ELSEVIER

Marine and Petroleum Geology 19 (2002) 181–192

Marine and Petroleum Geology

www.elsevier.com/locate/marpetgeo

Layer rotation around vertical fault overlap zones: observations from seismic data, field examples, and physical experiments

Erling Rykkelid[a], Haakon Fossen[b,*]

[a]*Norsk Hydro ASA, N-0246 Oslo, Norway*
[b]*Department of Geology, University of Bergen, Allégt. 41, N-5007 Bergen, Norway*

Received 26 March 2001; received in revised form 24 January 2002; accepted 29 January 2002

Abstract

Vertically overlapping fault segments are common structures in faulted hydrocarbon reservoirs. Experimental work and field observations show a close relationship between the rotation of layers in the region of overlap, the type of overlap (restraining vs. releasing) and fault curvature. In general, releasing overlap zones (where the normal fault steps upward into the hanging-wall) show normal rotation or drag, thus decreasing the effective throw on the fault. In contrast, restraining overlaps tend to develop reverse rotation in the overlap zone, particularly if the normal fault tips curve toward each other. Releasing overlap zones seem to be more common than the restraining zones, and the overlaps tend to form in shaly layers between thicker sandstones. Narrow overlaps of this type typically develop zones of drag or shale smear that could seal or reduce communication across the adjacent sandstone layers. Hence, overlap zones may significantly influence communication in a reservoir, depending on the fault arrangement, geometry, and lithological properties. Seismic interpreters and structural geologists should pay particular attention to layer rotation to identify vertical overlap structures and to evaluate their influence on reservoir performance. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Fault overlap zones; Fault sealing; Drag

1. Introduction

Successful management of structurally compartmentalized and fault bounded oil fields relies on having a detailed knowledge of the fault population in the reservoir (Childs, Walsh, & Watterson, 1997; Lia, Omre, Tjelmeland, Holden, & Egeland, 1997; Manzocchi, Ringrose, & Underhill, 1998). Understanding the spatial distribution in properties such as fault segment length, fault zone thickness, sealing properties and fault linkage may be important for defining effective reservoir management strategies. Whereas lateral overlap zones have received considerable recent attention (Huggins, Watterson, Walsh, & Childs, 1995; Larsen, 1988; Peacock & Sanderson, 1991; Trudgill & Cartwright, 1994), several important geometrical aspects of vertical overlap zones merit additional study. The limited treatment of vertical overlap zones in the literature (Childs, Nicol, Walsh, & Watterson, 1996; Koledoye, Aydin, & May, 2000; Mansfield & Cartwright, 1996; Peacock & Zhang, 1993) could be related to the difficulties involved in observing such structures. Most of them are too small to be observed on 3D seismic surveys, and vertical outcrops are rarely large enough to fully expose their true nature.

Connectivity within faulted sandstone reservoirs is dependent on the throw on individual faults and the sealing properties of the faults themselves, including clay smearing or ductile drag along the fault surface. Such factors can be strongly influenced by the presence of vertical overlap zones, so such structures should be of special interest to the reservoir geoscientists. Normal drag along normal faults reduces the effective or discrete offset along the fault, whereas reverse drag causes an increase in discrete offset. Drag and related local rotation of the layers, are to some extent related to ramps and fault links. Mapping and understanding of the relationships between geometric elements of fault systems such as overlap zones, drag, block rotation and variations in fault throw are important as they can increase the confidence in the structural model for a given reservoir.

In this work, we present examples of vertically overlapping fault segments that have been mapped in three dimensions in North Sea sandstone reservoirs. We then compare these observations with smaller-scale field examples and physical models to explore the geometric relationship between fault geometry, fault arrangement and layer

* Corresponding author. Tel.: +47-5558-3495; fax: +47-5558-9416.
E-mail addresses: erling.rykkelid@hydro.com (E. Rykkelid), haakon.fossen@geol.uib.no (H. Fossen).

PII: S0264-8172(02)00007-7

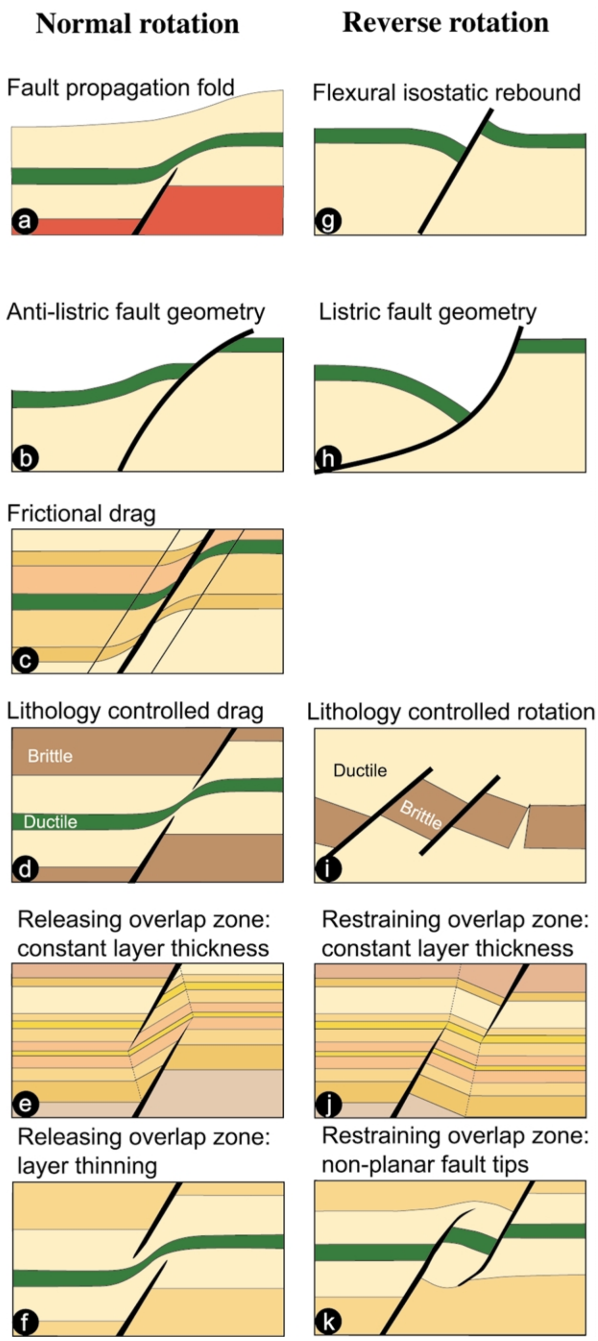

Fig. 1. Different styles of layer rotation observed adjacent to normal faults.

