Fault interaction in porous sandstone and implications for reservoir management; examples from southern Utah

Haakon Fossen, Tord Erlend Skeie Johansen, Jonny Hesthammer, and Atle Rotevatn

ABSTRACT

Different types of fault interaction are examined and compared to a single fault situation with respect to density, distribution, and orientation of subseismic structures. Fault branch points are found to be considerably more complex than single faults. The damage zone in these areas shows a wider range in orientation of deformation bands and fractures, and the damaged volume extends far into the fault blocks. Overlapping structures develop wide damage zones at early stages, typically with structures that are oblique to the faults and, thus, represent potential flow barriers. The damage associated with relay structures is inherited by later stages, when the fault segments are coalesced and behave as a single fault. At advanced stages, the damage zones are uncommonly wide in breached relay locations. Such locations can be recognized as places where faults make abrupt steps or bends.

The extent to which complications associated with both single-tip and double-tip interactions affect reservoir performance depends on the nature of the minor structures in the damage zone. It is thus crucial that the physical nature of minor structures is investigated so that their influence on reservoir performance can be evaluated.

INTRODUCTION

During oil- and gas-field operation, and particularly during the last part of the field production history, it becomes increasingly necessary to understand the communication within small parts of

Manuscript received February 28, 2005; provisional acceptance June 8, 2005; revised manuscript received June 20, 2005; final acceptance July 29, 2005.
DOI:10.1306/07290505041

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ACKNOWLEDGEMENTS

We thank Dave Pivnik and Sandro Serra for their reviews and editor Ernest A. Mancini for useful editorial comments.

the field, including reservoir volumes near fault branch points. Subseismic faults, fractures, and deformation bands associated with larger faults represent potential barriers for fluid flow (e.g., Knipe, 1992; Manzocchi et al., 1999). Such structures occur within a narrow zone along the fault, known as the fault damage zone. Structural maps from faulted sandstone petroleum reservoirs almost invariably show faults of different orientations that branch, bifurcate, or link (e.g., Peacock and Sanderson, 1991; Anders and Schlische, 1994; Needham et al., 1996; Dawers and Underhill, 2000; Childs et al., 2003). Hence, understanding of the distribution and nature of subseismic structures in relation to seismically mappable fault constellations may be very useful, for instance, when considering placing a producer or injector near a fault branch point.

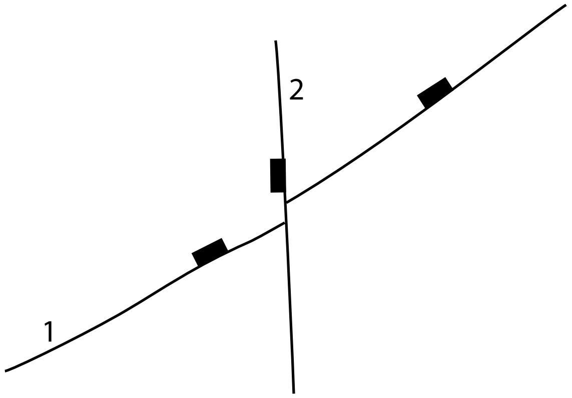
In this article, we will examine outcrop examples of the complications that can be expected in locations of fault interaction in porous sandstones. Localities from faulted porous sandstones on the Colorado Plateau are studied, and the examples will be compared with a simple single fault situation. Reference is given to similar structures mapped in North Sea oil fields. The aim of this contribution is to predict a qualitative relationship between subseismic deformation and fault interaction pattern as mapped from seismic data.

FAULTING IN SANDSTONE

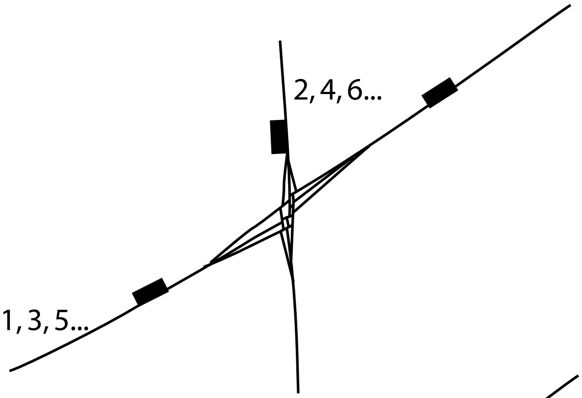
Porous media behave differently from nonporous media in many aspects. It is now well known that faults in rocks with a porosity of about 10–15% or higher form after a precursory stage of deformation-band formation (Aydin and Johnson, 1978), i.e., by a mechanism that, in many ways, is different from that of faulting through crack propagation and linking in low-porous and nonporous rocks.

Deformation bands are millimeter-wide, tabular structures that form through grain reorganization and/or cataclasis. They accumulate millimeter- to centimeter-scale displacements and are restricted to porous rocks. This is so because pore space is required for significant grain reorganization to occur and for stresses to build up at grain contacts to promote cataclasis. Deformation bands are commonly associated with local pore space collapse (e.g., Aydin 1978), although simple shear bands or even dilational deformation bands do exist.

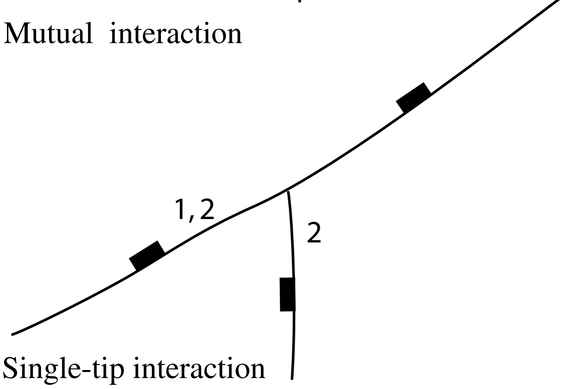
Deformation bands associated with faults in the study area are largely of the cataclastic type, where an approximately 1-mm-wide core consisting of crushed grains is mantled by a volume of compacted and reorganized grains (Aydin and Johnson, 1978). Single deformation bands are frequently encountered, but they more commonly occur in zones of some tens or hundreds of bands (Antonellini et al., 1994). Their growth from single structures to swarms of bands is generally attributed to strain hardening associated with pore collapse and cataclasis (Aydin, 1978).



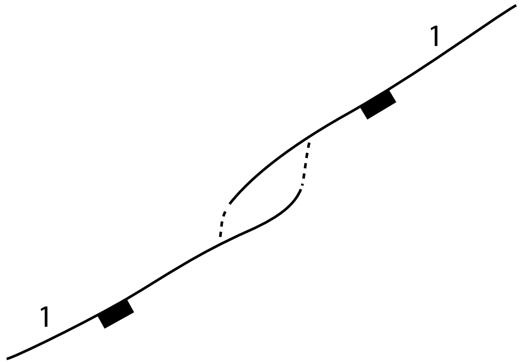
(a) Intersection (overprinting)



(b) Mutual interaction



(c) Single-tip interaction



(d) Double-tip interaction

Figure 1. The four main types of fault interaction. (a) Intersection, where one fault (1) is older than the other (2). (b) Mutual interaction between intersecting faults. Faults are of the same age with repeated movements on each fault. (c) Interaction between an active fault and an approaching and linking fault tip. (d) Fault overlap situation. Numbers indicate order of activity.

