationships) can only be resolved by studying outcrop data and will represent large uncertainties depending on how closely the outcrop data match those within the reservoir. A similar uncertainty is related to relay structures (7) as these cannot, in general, be studied using data collected from within the reservoir or from seismic data (although pressure and well history data combined with attribute maps may, in some cases, be helpful; see fig. 5b in Hesthammer & Fossen 1997*a*). Whether a major displacement structure consists of one or more faults (8) can to some extent be resolved by detailed analyses of well log correlation data. Finally, dipmeter data and core data can help understand the abundance and characteristics of drag zones (9).

In the following section, we will discuss how the uncertainties outlined above (with the exception of lateral discontinuities) can be reduced by detailed analyses of outcrop and subsurface data. This includes field analogue data, seismic data and abundant well data (well log correlaton data, dipmeter data and core data). The information has been collected from field studies in Utah and investigations of available data from the Gullfaks Field, Northern North Sea, and presented in more detail elsewhere (Fossen & Hesthammer 1997, 1998*a*, *b*, in press; Hesthammer & Fossen 1997*a*, *b*, 1998; Hesthammer 1999*b*).

REDUCING THE UNCERTAINTY

Fault zone properties, fault zone thickness and shale content

When studying the fault zone characteristics from areas other than the reservoir to be modelled, it is crucial that the deformation mechanisms are comparable. A common mistake is to assume that outcrop data can be directly compared to subsurface oil and gas reservoirs. This is only true if the lithology, deformation mechanism and degree of consolidation are comparable. Not uncommonly, deformation in outcrop analogues occurred after the rocks were consolidated. In addition, the rocks have later been uplifted and subjected to erosion (causing fracturing). In contrast, many of the subsurface reservoirs (e.g. North Sea fields) were deformed during or immediately after deposition when the sediments were only loosely consolidated. Consequently, the fault zones are less affected by cataclasis, the shales were more ductile and the deformation was not necessarily restricted to narrow zones. These differences will drastically affect the fault zone properties (whether a fault zone is brecciated, cemented, anastomosing etc.), fault zone thickness and shale content (more ductile shale leads to more continuous shale smears).

If good estimates of uncertainties related to fault zone properties are to be obtained, the geoscientist needs to incorporate all available core data (and FMS/FMI data if available). However, this is not an easy task since it is very hard to obtain good core data through a fault zone. On the Gullfaks Field, 18 faults have been cored within a total cored interval of 6 km. All of these are identified by several metres of missing section (as identified from well log correlation) and the presence of a damage zone with abundant deformation bands (Fig. 1). However, only for 3 of the 18 faults has the fault zone itself been preserved during the core operations. One of these faults is a cemented breccia. As such, it is not possible from these data alone to obtain reliable estimates of fault zone thickness as a function of displacement. Furthermore, this scarceness of data does not allow for a comparison with onshore field data to evaluate if they are comparable. The Gullfaks Field is one of the most heavily faulted reservoirs in the North Sea and clearly demonstrates the difficulty in understanding uncertainties related to fault zone properties. In order to resolve this problem, it is necessary to compile available data from many more offshore fields that have similar lithologies and deformation history.

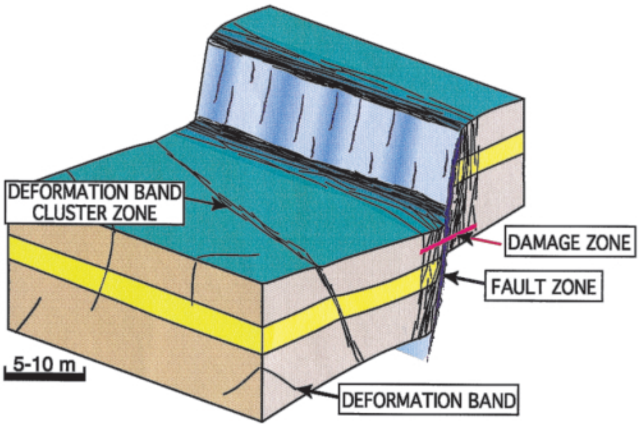

Fig. 2. Principal sketch of fault structure, consisting of a central fault zone of intense deformation, and an enveloping zone of microfaults or deformation bands. Deformation bands may also occur outside the damage zone as single or aggregate structures.