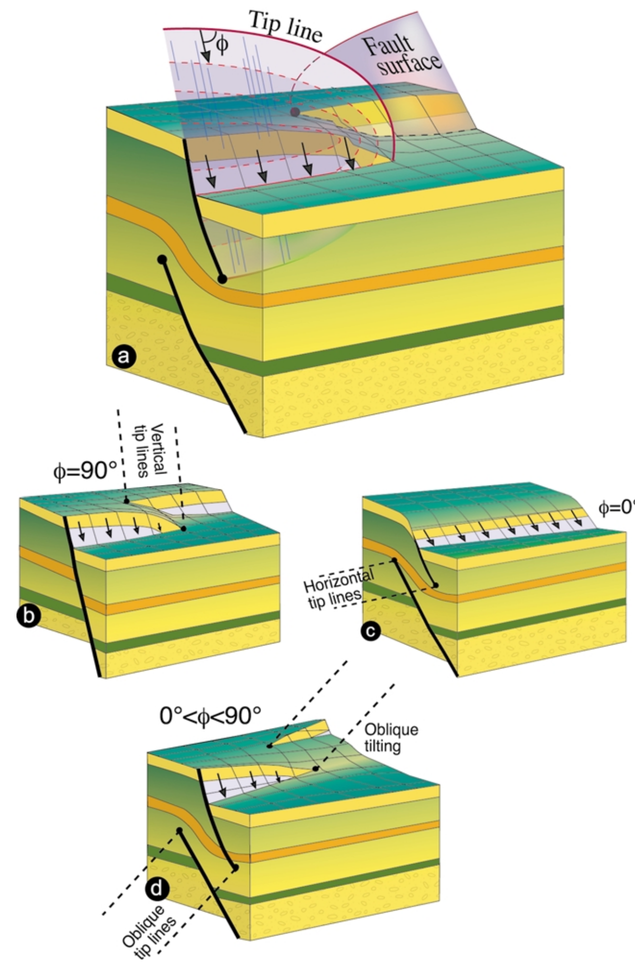

Fig. 2. (a) Illustration of fault surfaces interacting laterally and vertically to form different types of overlap zones. The fault tip lines within these overlap zones may be vertical (b), horizontal (c) or oblique (d).

rotation in regions of fault overlap. Eventually, the implications of these relationships for flow in hydrocarbon reservoirs are discussed.

2. Drag and related rotation of layers

Drag is the systematic variation of bedding dip adjacent to a fault (Reches & Eidelman, 1995). *Normal drag* is commonly considered to be formed prior to faulting (Groshong, 1999; Hesthammer & Fossen, 1998; Hobbs, Means, & Williams, 1976; Reches & Eidelman, 1995), and in this sense can be considered as a fault propagation fold (Fig. 1(a)). A more liberal usage of the term normal drag also includes other cases, such as growth of fault-adjacent folds in the hanging-wall due to fault curvature (Fig. 1(b)), strain hardening of the fault core to the extent that drag folding occurs or recurs in its walls (Fig. 1(c)). Also, ductile layers may show pronounced ductile deformation (rotation) in layers between aligned fault segments (Fig. 1(d)). Rotation of layering also occur where fault segments are not aligned, but rather step and overlap. In these cases, normal rotation or normal drag of the layering occurs in the overlap region if the fault segments are arranged as shown in Fig. 1(e) and (f).

Reverse drag is the geometric consequence of layer deflection in the ductile strain field around a fault, and is in this sense directly related to fault offset and mechanical properties of the rock (Fig. 1(g)), but can also be caused by non-planar fault geometry (Fig. 1(h)). Domino-style rotation of broken brittle layers generates the same sense of rotation as reverse drag (Fig. 1(i)). Reverse drag or backward rotation of the layering may also occur in overlap zones, as shown in Fig. 1(j) and (k). Overlapping fault segments (Fig. 1(e), (f), (j) and (k)) are given special attention in this work.

3. Faults and fault ramps

Isolated fault surfaces can be considered as elliptical planar features with maximum displacement in the centers that gradually decreases towards bounding tip lines (Watterson, 1986) (Fig. 2(a)). These ellipses are generally oriented with their long axis in the horizontal plane, causing sub-horizontal tip lines to be more common than vertical ones (Nicol, Watterson, Walsh, & Childs, 1996). Faults that interact, such as in en-echelon systems, tend to develop higher displacement gradients than do isolated faults (Peacock & Sanderson, 1991; Willemse, Pollard, & Aydin, 1996). Because faults nucleate and grow at various vertical and lateral positions in a faulted rock sequence, fault segments overlap not only in the slip direction and perpendicular to the slip direction, but also oblique to the slip direction (Fig. 2). The implications of overlap zones for reservoir communication are different for different cases, and oblique overlap zones contain elements of both lateral and vertical overlap zones. In this work, we consider the slip direction to be vertical, and focus on slip-parallel or vertical overlaps in sequences with sub-horizontal layering.

4. Vertical overlap zones

Vertical overlap zones (including underlap zones in this article) fall into two main categories, depending on the sense of stepping of the fault segments. *Releasing overlap zones* in normal fault systems develop where the fault system steps upward into the hanging-wall block across the overlap (Fig. 1(e) and (f)). For reverse faults, releasing overlap zones occur where the fault steps upward into the footwall block across the overlap. Both releasing and extensional overlap (overstep) structure has been used to describe this type of overlap (Childs et al., 1996; Peacock & Zhang, 1993), which is well known from strike-slip terminology.