Some deformation-band zones contain minor patches of incipient slip surfaces, whereas others have developed distinctive and striated slip surfaces with meter-scale displacement or more (Shipton and Cowie, 2001). According to the evolutionary model first suggested by Aydin and Johnson (1978), deformation-band zones are precursors to faults in porous sandstone. A consequence of this fault model is the formation of a zone of deformation bands in front of, as well as around, the fault-slip surface. Hence, any fault in porous sandstone will have a deformation-band damage zone, provided that the porosity of the sandstone is not too low for deformation bands to form. Damage zones may, however, grow because of complications during fault growth.

TYPES OF FAULT INTERACTION

Fault interaction is a necessary consequence of growing fault populations. Growing faults will, sooner or later, interfere with neighboring faults. Several cases of fault interaction can be envisaged, as shown in Figure 1.

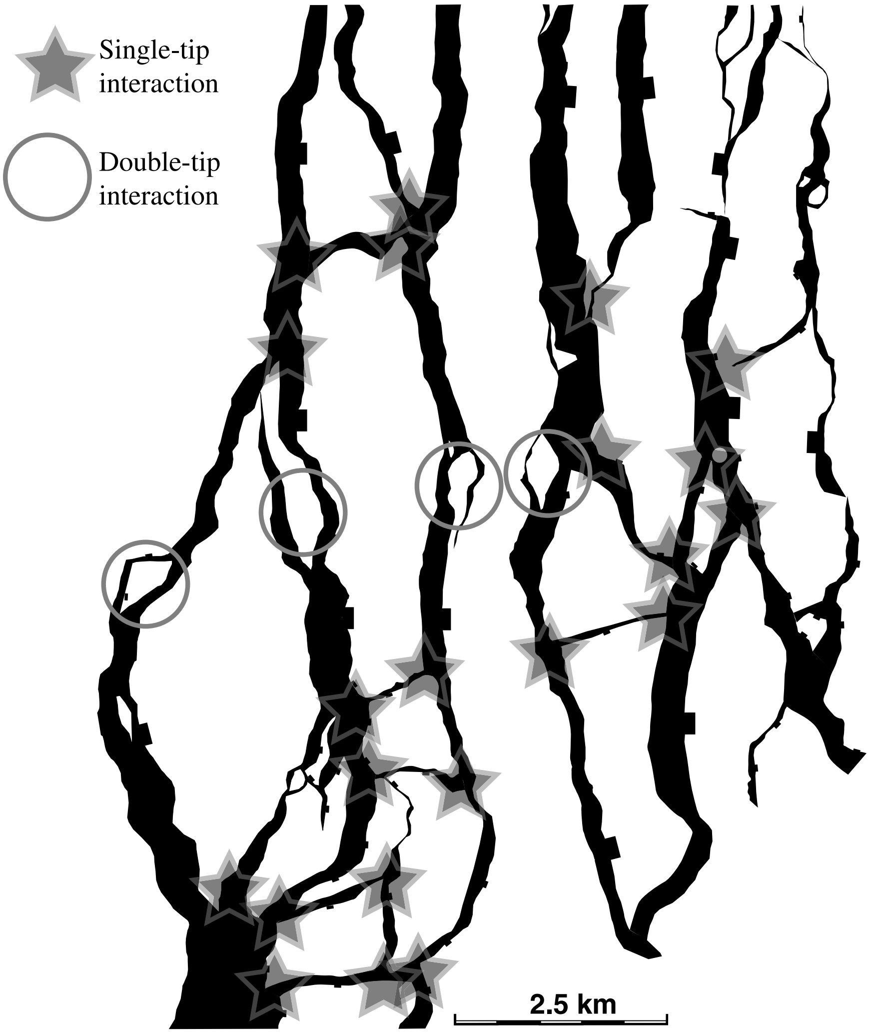
Crosscutting fault: One case is where a younger fault crosses and offsets an already inactivated fault (Figure 1a). In this case, a simple structural overprint is expected.

Mutual interaction: This is the case where there is repeated movement on both faults, resulting in mutually crosscutting relations in the volume of interaction (Figure 1b). This is the typical situation for crosscutting conjugate faults (e.g., Horsfield, 1980).

Single-tip interaction (branching faults): In this case, one fault grows into another, either orthogonally or at an oblique angle. At the point when they connect, they move in harmony, so that no crosscutting relations develop (Figure 1c).

Double-tip interaction: Two subparallel faults interfere as they grow to form an overlap structure

Figure 2. Examples of 100-m (330-ft)-scale fault-tip interactions from the North Sea Gullfaks field (top Statfjord Formation). See Fossen and Hesthammer (1998) for more information about the Gullfaks field.



and typically a relay ramp. The faults may be unconnected (soft linked) or connected (hard linked).

Although all of these relations can occur at any scale from micro- to mesoscale, we are here concerned with structures that are within or slightly below the resolution of three-dimensional (3-D) seismic data (Figure 2) and associated subseismic structures. The different cases are explored below and discussed in the perspective of petroleum production.

CROSSCUTTING FAULTS

Cases where faults of entirely different ages intersect result in simple overprinting relations, with the youngest damage zone overprinting the older one. Although the presence of the preexisting fault and damage zone poses a structural heterogeneity that inevitably affects the local stress field, the resulting structure is not expected to be significantly more complex than a pattern of simple superposition.

In some reservoir sandstones, the rheological and/or physical conditions changed during the time interval between the first and last faulting phases, in which case different types of structures may occur in the two damage zones. For instance, if the first fault formed shortly after the deposition of the sand, disaggregation bands (i.e., deformation bands where deformation is by rigid grain reorganization) may define the associated damage zone. Then, if the next fault forms at deeper depth and after a period of significant compaction and cementation, cataclastic deformation bands or even discrete shear fractures or joints may define its damage zone. An example from Utah is given by Davatzes et al. (2003), and an offshore oil-field example is presented in Cerveny et al. (2004) (the Hibernia field offshore Newfoundland).

MUTUALLY INTERACTING FAULTS

Faults that intersect at angles of about 60° and are active under the same stress field at more or less the same time are referred to as conjugate faults in the literature. Conjugate faults move repeatedly during strain accumulation, and the result is a mutually intersecting array of structures (Figure 3) (Freund, 1974; Horsfield, 1980; Watterson et al., 1998). In addition, faults that were not strictly conjugate but that intersected and were active at the same time behave in a similar way. The result is to form a zone of deformed rock that is significantly wider than what would have been expected if one fault or fault set were simply overprinted by the other set. Complications of this kind are seen in plaster and sand box models and in oil-field reservoirs (Figure 4). High frequencies of small faults are common in such areas.