Damage zone and the importance of deformation bands

Studies of faults in sandstones in Utah and the Gullfaks Field demonstrate that abundant deformation bands exist in a narrow zone around the fault (Figs 1 and 2). This zone is generally less than a few tens of metres wide and contains several tens to a few hundred deformation bands (Hesthammer 1999*b*). The deformation bands are different from other faults in that they lack a discrete slip surface (Fossen & Hesthammer 1998*b*). Instead, they are associated with a strain hardening process in which the individual grains eventually crack and become more densely packed, thereby reducing the permeability by up to four orders of magnitude. The exact amount of permeability reduction depends on the amount of cataclasis and phyllosilicate content (Antonellini & Aydin 1994; Statoil 1997). In Utah, the deformation bands are associated with much cataclasis that significantly reduces permeability (typically by three orders of magnitude).

On the Gullfaks Field, only minor cataclasis is present (Hesthammer 1999*b*) and the reduction in permeability is controlled by the phyllosilicate content (Statoil 1997). When the phyllosilicate content increases past 18–20%, or if phyllosilicate layers exceed 20–40% per metre, the deformation structures on the Gullfaks Field are dominated by a phyllosilicate framework which reduces the permeability by 2 or 3 orders of magnitude (Statoil 1997). When the phyllosilicate content exceeds 40%, phyllosilicate smear is the dominant process, and the permeability is reduced to less than 1 μD. Deformation bands in clean sandstones (containing less than a few per cent phyllosilicates) on the Gullfaks Field are characterized by a denser packing of sand grains and have only very limited effect on fluid flow. In comparison, recent studies of deformation bands from

Gullfaks Sør demonstrate that these bands are associated with abundant quartz dissolution which seriously lowers the porosity and permeability within the bands and thus restricts flow across them. The reason for the differences observed between the Gullfaks Field and Gullfaks Sør is related to the different depths at which the reservoir rocks are located. Whereas the Gullfaks Field reservoir rocks are generally located at 1800–2500 m depth, reservoir rocks on Gullfaks Sør are commonly situated below 3000 m depth. At such depths, the temperature exceeds 120°C, thus allowing for accelerated quartz dissolution. Since deformation bands tend to favour localized fluid flow along the bands, such zones will experience more dissolution of quartz grains than the surrounding rocks. Obviously, the failure to incorporate deformation bands and their physical properties into fault sealing analysis studies would not reveal any differences between fluid flow across faults on the Gullfaks Field and Gullfaks Sør, an error that has already resulted in serious complications associated with production from the Statfjord Formation on Gullfaks Sør.

The width of the deformation bands on the Gullfaks Field is a function of deformation band type, grain size and mineralogy (Fig. 3). Thus by knowing the phyllosilicate and quartz content of the reservoir rocks (obtained from well logs) as well as the grain size (obtained from core data), the amount of permeability reduction and width of deformation bands can be found. This can be combined with information on the number of deformation bands associated with a fault to provide a sound statistical input for reservoir simulation. Deformation bands tend to form prior to the development of a discrete slip surface (Antonellini & Aydin 1994; Fossen & Hesthammer 1997, 1998*b*). As such, there is no clear relationship between the width of the damage zone and the displacement across the fault zone as observed on the Gullfaks Field (Fig. 4) (there may be some indications that faults with missing sections larger than 15 m are associated with a wider damage zone; possibly related to the more complex geometries of larger faults). Studies from the Gullfaks Field show that the average width of a single deformation band is 1.4 mm (Hesthammer 1999*b*). Assuming that all faults identified by well log correlation represent a single slip surface, the average width of a damage zone is somewhat more than 24 m and the average number of deformation bands within a damage zone is slightly higher than 179 (Table 1). Although this type of statistic can be used for general simulaton purposes on the Gullfaks Field (the numbers may be field-specific), they should not be applied to single cases as the individual variations are large (Table 1).