Lithologic layering in releasing overlap zones can be deformed in a number of ways. Two end-members can be considered where the layer thickness is maintained (Fig. 3(a)), or where the deformation is accommodated by volume increase (Fig. 3(b)). The volume increase may be manifested by tension gashes or more complex arrangements of veins. Note that a change in layer thickness may occur without any change in the total volume, and that mechanical differences between different layers may cause a spectrum of possible geometries that we will not be discussed in detail in this article.

Restraining overlap zones in normal fault zones form where the fault steps upward into the footwall block across the overlap (Fig. 1(j) and (k)). The structure is similar to restraining overlap zones in strike-slip fault zones in many ways. As for releasing zones, two end-members can be considered that show either constant-layer thickness (Fig. 3(c) and (d)) or may involve volume reduction (Fig. 3(e)). Volume reduction is typically localized in certain layers, typically shales in shale-sand sequences. Volume reduction may occur through dewatering or escape of material (shale or clay) along the fault surfaces.

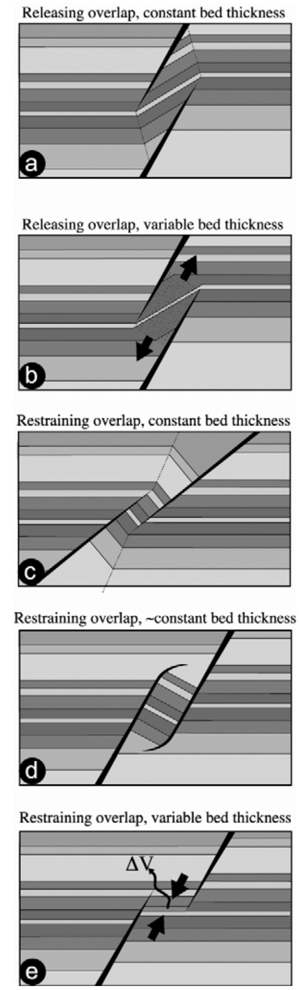

Fig. 3. (a) Releasing overlap zone where layer thickness is maintained across the structure. (b) Releasing overlap zone where the deformation in the zone is governed by dilation. (c) Constant-layer construction of a restraining overlap zone. This type of construction easily yields reverse offset across the total zone unless the fault dip is low and the overlap zone is narrow. This problem is resolved in many natural cases by curving fault tips and lateral flow in layers of fault termination (d). (e) Restraining overlap zone deformed by volume loss.

5. Ramps and drag from 3D seismic data: the Oseberg example

Three-dimensional seismic data provides the opportunity to map fault geometry in three dimensions. Assuming good stratigraphic imaging, fault surfaces and their associated displacement variations can be mapped both laterally and vertically (Chapman & Meneilly, 1990; Freeman, Yielding,

& Badley, 1990; Mansfield & Cartwright, 1996). Imaging of fault geometry and layer orientation (drag) is, however, strongly dependent on seismic data quality relative to the size of the structure. In our experience, the choice of seismic data processing method may in some cases be crucial to whether overlap structures can be mapped from seismic data.

The seismic examples chosen here are located within Cretaceous and Jurassic stratigraphy cut by the Oseberg Fault. This fault is a large normal fault on the Horda Platform of the northeastern North Sea (Færseth & Ravnås, 1998). The fault was moved repeatedly during Permo-Triassic and late Jurassic–early Cretaceous rifting events. Post-tectonically, it was reactivated due to differential compaction across the fault crest as the subsequent Cretaceous and Tertiary sediments accumulated, i.e. the comparatively thicker Cretaceous sequence in the hanging-wall compacted more than the pre-Cretaceous strata in the footwall. During the Cretaceous–Tertiary sedimentation history, fault growth apparently started at several places along the scarp above the Oseberg Fault. Detailed seismic mapping has revealed that these segments overlapped not only laterally but also vertically to form a system of overlapping segments, as shown in Fig. 4. Layer orientation is not well-imaged in and near the overlap zone in this case, as in most cases where such structures are interpreted from seismic data. Thus, the interpretation partly hinges on the interpreter's experience drawing on field examples, numerical modeling, or experimental modeling.

Both releasing and restraining overlaps are interpreted along the fault. In Fig. 5(a), pronounced rotation of Jurassic layers in the upper part of the main Oseberg Fault is explained by rotation within a releasing overlap structure. The fold can be shown to be tectonic, as only a portion of the folding can be explained by differential compaction. The restraining overlap structure shown in Fig. 5(b) explains the rotation of the Upper Jurassic and Cretaceous layers within the overlap zone.

6. Experimental work

Simple experiments were performed to investigate and illustrate some of the basic geometrical features of the vertical overlap zones. Because the structures in question are largely scale independent, and since the purpose was a qualitative rather than quantitative investigation, the models were not scaled with respect to any particular natural example.

Clay layers were confined between two wooden plates that were pre-cut at 45°, as shown in Fig. 6. Clays with slightly different mechanical properties were used such that their competence contrast was representative of interbedded clay/sand sequences. Several runs were performed where fractures were pre-cut to produce the desired fault systems. The pre-cut fractures were activated in the dip direction as normal-slip shear fractures (i.e. oblique to the layering; Fig. 6(c)).

6.1. Two aligned, straight fault segments

The simplest case contained two aligned and straight fault segments that were cut through the upper and lower parts of the clay sequence (Fig. 7). As anticipated, this experiment produced a straight shear fracture with a poorly developed normal drag zone along the fault surface in the middle region, corresponding to Fig. 1(d).

6.2. Releasing overlap structures

Vertical overlap structures, where the fault steps upward into the hanging-wall block are shown in Figs. 6 and 8 (run B). A drag zone exhibiting normal rotation develops in the overlap area (Figs. 6, 8(b) and (c)). The geometry is similar to that shown in the seismic line in Fig. 5(a). This experiment illustrates how drag or smearing (if the overlap area is narrow) can occur locally along a fault that has grown by vertical linkage. Obviously, this type of overlap rotation may lead to smearing if displacement is increased (Fig. 6, run A).