The effect is well documented in sections containing the slip vector, i.e., in vertical sections for dip-slip faults and in map view for strike-slip faults. However, even normal faults tend to intersect also in map view because local stress perturbations and/or nonplane strain conditions cause deviations from Anderson's (1951) ideal stress regimes (Figure 5).

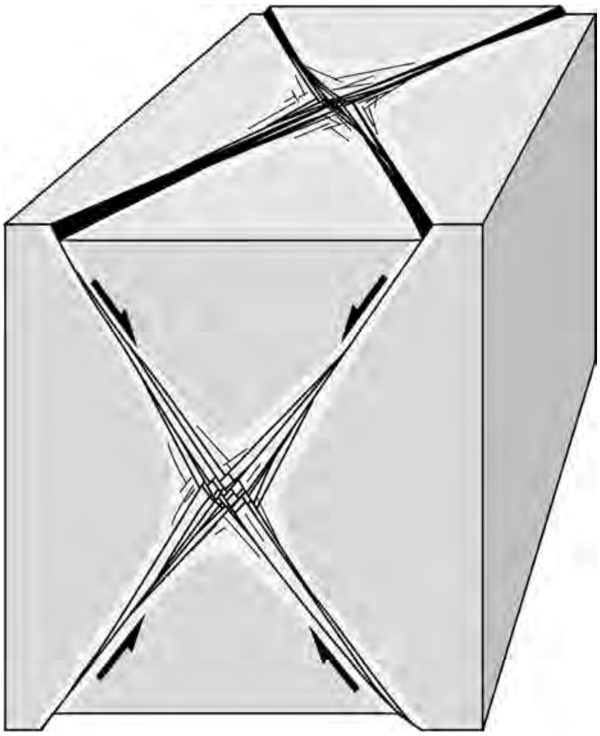


Figure 3. Crossing faults with contemporary movements. The damage zone is considerably wider in the crossing area than elsewhere.

SINGLE FAULT: BARTLETT AND COURTHOUSE FAULTS

General Description

Numerous examples of single fault structures are available from both onshore and offshore areas. We will use an uncommonly well-exposed set of faults linked to the Moab fault in southern Utah as an example (Foxford et al., 1998). The fault array consists of three main segments, here named the Bartlett, Tusher, and Courthouse segments (Figure 6). The segments are hard linked but appear as fairly simple, single faults between the areas of linkage. The localities where single faults are best exposed are the Hidden Canyon and Bartlett Wash. Data from Mill Canyon and Courthouse Canyon will also be presented, although these localities are closer to the single-tip fault interaction locality (see the next section).

The Bartlett fault has a total vertical offset of about 250 m (820 ft), juxtaposing fluvial deposits of the Cretaceous Cedar Mountain Formation against the mostly eolian Jurassic San Rafael Group (Entrada Sandstone). Up to 75 m (246 ft) of the offset is accommodated by ductile folding (drag) of the hanging-wall sequence, whereas the rest is accommodated by localized slip along the fault core. The fault core of the Bartlett fault is a few meters wide and is composed of one or a few main slip zones and can locally be seen to contain lenses of footwall rocks.

A damage zone is developed around the fault core, consisting of deformation bands in the footwall and deformation bands and fractures in the hanging wall. The San Rafael Group consists of porous sandstones of good reservoir quality, whereas the hanging-wall strata are composed of quartz-cemented conglomerate and sandstone layers intercalated with silty and clay-rich beds. We will focus on the porous sandstones in the footwall of the fault because they are most relevant to the petroleum industry and can more easily be compared to other examples in the same area.

Two stratigraphic units, the Slick Rock Member and the overlying Moab (Tongue) Member of the San Rafael Group (Doelling, 2001), are made up of reservoir-quality sandstones particularly suited for the present study. The Slick Rock Member consists of several meter-thick eolian sandstone (dune) deposits separated by thinner interdune (flash-flood) deposits. The Moab Member is entirely made up of dune deposits and is everywhere light gray from bleaching (Parry et al., 2004), whereas the Slick Rock Member is only

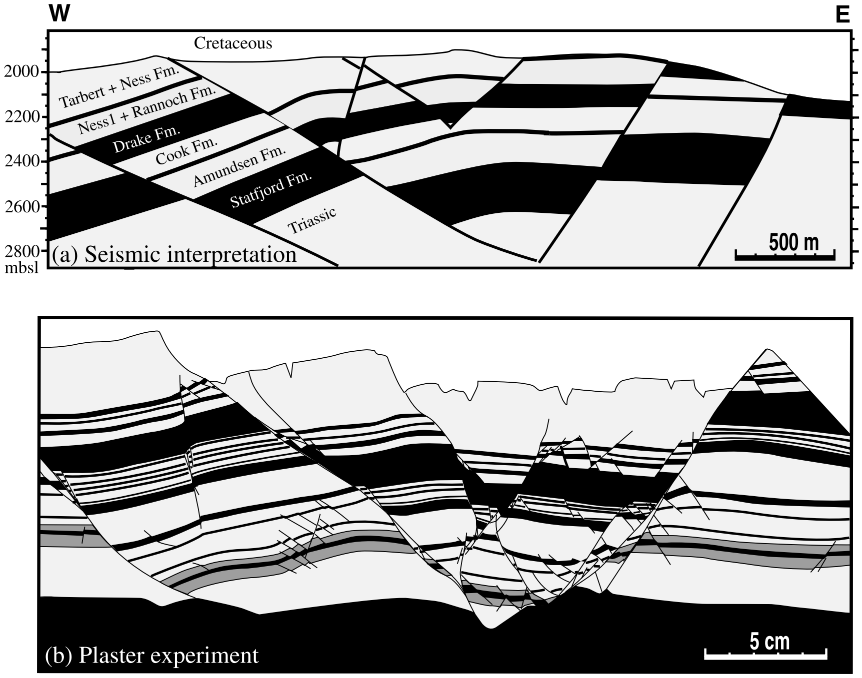


Figure 4. (a) Depth-converted seismic interpretation from the Gullfaks field, showing oppositely dipping faults (conjugate faults) (Fossen and Hesthammer, 1998). (b) Plaster model deformed by plane strain extension. The plaster model shows many small-scale structural complications that are expected to exist also in the Gullfaks profile, but below seismic resolution. Note that the complications are largest in the area of mutually interacting and oppositely dipping faults.

bleached in patches and along high-permeability layers close to the fault and generally exhibit a characteristic reddish color.

Damage Zone Structure

The deformation bands that constitute the damage zone of the Bartlett fault show a density of more than 100 m^{-1} (30.30 ft^{-1}) close to the fault, tapering off to 1–2 m^{-1} (0.30–0.60 ft^{-1}) some 10–20 m (32–65 ft) into the footwall in the Slick Rock Member, where deformation bands are best developed (Figure 7). The deformation bands are cataclastic in the eolian sandstone layers (dune deposits) but can be followed into and locally across less well-sorted flash-flood deposits, where the dominating deformation mechanism changes from cataclasis to that of grain reorganization. Deformation bands qualitatively show a similar distribution in the Moab Member but with a lower frequency (Figure 7).