Core studies from the Gullfaks Field demonstrate that approximately 70% of the deformation bands occur within damage zones where the bands are interconnected in complex networking zones (Hesthammer 1999*b*). The remaining 30%, located outside damage zones, commonly occur as single deformation bands or linked by soft-link or hard-link structures to only a few other bands (Fossen & Hesthammer 1998*b*). Since a single deformation band can be associated with a permeability reduction of as much as four orders of magnitude and thereby significantly reduce fluid flow, the geometry of these bands is important to understand. Furthermore, studies from Utah (Fossen & Hesthammer 1997, 1998*b*) show that deformation bands in consolidated sandstones have a displacement–length relationship that is different from faults with discrete slip surfaces (Fig. 5). The deformation bands are much longer than faults with discrete slip surfaces for the same displacement. Although this relationship is clear from studies in Utah, it is unclear whether the same relationship applies to deformation bands on the Gullfaks Field (which developed in poorly consolidated sandstones). In fact, recent studies from Morocco (Wibberley *et al.* 1999) may indicate that deformation bands in loose sand behave like ordinary faults (Fig. 5). Until more data are available, it is not possible to use this information to accurately simulate the effect a single deformation band has on fluid flow. Some general statistics can be implemented by considering the percentage of deformation bands located outside damage zones. In addition, studies of fracture frequency diagrams from the Gullfaks Field show that deformation bands

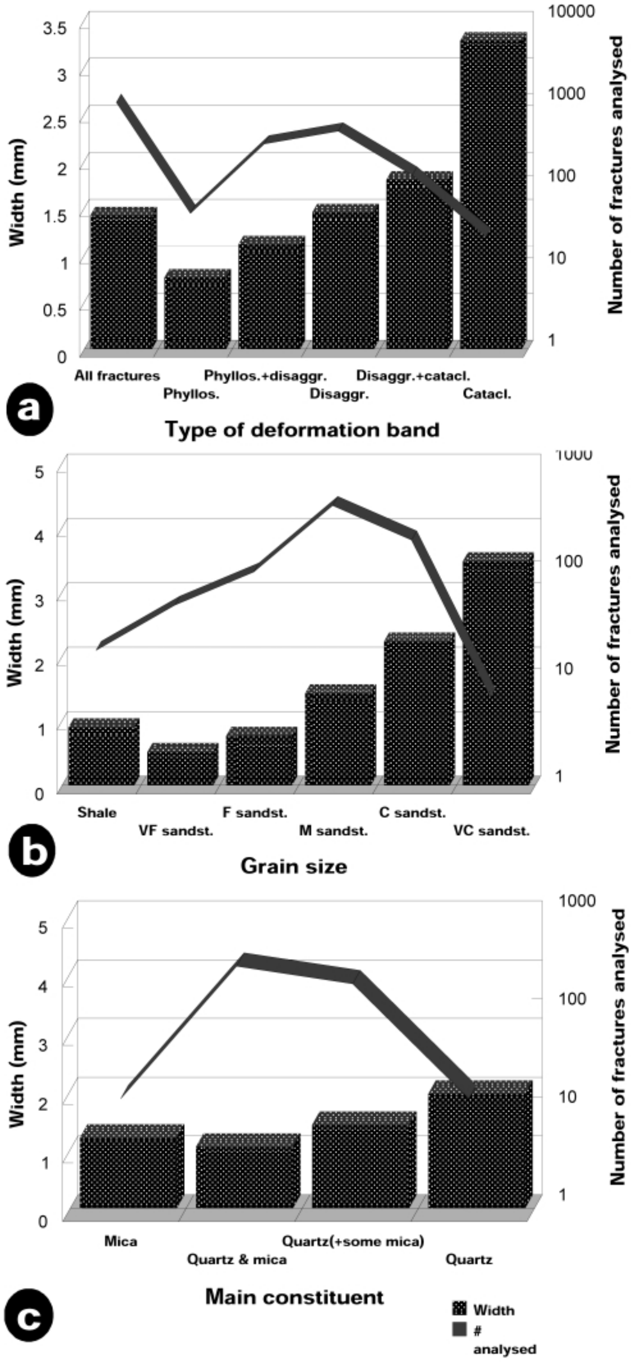

Fig. 3. (**a**) Width of deformation bands versus type. Deformation bands associated with cataclasis are wider than those that are only affected by disaggregation structures. (**b**) A plot of grain size versus width of deformation bands show that the width increases with increasing grain size. (**c**) Plot of the width of deformation bands with respect to the main constituent. Quartz-rich clean sandstones are generally associated with wider deformation bands than sandstones rich in phyllosilicates.