A third experiment of this kind was performed with curved pre-cut fractures (Fig. 8, run C). A modest reverse (clockwise) rotation is seen within the overlap zone. This small rotation, which is opposite to that seen in run B, is due to the listric geometry of the footwall fault.

6.3. Restraining overlap structures

A restraining overlap experiment was performed with planar fault segments (Fig. 9, run D). Unlike the releasing overlap examples discussed earlier, planar faults did not generate layer rotation in the overlap zone. In the second experiment, where the pre-cut 'fault' tips curved toward each other, the overlap area shows marked reverse (clockwise) rotation (Fig. 9, run E). An example is given by the seismic line in Fig. 5(b). Thus, the sense of rotation is closely connected to the fault geometry.

An additional experiment involved two competent layers of clay (Fig. 10, run F). The width of the overlap zone was made narrow, and the step-like geometry of the linkage caused marked rotation or smearing of the adjacent competent layer (Fig. 10(c)). The resulting structure is in fact not an overlap structure, but a single fault surface with local smearing.

7. Observations of vertical overlaps in sandstone-shale sequences

7.1. Moab fault, Utah

A series of minor faults occur close to the main Moab fault near Arches National Park (Fig. 11). Striations indicate that they are normal faults and stratigraphic correlation

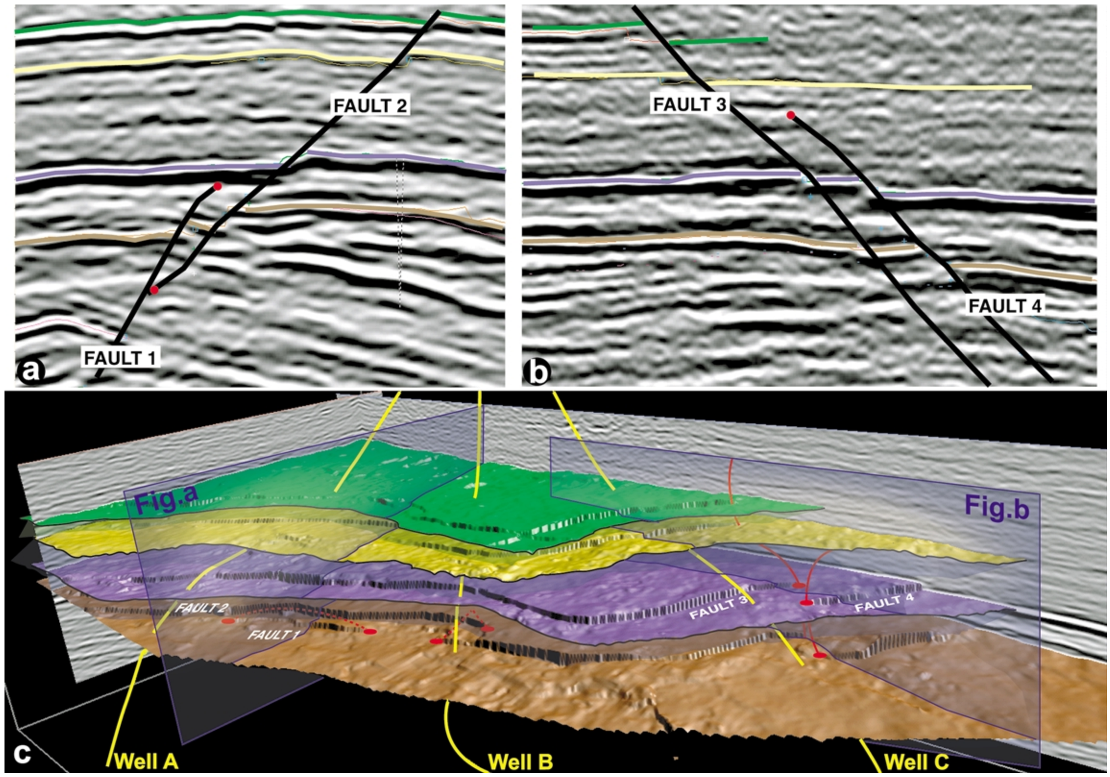

Fig. 4. Examples of overlap zones interpreted on seismic sections (3D seismic data cube) from the Oseberg Fault. (a) Fault segmentation with sub-horizontal tip lines. (b) Restraining overlap zone with sub-vertical tip lines. (c) 3D perspective of Oseberg Fault scarps, observed at four seismic surfaces of Cretaceous age. Surface colors correspond to those on the seismic lines (a and b). Wells are marked in yellow, tip lines in red. Length of profiles (a) and (b) is 7 km, and fault offset is in the range of 50–100 m.