Figure 5. Mutually crosscutting deformation bands in porous sandstone, as seen in map view. Moab fault pullout, Arches National Park, Utah.

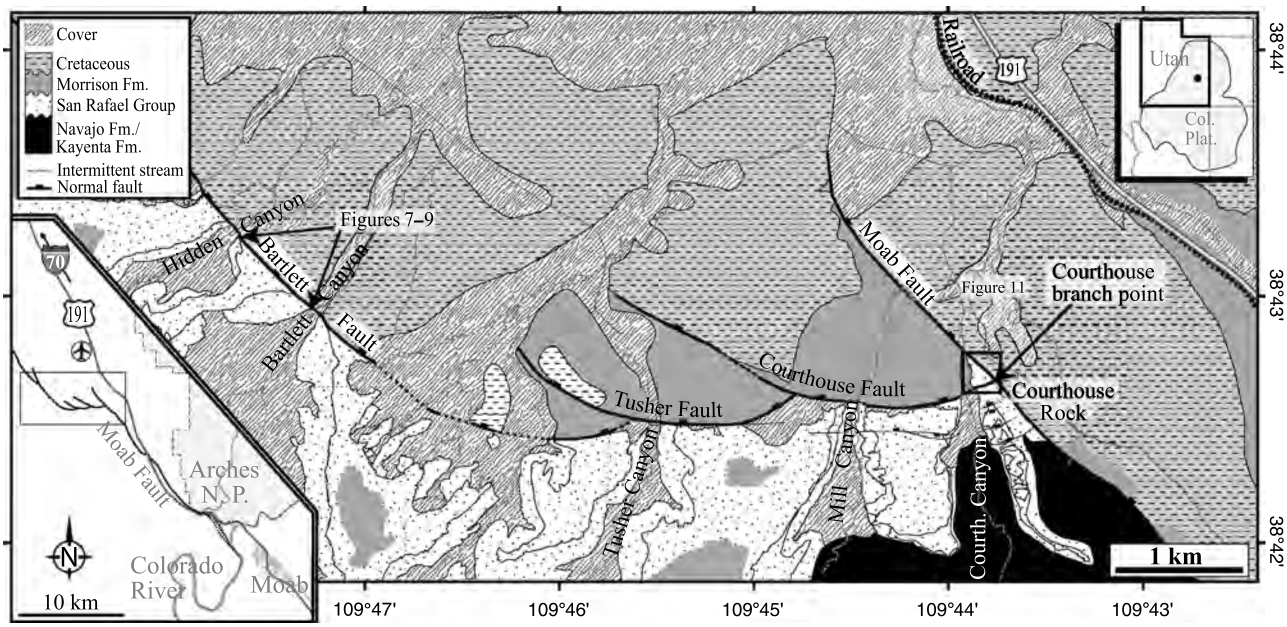


Figure 6. Geologic map of the northern part of the Moab fault. Several fault branch points that we interpret as areas of single-tip interaction are seen. Based on Doelling (2001) and own mapping.

The stereoplots of the orientations of the hanging-wall deformation bands indicate fairly consistently southeast- and northwest-striking bands that can be distinguished into two sets of different dip direction (Figure 8). One set appears to be antithetic to the main fault, whereas the other is almost synthetic, albeit with a slightly steeper average dip. A slight inconsistency is seen for the Hidden Canyon data in that the strike of the main fault (core) is slightly more east–west than those of its hanging-wall deformation bands (Figure 8a, b). This discrepancy is not apparent in the Bartlett Wash data set (Figure 8c, d), where one of the conjugate sets of deformation bands is parallel with the average orientation of the fault core.

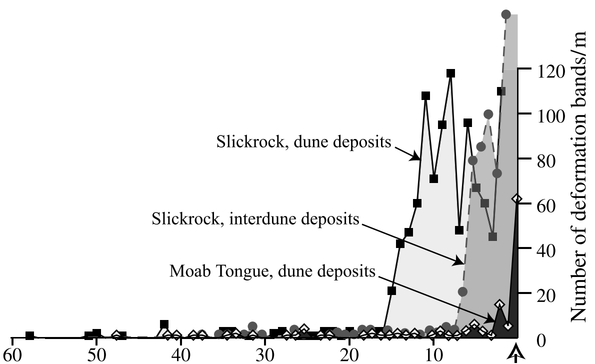


Figure 7. Deformation band frequency in the footwall to the Bartlett fault in Bartlett Wash.

The simple pattern of two sets of conjugate deformation bands in the damage zone is not seen along the Courthouse fault, where both strike and dip values are more variable. Nevertheless, most deformation bands strike subparallel to the main fault core and are antithetic or synthetic to the fault.

SINGLE-TIP INTERACTION: COURTHOUSE BRANCH POINT

The area where the Courthouse fault joins the Moab fault is located close to Courthouse rock to the north-northwest of Moab, Utah (Figures 9, 10) (see Davatzes and Aydin, 2003; Johansen et al., in press, for a more detailed description and discussion). This area is herein referred to as the Courthouse branch point. Here, the throw on the Courthouse fault decreases eastward toward the Moab fault, reaching about 80–90 m (262–295 ft) where they coalesce.

Upon approaching the Courthouse branch point, the Courthouse fault develops an approximately 400-m (1300-ft)-wide zone of minor faults in its footwall (Figure 9). The minor faults are strike parallel and both synthetic and antithetic to the Courthouse fault. This consistency in strike between the minor and major faults strengthens the assumption that they are all genetically related. It is a matter of definition whether

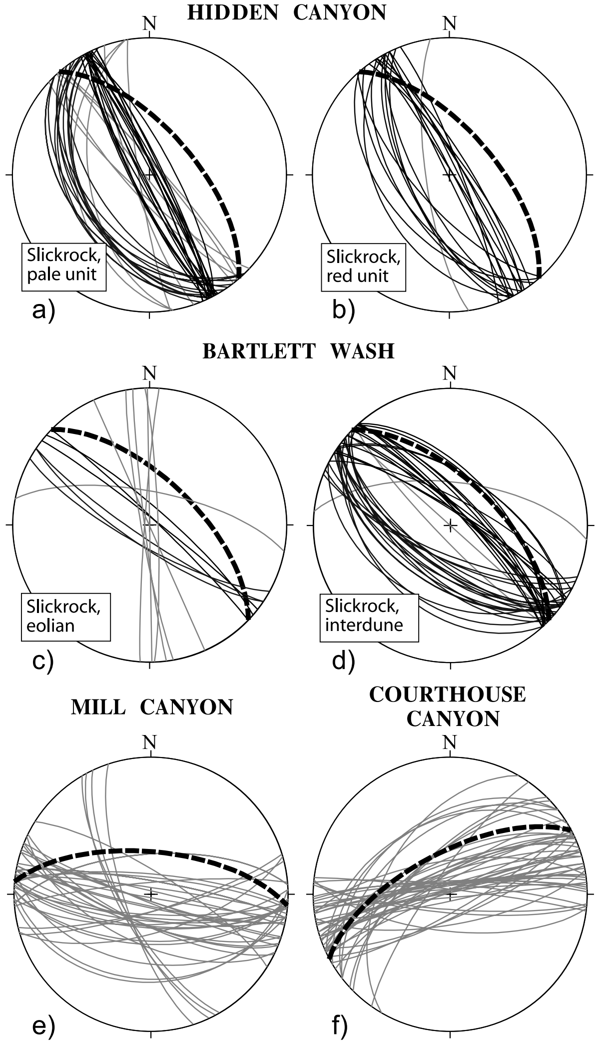


Figure 8. Deformation band orientations along single faults (equal area, lower hemisphere stereoprojections). Thick dashed lines indicate the orientation of the main fault at each locality (canyon).