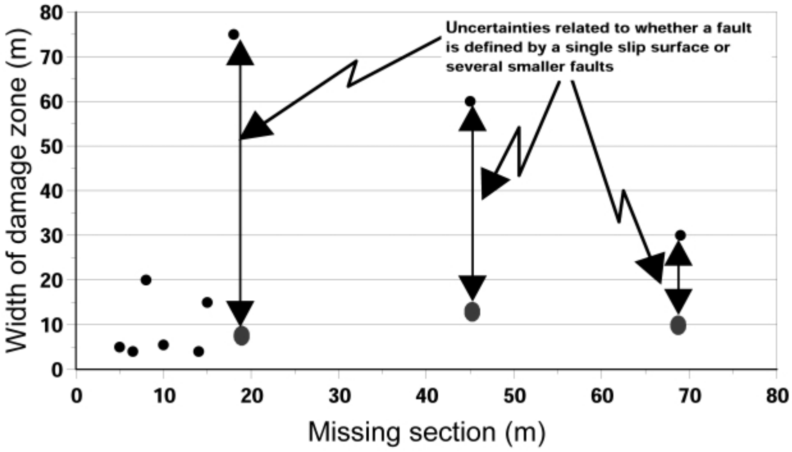

Fig. 4. Plot of missing section (as identified from detailed well log correlation) associated with faults versus the width of the damage zone. There is no clear relationship to suggest that the width of damage zones increases systematically with increasing offset. However, there are large uncertainties related to the larger-scale faults, and it is possible that faults with more than approximately 15 m of missing section have wider damage zones than smaller faults. This may be due to the more complex geometry of larger-scale faults.

located outside damage zones occur as 1–5 bands within a narrow zone of less than 0.5 m width.

Subseismic structures

Studies of outcrop data demonstrate that faults commonly exhibit relay structures (Cartwright *et al.* 1995) rather than single continuous surfaces. The relay structure may be soft-linked, in which the faults affect each other without physically touching, or hard-linked, in which the faults are connected across the relay zone. Both types of structure will typically improve rather than restrict communication. A soft-linked relay structure provides a communication path for fluids across an otherwise

Table 1. *(**a**) General statistics for deformation bands. See main text for discussion. (**b**) Information related to damage zones associated with larger-scale faults that have developed discrete slip surfaces*

(**a**)

Formation	Deformation bands total (number)	Width (average) (mm)	Displacement (average) (mm)
All	4824	1.42	8.61
Heather	151	NA	NA
Tarbert	669	1.65	11.18
Ness	970	1.02	9.24
Etive	201	2.21	5.00
Rannoch	1624	1.05	5.43
Drake	46	2.51	NA
Cook	299	1.02	14.11
Amundsen	54	NA	NA
Statfjord	679	1.69	8.35
Lunde	131	2.13	13.50

(**b**)

Well	Damage zone From (mMD)	Damage zone To (mMD)	DZ width (m)	Deformation bands in DZ	Missing section (m)
34/10-5	1912	>1933	>21	>63	15
34/10-A5H	1848	1853	5	4	6.5
34/10-A5H	1885	1892	7	106	?
34/10-A8	2121	2127	6	238	5
34/10-A14	2281	2286	5	23	10
34/10-A15	2577	2581	4	109	11
34/10-A16	2425	2457	32	236	20
34/10-B1	2223	>2285	>62	>789	45
34/10-B12	2883	2913	30	210	69
34/10-C1	2083	2086	3	84	14
34/10-C3	2363	2442	79	188	18
34/10-C5	<3115	3159	>44	>272	?
34/10-C14	3650	3673	23	25	8
34/10-C14	<3543	3563	>20	>155	?
Sum	—	—	>341	>2502	221.5

DZ, damage zone.