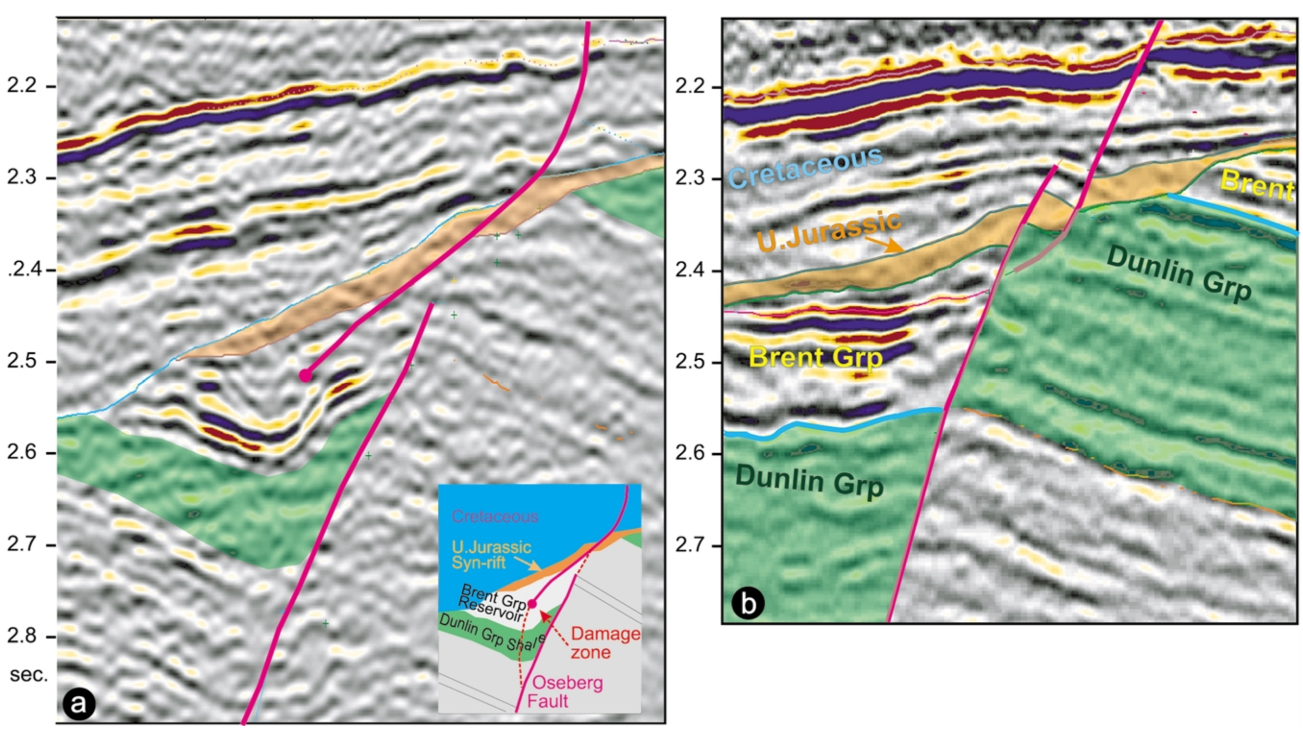

Fig. 5. (a) Example of normal drag of reservoir layers along the Oseberg Fault. Interpretation as a releasing overlap explains absence of drag in the underlying section. (b) Possible restraining overlap structure along the Oseberg Fault. Fault separation of the Upper Jurassic layer depends on reverse rotation within the overlap zone.

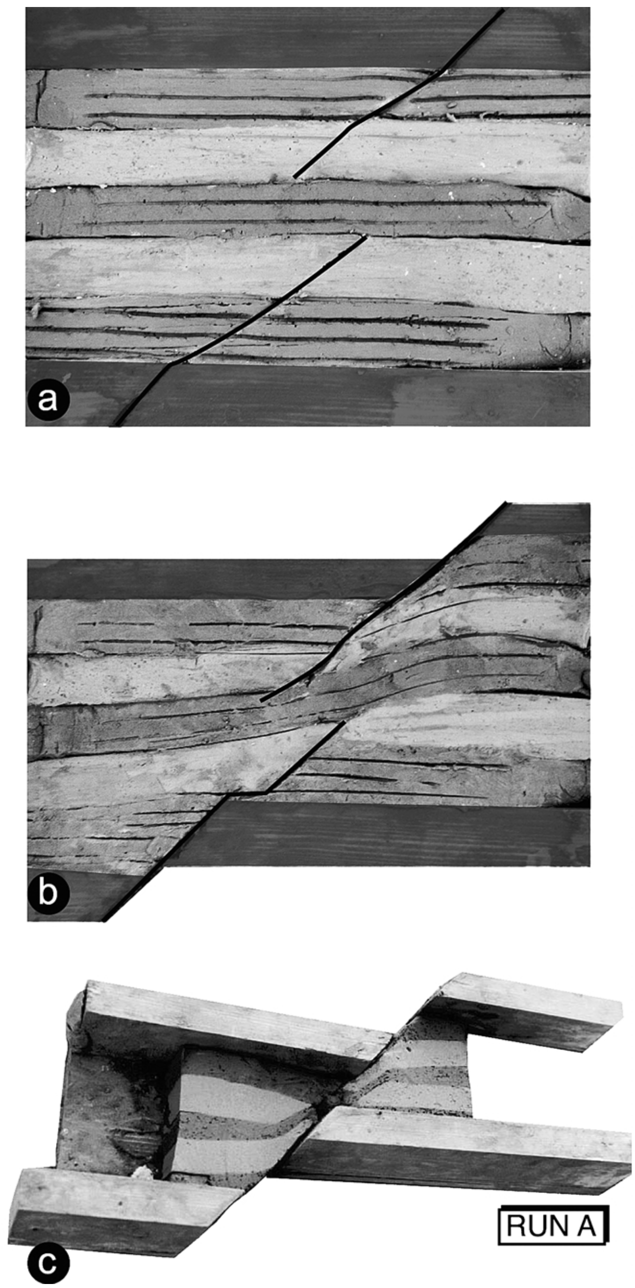

Fig. 6. Physical model experiment of a releasing fault overlap structure developed from pre-cut fractures in the clay layers. Layers show normal rotation and define as a zone of smearing at the final stage.

reveals offsets on the order of 1–10 m, whereas the Moab fault itself has accumulated close to 1 km of sub-vertical offset. A road cut along highway 191 provides an excellent section perpendicular to the strike of these faults. The faults affect sandstones with interbedded silty and shaly layers of the Permian Cutler Fm.

The faults are well defined, mm- to cm-thick zones of cataclasite with striated slip surfaces. General absence of drag in the sandstones suggests localization of strain along the weak fault surfaces. Drag is limited to local zones in silty layers, but only some of the faults show drag in these

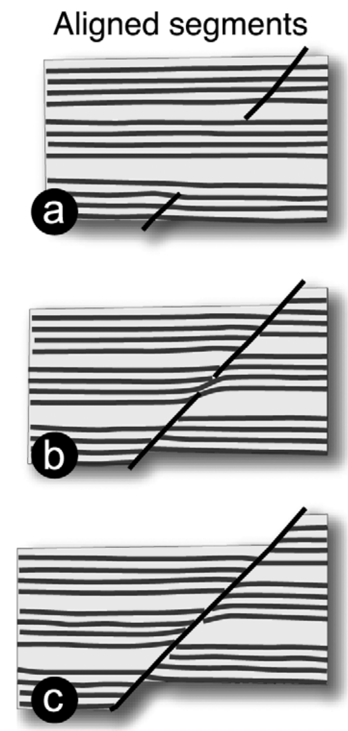

Fig. 7. Aligned fault segments in a simple clay model. Note normal drag zone between fault tips at stage b and the absence of fault overlap.