this zone of minor faults should be attributed to the damage zone of the Courthouse fault, but its appearance seems to reflect a widening of the total strain zone and increase in complications associated with the Courthouse branch point. Compared to the 10–15-m (33–49-ft)-wide footwall damage zone found in the single fault example (Bartlett Wash/Hidden Canyon) above (Figure 7), the width of the deformation zone into the footwall is here (Figure 10) an order of magnitude larger.

The volume of rock occupying the acute sector between the Courthouse fault and the main Moab fault is the main subject of this section. A triangular area of the Moab Member is beautifully exposed, exhibiting a large number of deformation bands and fractures (see Johansen et al., in press, for a more detailed description of the microstructures exposed at this locality). These structures show a large range in orientations. Of particular interest are the strike orientations, which are not only parallel to the Moab and Courthouse faults, but also show orientations oblique to both of the main faults (Figure 10). This finding indicates that the deformation is more complex around the Courthouse branch point than elsewhere (Figure 11). In general, the rock is more compartmentalized than was seen in the single fault situation.

Another characteristic feature of the Courthouse branch point area is the occurrence of several sets of minor structures (see Johansen et al., in press, for details). Uncommonly thin deformation bands, tension fractures, and shear fractures occur along and between both faults, whereas ordinary deformation bands occur along the Moab fault only. The ordinary deformation bands can be seen to be the oldest structures in the area

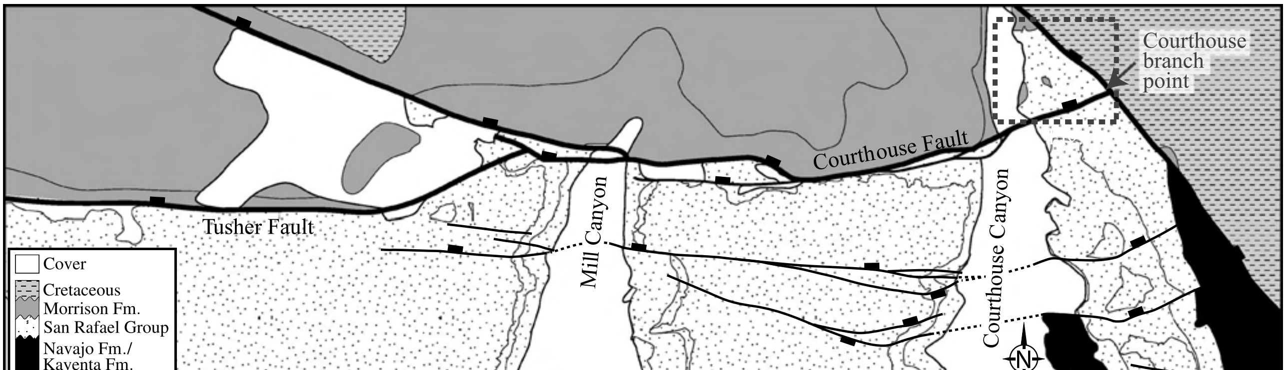


Figure 9. Geologic map of the Courthouse–Mill Canyon area. Based on Doelling (2001), Davatzes et al. (2005), and own mapping.

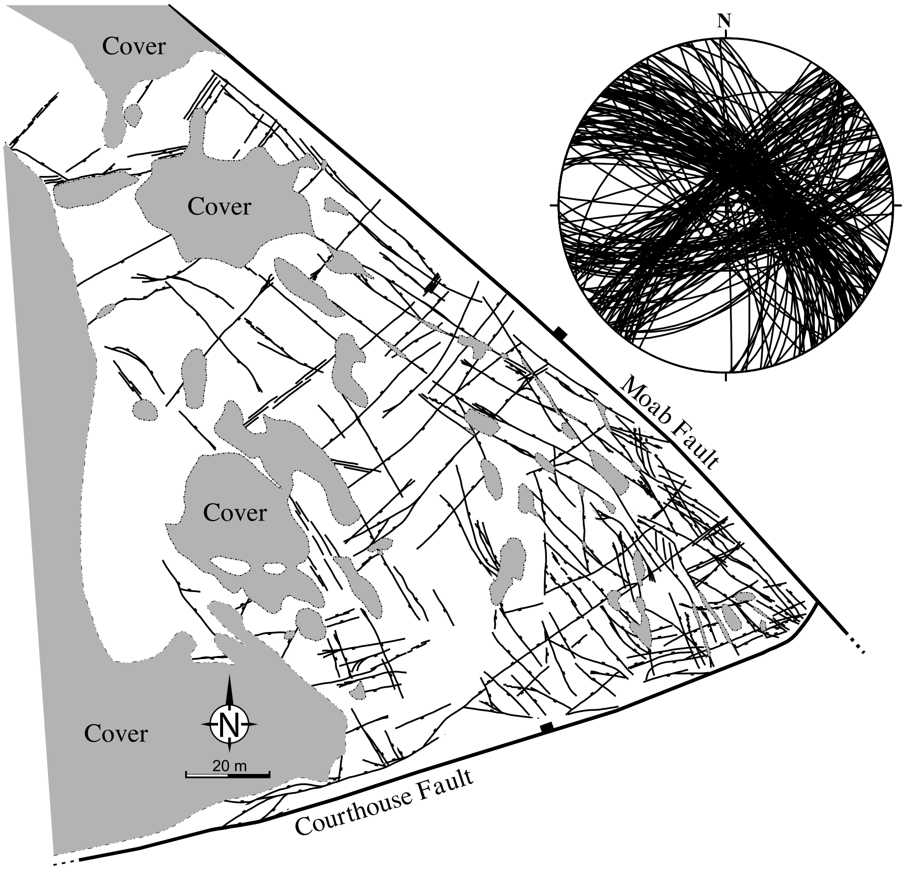


Figure 10. Map of deformation structures in the Courthouse branch point area and stereoplot (equal area, lower hemisphere) of the different structures in the same area. See Johansen et al. (in press) for a closer description.