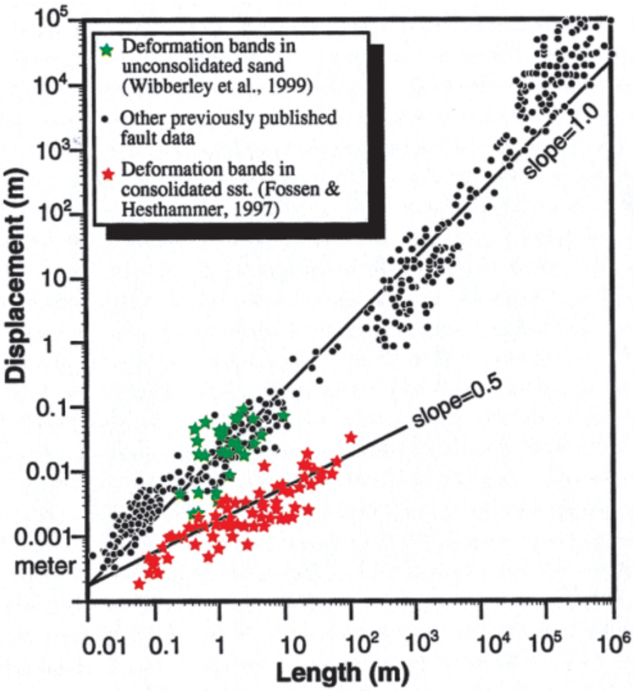

Fig. 5. Displacement–length diagram for faults and deformation bands. The plot shows that deformation bands in consolidated sandstones from Utah (Fossen & Hesthammer 1997) are longer than faults with discrete slip surfaces, whereas deformation bands in unconsolidated sandstones from Morocco (Wibberley *et al.* 1999) display the same slope as faults with discrete slip surfaces. The sources for other previously published fault data are cited in Schlische *et al.* (1996).

sealing structure, whereas a hard-linked structure increases the likelihood of preserving a sand-to-sand contact across the fault (due to a smaller offset associated with each fault). A typical problem with seismic interpretation of oil and gas fields is that the relay structures are below seismic resolution and therefore remain undetected by the seismic interpreter. On the Gullfaks Field, limits in seismic resolution do not in general allow definition of faults located less than a few hundred metres apart (Hesthammer & Henden in press). Thus, unless the fault strands within a relay structure are placed sufficiently far apart, the faults will likely be interpreted as a single, continuous surface. However, the presence of 'kinks' and sudden changes in fault strike may often indicate the location of a relay structure and should be considered when studying fault seal potential for a specific area. For full field reservoir simulation, the uncertainty related to the presence of relay structures will always exist and will drastically reduce the reliability of the analyses.

A related problem is the ability to distinguish whether a fault zone consists of more than one fault surface. Commonly on the Gullfaks Field, faults interpreted as a single structure from seismic data are shown to consist of several smaller faults based on detailed well log correlation. Although this will always remain an uncertainty in areas not penetrated by wells, statistical analyses can be used for general simulation purposes. A study of 280 faults identified from detailed well log correlation on the Gullfaks Field demonstrates that 119 (42%) of the faults occur within intervals less than 100 m wide (along the wellbore path). These faults are located too close to each other to be identified from seismic interpretation. As many as 194 (69%) of the faults are located less than 300 m apart (along the wellbore path). Assuming a lateral resolution of less than 300 m, it can be inferred from this study that more than 69% of the faults identified from seismic interpretation on the Gullfaks Field will consist of more than a single fault surface (the true number is likely to be somewhat higher since not all faults in a fault zone are likely to be penetrated by a single well). Unless this is accounted for, fault seal analyses based on seismic interpretation alone will be erroneous in most cases.

Figure 6a shows that faults on the Gullfaks Field are more abundant at shallower reservoir levels (Tarbert, Ness and Rannoch formations). In addition, Fig. 6b shows that the displacement increases with depth. There is no clear relationship between numbers of faults and lithology (Drake, Amundsen and parts of Ness formations consist mainly of shale whereas the other formations contain mainly sandstone). This important information can be used to model the effect of fault sealing capacity with respect to formation and depth. However, drilling of more than 180 wells on the Gullfaks Field clearly demonstrates that the local variations are great. Whereas a main fault can be proved to consist of a single fault surface by the drilling of one well, drilling of another well through the same fault a few hundred metres away may reveal that the fault consists of 3–5 smaller faults.

The effect of drag of bedding towards a fault will also drastically influence fluid flow paths across a fault structure (Fig. 7). A study of 23 km of dipmeter data from the Gullfaks Field demonstrates that as much as 60% of all faults on the field are associated with drag of bedding on a scale that is below seismic resolution (Hesthammer & Fossen, 1998). Furthermore, the difference in missing section as identified from well log correlation and the total offset outside the zone affected by drag can be as much as one order of magnitude (Fig. 8). Obviously, this important information must be considered when modelling fluid flow in a reservoir. The individual variations are too large to allow a systematic use of these data (at least based on present analyses). The sensitivity to the uncertainties can be estimated by the use of Allan diagrams (Allan 1989; Knipe 1997).