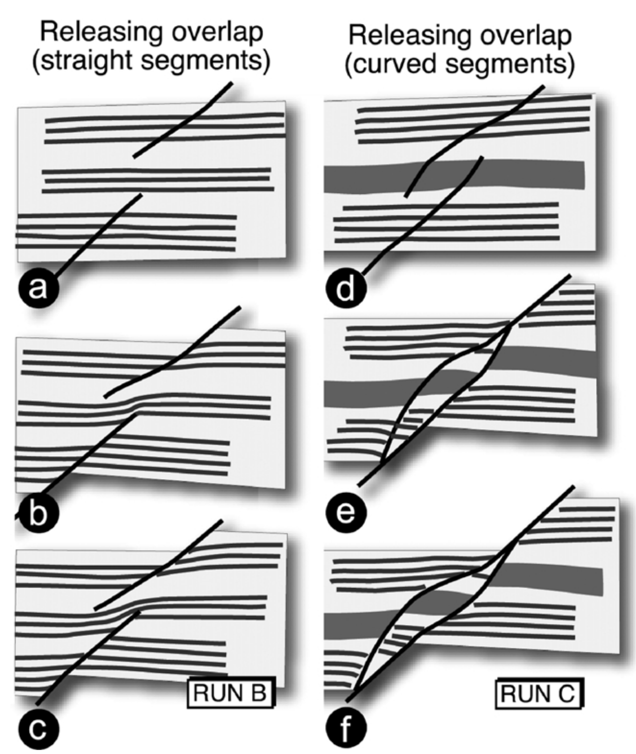

Fig. 8. Sketches of releasing overlap structures developed in clay resulting from pre-cut straight (run B) and curved (run C) fault segments. See text for discussion.

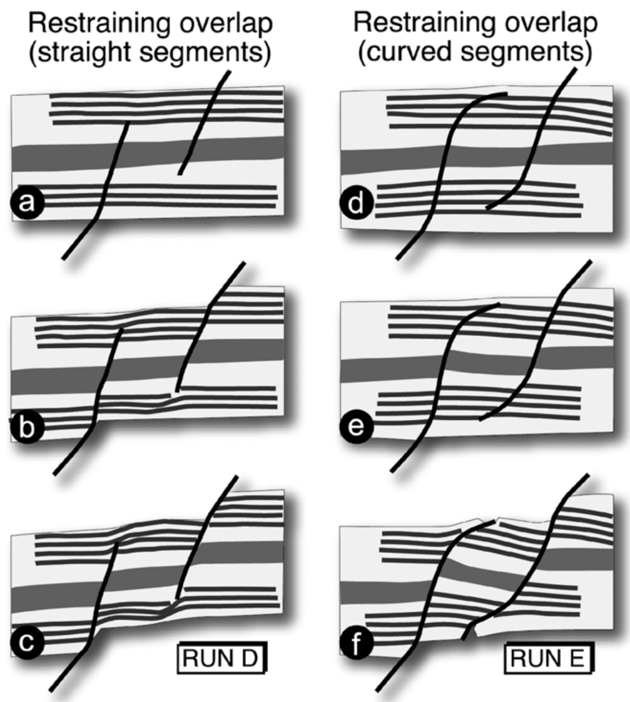

Fig. 9. Models of restraining overlap structures developed from a pre-cut fracture overlap configuration in the clay layers. Run D: straight fault tips. Run E: curved fault tips. Layers in the overlap zone show little rotation for run D, but the listric fault geometry causes backward (reverse) rotation in run E.