because they are offset by the other minor structures. Our interpretation is that the Moab fault first formed from deformation bands, as described above. After the Moab fault had been established in the area, the Courthouse fault grew toward the still active Moab fault. However, instead of the deformation bands seen along the Moab fault, brittle fractures and very thin cataclastic deformation bands in this area define the Courthouse fault damage zone. This change in small-scale deformation style is likely related to a reduction in porosity caused by the precipitation of quartz and calcite from circulating fluids along the faults, for which abundant evidence is present (e.g., Foxford et al., 1998). Because deformation bands only form in highly porous media, this reduction in porosity may have caused the change in deformation mechanism and, hence, the nature of minor structures associated with the last part of the faulting history (an alternative model, where the late fracturing is ascribed to stress perturbation in the branch point area, was suggested by Davatzes and Aydin, 2003). A more detailed discussion of this model is found in Johansen et al. (in press). This example illustrates how single-tip fault interaction can result

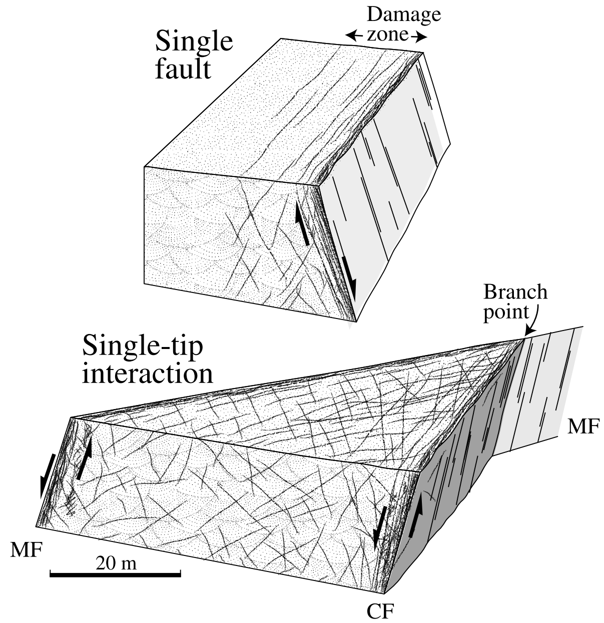


Figure 11. Schematic sketch of single fault and single-tip interaction situations based on observations along the Moab fault (MF) and related branches. CF = Courthouse fault.

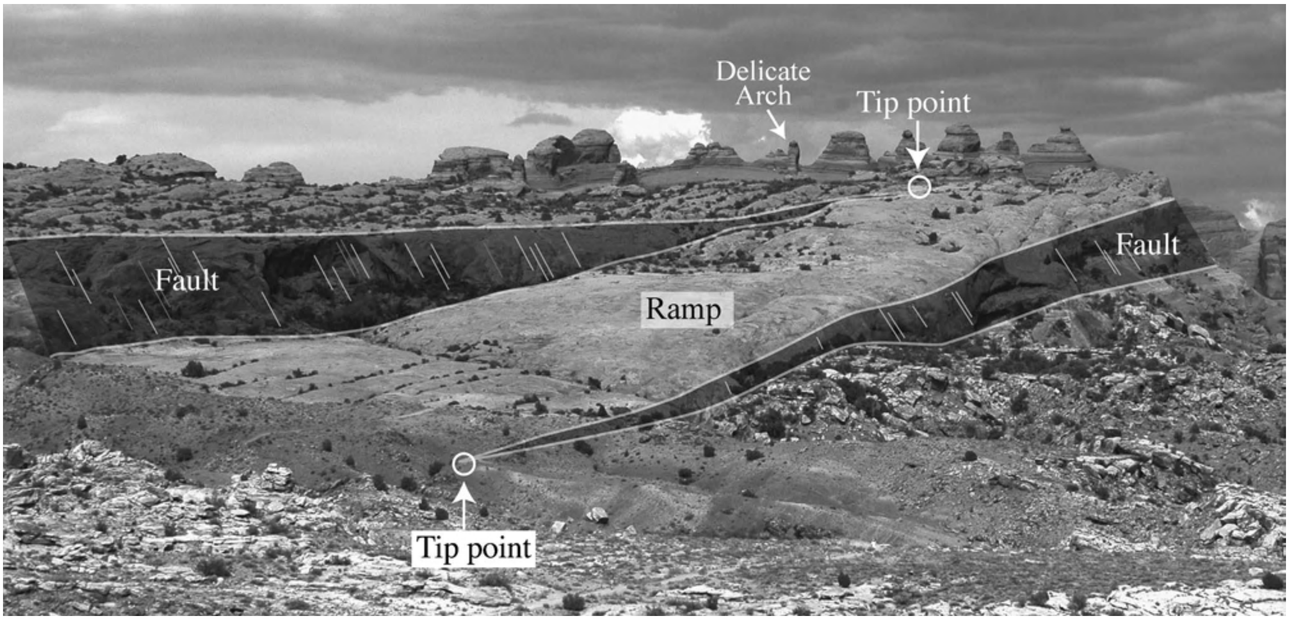


Figure 12. The Delicate Arch relay structure in Arches National Park. Note that tip point locations are approximations only.

in a wide area of deformed rock and also how the small-scale structures may change in nature during the process of linking.

DOUBLE-TIP INTERACTION

Faults with similar strike orientations interact through the formation of soft-linked overlap structures, typically with a relay ramp and/or small-scale structures in the overlap zones, to hard-linked structures where the relay ramp is overprinted and the two fault segments are connected (Childs et al., 1995). The formation and destruction of overlap zones and relay structures occurs repeatedly at a large range of scales throughout the growth history of any fault population. Examples are seen worldwide, e.g., in Canyonlands (Moore and Schultz, 1999), Greenland (Peacock et al., 2000), and the North Sea (Dawers and Underhill, 2000). The result is an abnormally wide damage zone in the area of linkage as compared to the damage zone width away from the relay structure.

A relay ramp in porous sandstones, probably formed at a depth on the order of 2 km (1.2 mi), is found in the Cache Valley near Delicate Arch, Utah (Antonellini and Aydin, 1995), hereafter referred to as the Delicate Arch ramp (Figure 12). This ramp is exposed in the Jurassic Slick Rock Member of the San Rafael Group, and the overlapping faults are developed from deformation bands, as described above. A detailed survey of the Delicate Arch ramp and the overlapping fault has shown that the faults have damage zones comparable in width and intensity to other faults of similar throw in similar lithology, i.e., high concentrations of bands in a zone of about 10–20 m (33–65 ft) width on each side of the fault (Figure 13) and directly comparable to, for example, the Bartlett fault (Figure 7). The orientations of these deformation bands are strike parallel to the fault but may be synthetic or antithetic with respect to dip direction. The overlap zone, which at first glance looks rather unaffected by deformation, contains a significant number of deformation bands (Figure 13). An average density of about 2–4 m^{-1} (0.60–1.2 ft^{-1}) is representative for the ramp area. This density value represents the number of deformation bands as counted along north–south scan lines across the ramp. The density is not very high but higher than the density north and away from the ramp where the bands eventually disappear (to the south, another fault influences the density of deformation bands).