Further important information from analysis of dipmeter data is that drag is only associated with north–south trending faults on the Gullfaks Field (Fig. 9a). There is no clear relationship between displacement and the width of the drag zone (Fig. 9b). This may be explained by drag being developed prior to the establishment of a distinct fault slip surface (Hesthammer & Fossen 1998). Once a distinct slip surface has developed, further deformation will occur along this weak zone, and the drag zone becomes fossilized. The average width of the detected drag zones is 60 m in the hanging wall and 29 m in the footwall (measured along the wellbore path). There is no clear relationship between the width of the drag zone and lithology or depth, probably because the sandstones were only loosely consolidated when deformation occurred in the late Jurassic (Hesthammer & Fossen 1998). Faults at deeper stratigraphic levels are less affected by drag than faults at shallower reservoir levels (Fig. 10). This is probably because deeper stratigraphic levels were somewhat more consolidated at the time of deformation. Although the results from analyses of dipmeter data are not always conclusive, it should be possible to enhance existing models for fluid flow simulations by incorporating the general information obtained from the many detailed analyses carried out on the Gullfaks Field.

Several studies have focused on the abundance of faults in sandstone reservoirs close to or below the limits of seismic resolution (Jones & Knipe 1996; Hesthammer & Fossen 1997*a*, *b*; Hesthammer 1998, 1999*a*). In general, the fault population in the Gullfaks Field follows a power-law distribution down to approximately 5–10 m displacement (Fossen & Rørnes 1996). Furthermore, there appears to be a gap in fault

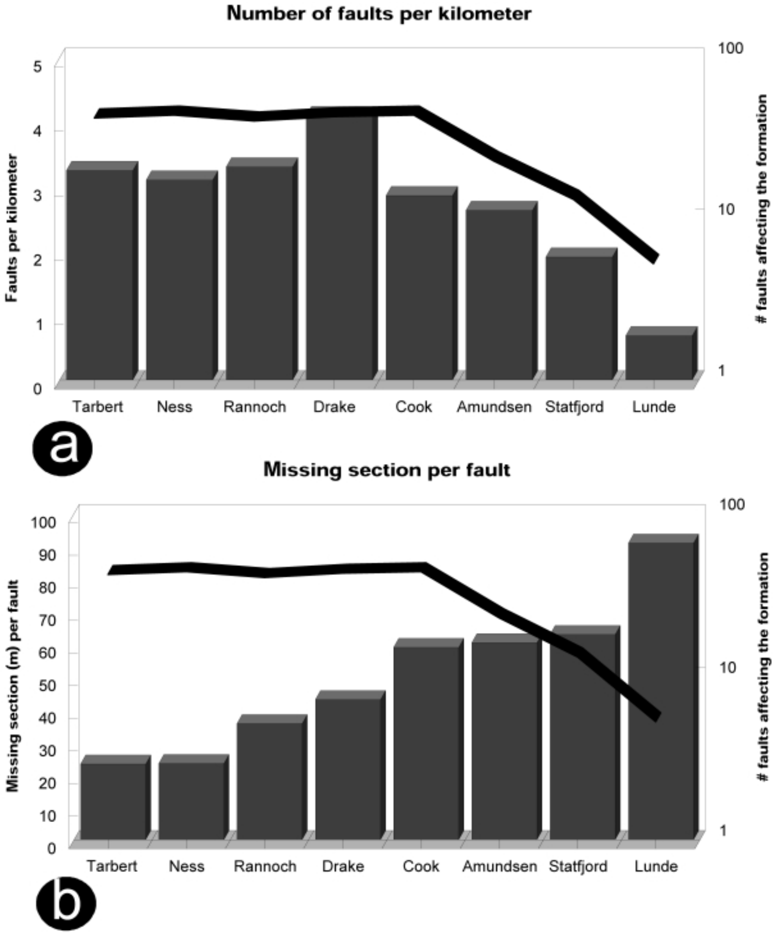

Fig. 6. (**a**) Faults at shallower reservoir levels (Brent Group) are more abundant than at deeper stratigraphic levels.
(**b**) The offset associated with faults increases with depth. See main text for discussion.

frequency between 10 cm and 5–10 m (Fossen & Hesthammer in press). Based on seismic data alone, it is easy to overinterpret the presence and locations of small-scale faults (Hesthammer 1999*a*). Thus, extreme caution is advised if seismic interpretation alone is to provide the input to models of reservoir performance. Failing to do so can cause serious misinterpretations which may, in the worst case, lead to an erroneous plan for field development.