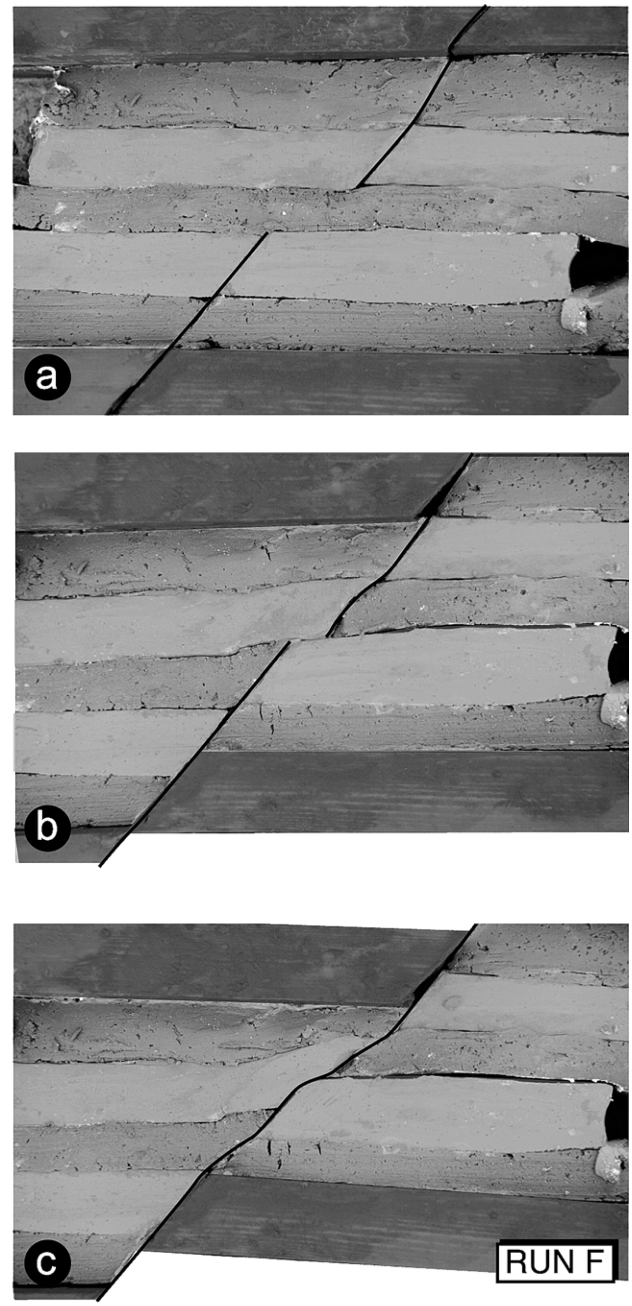

Fig. 10. Two fault segments growing into a non-planar fault structure. (b) The fault segments form a restraining overlap structure where the gray clay has been extruded. (c) The fault segments join to form a ramp. Note that the normal rotation of the clay layer above the fault bend at this stage.

layers (Fig. 11). Hence, drag cannot be controlled by host-rock lithology alone. The variable development of drag in the same silty layer could be a result of two faulting events under different physical conditions. However, we think that these faults developed during the same phase of deformation at more or less the same burial depth because of their consistent orientations and slip directions (Fig. 11), their similar fault rock products, and the absence of deformation bands of the kind seen in higher (Triassic–Jurassic) sandstones (Antonellini & Aydin, 1994). Instead, we believe that the local drag is controlled by fault interaction and the formation of overlap zones.

Three examples of what can be interpreted as narrow, releasing overlaps can be seen in Fig. 11 (red lines). The right inset figure shows a closer view of one of these. We interpret this as layer rotation similar to that seen in run B (Fig. 8). An example of counterclockwise rotation of layers is seen in the middle of the picture which may also be related to the fault overlap processes (restraining overlap), but a larger exposed section would be required to evaluate the details of this structure. No clay smear is seen along this zone, where the lower and upper sands are in direct contact across the fault (Fig. 11, left inset).

7.2. San Rafael Swell, Utah

A number of vertical overlap structures are exposed in alternating sand-silt/shale sequences of the Jurassic Entrada Formation on the east flank of the San Rafael Swell. Fig. 12 shows two overlapping planar faults forming a releasing overlap structure. The marked normal rotation of layer A is consistent with the rotation obtained in the experimental model of a releasing overlap zone bound by planar faults (Fig. 8, run B).

In a near-by locality, two overlaps occur along the same fault zone (Fig. 13). The lower is a releasing overlap, where the layers are rotated in a normal sense, similar to the

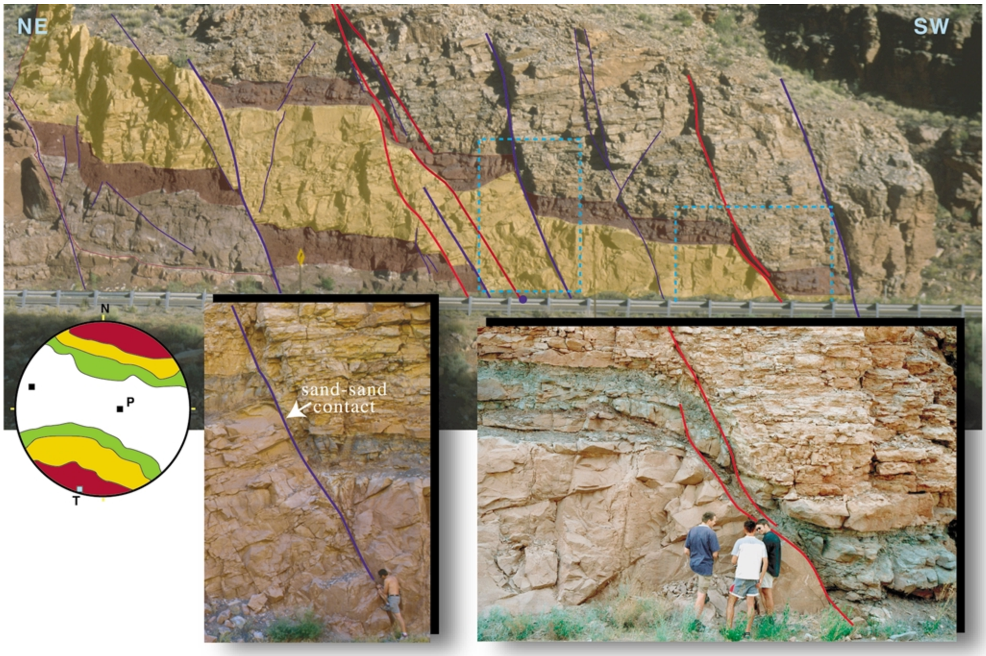

Fig. 11. Minor faults in the Permian Cutler Fm. close to the main Moab fault at road cut near Arches National Park, Utah. Rotation and smearing of silty/shaly layers is highly variable and related to the presence of releasing fault overlap zones (red fault lines). Inset: kinematics of the fault population. See text for discussion.

example above. In contrast, the upper overlap is restraining and a marked reverse rotation of the layers within the zone is seen. The zone is bounded by curved fault tips, and we interpret this example as analogous to run E (Fig. 9).

An example of a restraining overlap zone along a reverse fault system is shown by Fig. 14, where two moderately dipping fault segments interact. Layers are rotated in an area between and around the fault tips. In addition, fractures are widespread in the area of folding, forming a damage

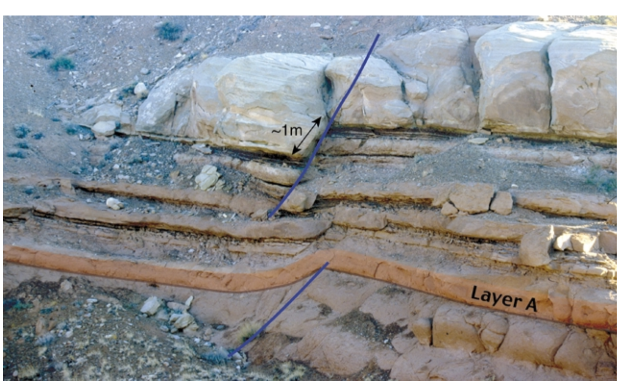

Fig. 12. Releasing overlap zone in the Entrada Sandstone, E. Flank of San Rafael Swell, Utah. The upper sandstone layer is cut by the fault without any sign of rotation (drag), whereas the lower sandstone layer above the lower fault tip show well-developed normal rotation consistent with Fig. 7(c). Shale layers above show significant changes in layer thickness, which may explain the more gentle rotation of the upper part of the overlap zone.