The orientations of deformation bands in relay zones may be important to hydrocarbon flow. In the example shown in Figure 13, some bands are subparallel to the two faults, i.e., east–west oriented. In addition, several bands run diagonally across the ramp. Many of these curve from being subparallel with the northern fault to form a high angle to the southern fault (Figure 13), giving the impression of growing from the tip zone of the northern fault toward the already existing southern fault. Regardless of the growth

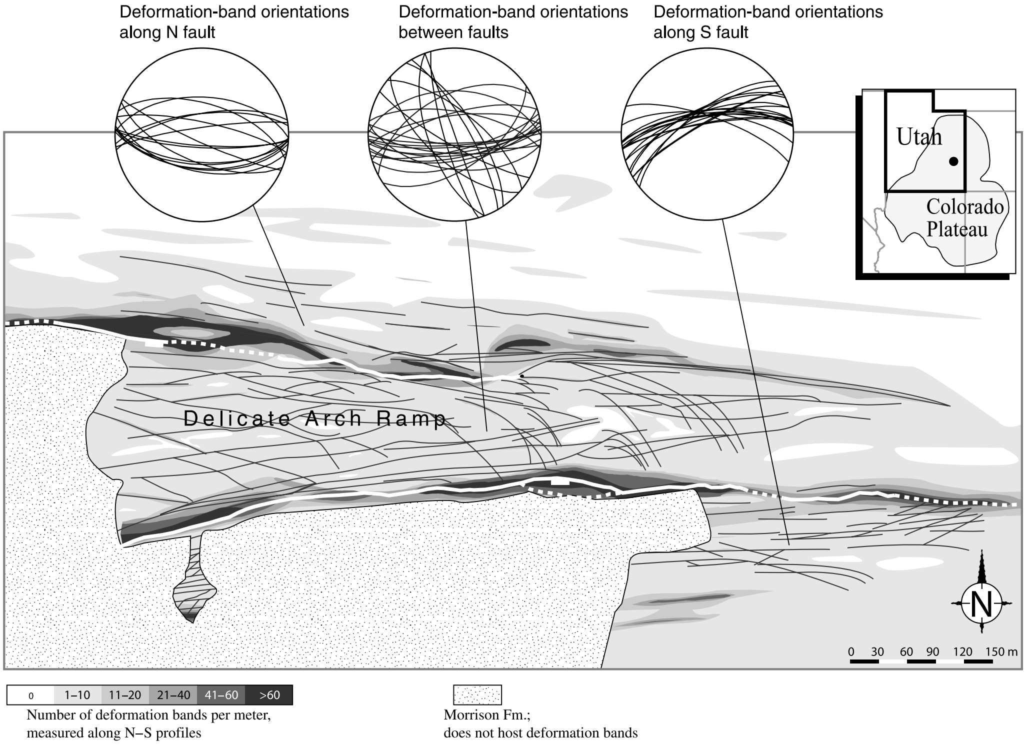


Figure 13. Map of the Delicate Arch relay structure and the density of deformation bands in the Arches National Park. The orientations of deformation bands near and between the overlapping fault segments are shown as stereoplots (equal area, lower hemisphere). Faults are shown as white, thick lines. Thinner lines are deformation bands or deformation-band zones.

history of these structures, the fault-parallel deformation bands are unlikely to affect fluid flow to any significant extent except for their potential for channeling flow parallel to the faults. However, in combination with the oblique deformation bands, they have a considerably larger potential of hindering flow up the relay ramp, depending on the petrophysical properties of the bands.

The occurrence of obliquely oriented deformation bands is also observed in other normal fault overlap structures. An additional, smaller scale example is given in Figure 14, where two normal faults in the Entrada Sandstone overlap. An array of consistently oriented oblique deformation bands occupies the overlap area, very similar to the Delicate Arch example. Interestingly, a lower order overlap structure in the same structure (Figure 14, inset map) shows very similar, obliquely oriented deformation bands in the overlap area.

DISCUSSION AND IMPLICATIONS

The above examples demonstrate how significant differences exist between single fault structures and areas of more or less contemporaneous fault interaction. Single faults develop damage zones that are narrow

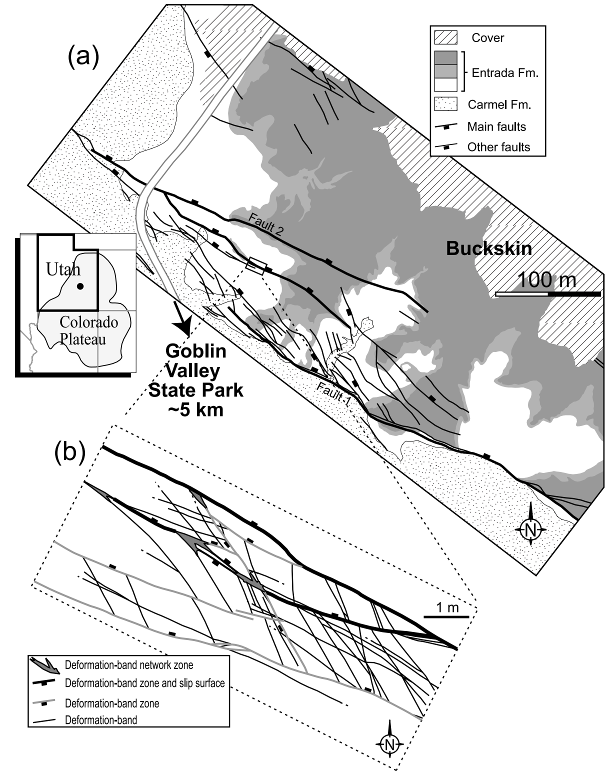


Figure 14. Relay structure at Buckskin Spring near Goblin Valley. Oblique deformation bands in the wide overlap damage zone are present.

enough that they are of little concern when drilling targets close to single faults. However, although single fault structures are generally simple structures with mostly strike-parallel deformation bands or other shear structures in a fairly narrow fault damage zone, both the width of the damage zone and the range in orientation of related small-scale structures are significantly greater in areas of fault interaction. Provided that the small-scale structures impede fluid flow, these differences should be of concern in a hydrocarbon production situation if the local faults and deformation bands are thought to have a negative influence on fluid flow.

In the case of single fault tip interaction, placing a well close to a fault branch point (Figure 10) should be avoided if an alternative and more remote location can be found. If not, a well path that transects the deformation bands should be attempted.

Double-tip fault interaction also produces anomalously wide damage zones with orientations that are more complex than those along single faults. The reason is the need for accumulating strain to be transferred from one tip to the other, a situation that produces local stress as well as strain anomalies (Kattenhorn et al., 2000). The consequence for unbreached ramps is obvious: there is a possibility that what would be expected to be a simple pathway for fluid or gas flow is influenced by flow-reducing structures such as very low-permeable deformation bands. Furthermore, the consequence for breached ramps, where fault segments have merged and behave as a single, long fault, is that an anomalously wide area of damage remains around the location of the breached ramp. Breached relay structures may be identified as abrupt steps along continuous faults, as shown in Figure 15e. Hence, unless good reasons exist for placing a well in such areas, both production and injection wells should be avoided near the suspected locations of breached relay structures.