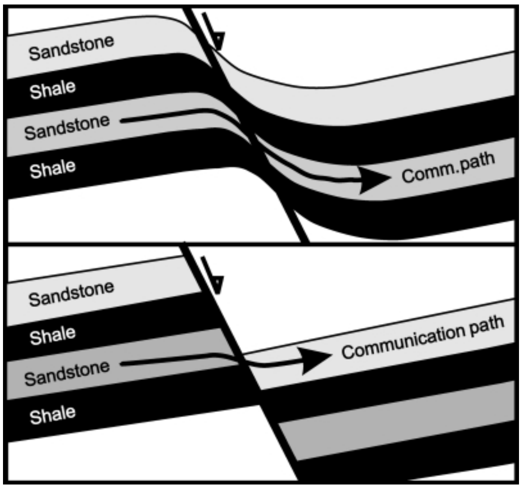

Fig. 7. Due to the effect of local drag on a subseismic scale, the real communication path may be very different to that estimated from the use of fault juxtaposition diagrams. This must be considered when evaluating fault seal potential.

DISCUSSION AND CONCLUSIONS

Several advances in understanding fluid flow across faults have led to large improvements in models for reservoir simulations. There are, however, many important factors governing fault sealing potential that are not incorporated into the existing models. The above analyses demonstrate how the existing models for estimating fault seal potential and understanding fluid flow in sandstone reservoirs can benefit from detailed analyses of seismic and well data from oil and gas fields.

The use of core data can help reduce uncertainties related to estimation of fault zone thickness and properties. Similarly, core analysis helps understand the effect of deformation bands on reservoir simulation, although the effect of lateral variations cannot be revealed by analyses of core data alone. Dipmeter data help identify the presence and characteristics of drag zones, whereas well log correlation can reveal if the fault structure consists of one large- or several smaller-scale faults. By combining seismic data, well log correlation data, dipmeter data and core data, detailed information can be obtained about structural reservoir characteristics. This information can then be used to enhance the models for simulating fluid flow in reservoirs.

Although many of the results from the Gullfaks Field can be used for general evaluation of reservoir behaviour, extreme caution must be used when applying the data to individual case studies (such as evaluation of fault seal potential across a single fault for input to decisions on whether to drill a well or not). In order to evaluate the generality of the results, it is necessary to quality control the established models against dynamic data

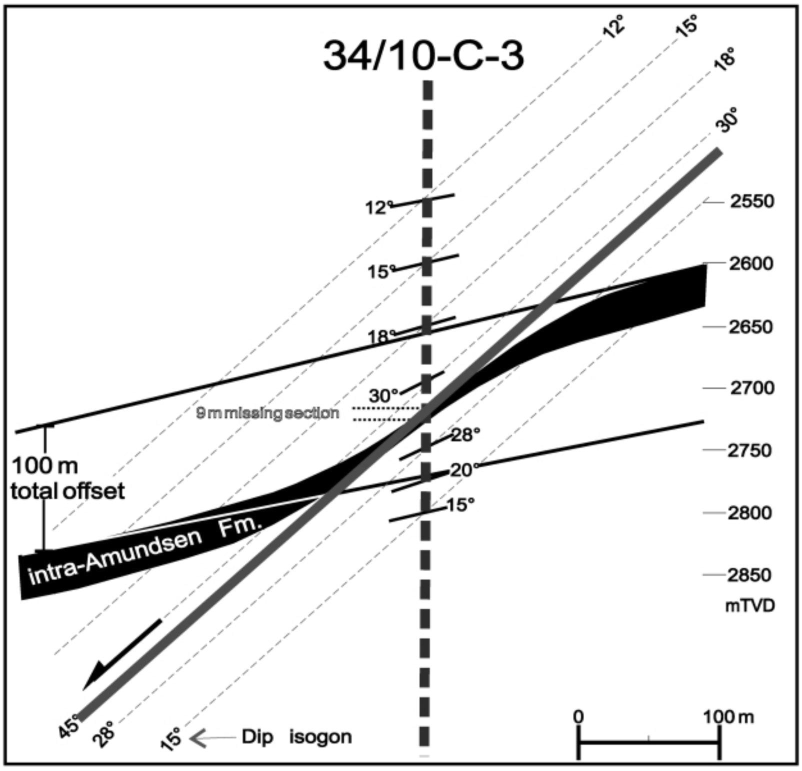

Fig. 8. Studies of dipmeter data from the Gullfaks Field show that the difference between total offset (i.e. the offset outside the zone affected by drag) and missing section can be drastically different, as shown for a fault identified in well 34/10-C-3. See main text for detailed discussion.

obtained from wells. On the Gullfaks Field, where data from more than 115 km of drilled reservoir from 180 wells exist, such quality control is possible, but the large amount of data and high structural complexity require much future work to fully utilize all the available information.

Many of the analyses carried out on the Gullfaks Field are still associated with large uncertainties. The results from the analyses may not be applicable to other fields. In order to further enhance our understanding of reservoir properties, it is necessary to compile data from other fields in a manner similar to that carried out on the Gullfaks Field. This demands an approach to knowledge management where oil companies are willing to share information in order to optimize oil recovery. Competition, as such, should not be associated with

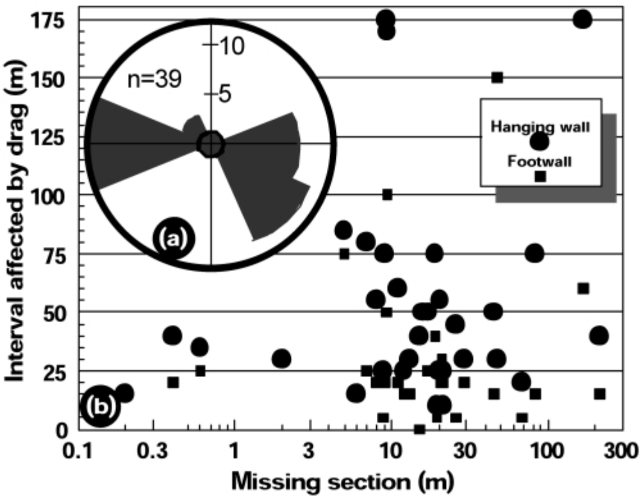

Fig. 9. (**a**) Orientation analysis shows that mainly north–south trending faults on the Gullfaks Field are associated with drag. (**b**) There is no clear relationship between missing section associated with a fault and the interval affected by drag. This is probably because drag mainly developed prior to the development of a distinct slip surface (see main text). However, the drag zone is generally wider in the hanging wall than in the footwall.

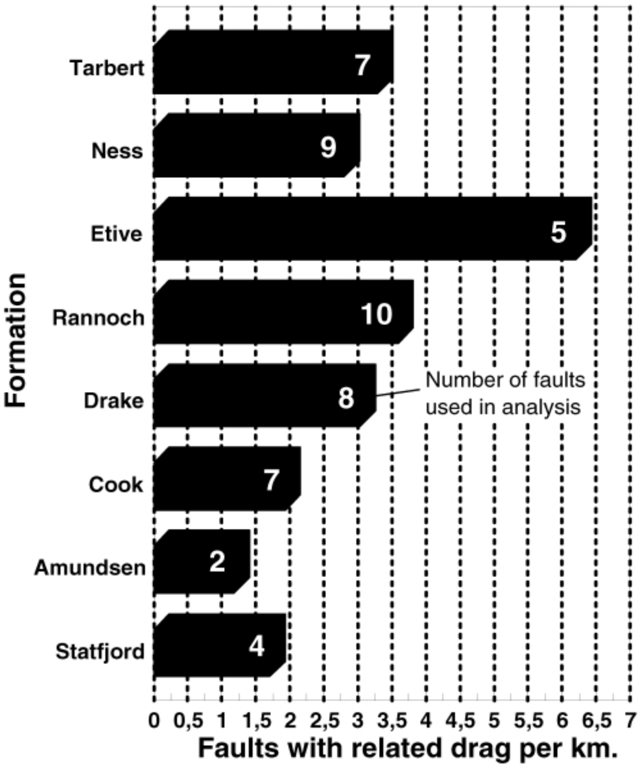

Fig. 10. A plot of formation versus number of faults associated with drag per kilometre shows that faults at shallower stratigraphic levels (Brent Group) are more often associated with drag than faults at deeper stratigraphic levels. This is probably because the deeper strata was more consolidated at the time of deformation.

monopolization of routine data (seismic, core and standard well log data) but rather how that shared information is utilized.

The authors would like to thank Statoil, Norsk Hydro and Saga Petroleum for permission to publish the article. The manuscript has benefitted from comments by Graham Yielding and an anonymous reviewer.

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Received 30 April 1999; revised typescript accepted 27 September 1999.