Double-tip interaction structures (overlap structures) may be particularly challenging structures in a reservoir situation. Although branch points are easily

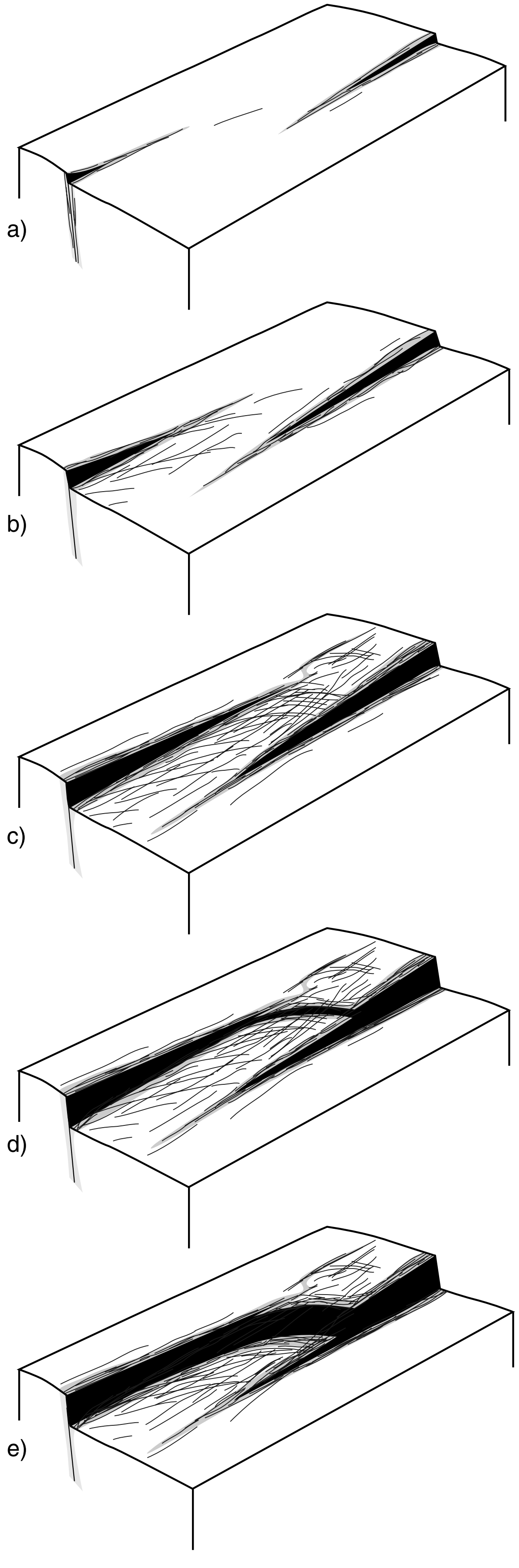


Figure 15. Double-tip interaction and the formation and destruction of a relay ramp, illustrated at five different stages. At the latter stage, the faults are completely linked and behave as a single fault. The location of the former overlap zone is reflected by the bend in fault trace. When planning wells in such locations, one should be aware of the possibility of high deformation-band frequency and minor (subseismic) faults.

mapped in most cases, overlap structures may be hard to map because of the limited resolution of seismic data. Even where fault overlap can be mapped, the internal details of the overlap zone typically fall below seismic resolution. Hence, the level of maturity, as shown in Figure 15, becomes difficult to decide. An example from the Gullfaks Sør field is shown in Figure 16, where relay structures have been mapped from 3-D seismic data. The field is a typical northern North Sea oil and gas field with Jurassic sandstone reservoirs faulted during a regional Late Jurassic extension phase (see Hesthammer et al., 2002, for more details). The main faults are east dipping, and based on the seismic interpretation, the fault structures portrayed in Figure 16 appear to be soft linked (faults are not connected). The onshore field examples presented above suggest that additional subseismic fault structures and deformation bands exist. An exploration well (Statoil 34/10-2) penetrates one of the structures shown in Figure 16. Dipmeter data from this well indicate several subseismic faults in the overlap area (Barstad, 2003), and a large number of deformation bands are found in the cores (Hesthammer, 1999). Hence, the relay appears to be considerably more complex than the simple pattern outlined in Figure 15, in keeping with the onshore field examples. Low performance of wells in the area (Hesthammer et al., 2002) suggests that small-scale structures between the mapped faults have a significant effect on fluid flow in this field, particularly in the deeper Statfjord reservoir where deformation bands have been cemented during burial and have lower permeability than those at higher (Brent Group) levels (Hesthammer et al., 2002).

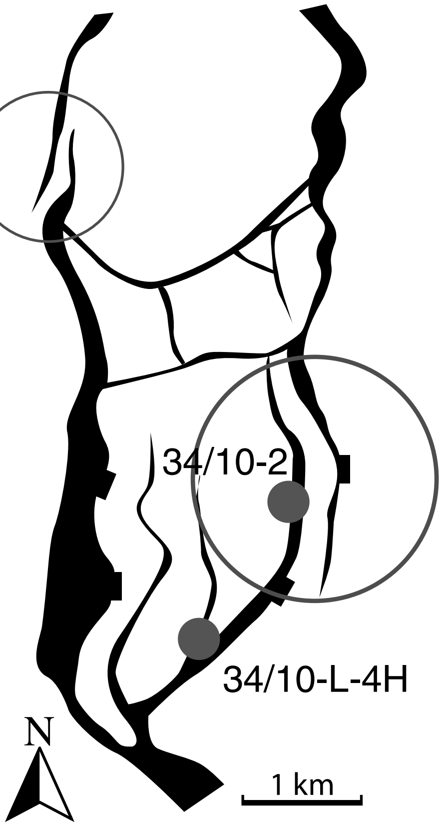


Figure 16. Map of an internal part of the Gullfaks Sør field in the northern North Sea. Two areas mapped as fault overlap structures (areas of double-tip interaction) are circled. One is penetrated by a well (34/10-2), which indicates multiple subseismic faults and numerous deformation bands. The map is based on Barstad (2003).

CONCLUSIONS

We have discussed field examples of various types of fault interaction in the light of fluid flow in petroleum reservoirs. The main conclusions from the study, which generally agree with assumptions that are commonly made during structural reservoir evaluation, are as follows:

1. Different types of fault interaction produce different levels of complication. Faults that interact during simultaneous movements produce more complex and extensive subseismic deformation than single faults or faults separated in time.
2. Branch points are particularly complex regions where subseismic structures have the largest spectrum of orientations, and where wells may show anomalous behavior. The actual behavior of wells in structurally complex areas will depend on the permeability structure of the subseismic structures and their effect on fluid flow.
3. Fault overlaps should be searched for with care during seismic interpretation, and particular attention should be paid to unexpected bends in the fault trace of seismically mapped faults. Such bends could represent overlooked or subseismic relay ramps or breached ramps where overlapping fault segments have been connected. Although the former case may increase communication across a fault, the breached ramp situation will represent an area of extensive off-fault damage that may have unpredicted consequences if a well is placed in such an area. These effects will have to be considered independently for each specific case.

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