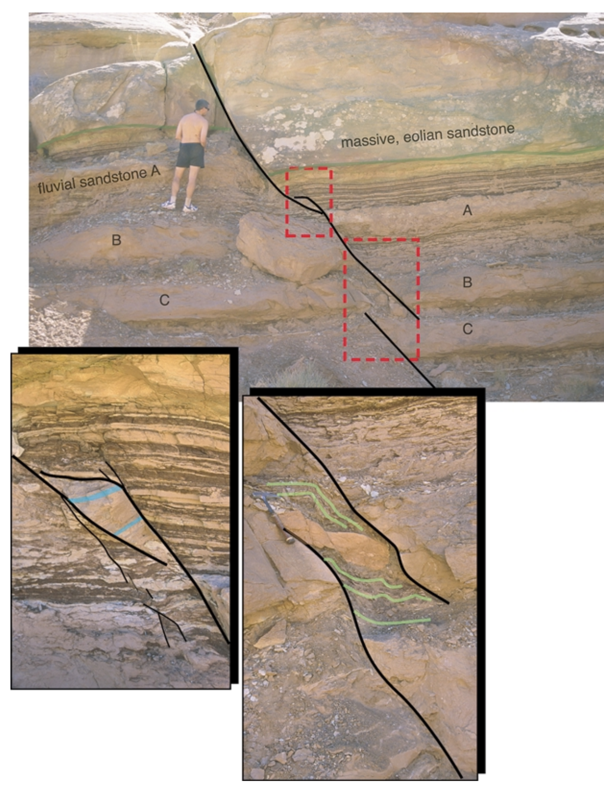

Fig. 13. Locality near Fig. 12, showing a releasing (lower) and a smaller restraining overlap zone in the Entrada Sandstone. The sense of rotation within the overlap zones is opposite in the two cases (reverse for the restraining and normal for the releasing zone), consistent with rotations shown in Fig. 1 and in experiments.

zone that is much wider here than along the faults away from the overlap zone.

8. Observations of drag and vertical overlaps in shale/limestone

Faulted marls and calcareous sandstones of the Eocene Green River Formation are well exposed along the highway east of Thistle, Utah. The small-scale restraining overlap zone shown in Fig. 15 contains layers that show reverse rotation. The sense of rotation and overlap geometry is consistent with Figs. 1(k) and 9 (run E). A releasing overlap zone is also preserved along the same fault zone, where rotation is normal and consistent with Fig. 8 (run B).

A larger-scale fault structure exists in the same area (Fig. 16). Based on the observations and experiments described earlier, we interpret this structure as a part of a large overlap zone, even though the outcrop does not extend far enough vertically to verify this interpretation. However, the sense of rotation and termination of one of the faults is consistent with a releasing overlap zone (e.g. run B in Fig. 8). This situation may be comparable to a poorly imaged seismic example, where an interpretation largely depends on the interpreter's knowledge of geometric relations between the layer orientation, fault geometry, and fault termination (Fig. 5).

9. Discussion and conclusions

Vertical overlap structures are common features at a wide range of scales. Both field examples and preliminary experimental results consistently show that there is a relationship between the type (geometry and kinematics) of overlap structure and the sense of rotation of the layers involved. In general, normal rotation occurs in releasing overlap zones while reverse rotation is commonly observed within the restraining zones. However, a number of factors influence the amount or even the sense of rotation. In particular, the rotational effect of curved overlapping fault tips is significant, and may control the sense of layer rotation. This effect was seen in run C (Fig. 8) where curved fault segments caused reverse rotation of a competent layer in a releasing overlap zone at the mature (hard-linked) stage.

The strain and the way the strain is accommodated in the zone are also important. For example, if layer thickness is preserved, reverse rotation can occur in restraining overlaps. However, if local volume changes take place, rotation is generally reduced or even absent.

Interpretation of rotations around and along fault surfaces may be difficult and relies on the interpreter's knowledge of feasible geometries and relationships. Apparent rotation of layers along faults can be related to geophysical noise or incorrect migration. Only if the rotations observed show a relationship with fault geometry and displacement gradients that is consistent with observed or modeled examples, can they be confidently interpreted as real structures.

9.1. Formation of overlap zones

Overlap zones are typically localized within the most ductile (weakest) layer within the faulted sequence, typically clay or shale layers. This can be interpreted to indicate that faults nucleate in brittle (sand or chalk) layers, not in the more ductile clay layers or at the clay–sand interface (Gupta & Scholz, 2000; Koledoye et al., 2000). The fact that many faults show displacement maxima within the sand layers (Fossen & Hesthammer, 1997; Schulz & Fossen, 2002) and disappears or loose displacement in adjacent shaly layers supports this model. Propagation of faults in sand layers gives rise to overlap zones across the shale layer. Du and Aydin (1991) demonstrated how an echelon crack will prefer to interact with another crack that has the same, consistent sense of step. These findings, although calculated for dilatant cracks, may also apply to fault growth and could explain why the sense of vertical stepping along a fault system through a layered sequence is consistent in many cases (Koledoye et al., 2000).

An important consequence of this model is that the thicknesses of the stratigraphic units imposes a control on both the location, frequency and scale of the overlap structures. Layer thickness of a few meters will give rise to meter-scale overlap zones that affect reservoir communication. As such fault systems continue to grow, these overlaps will be breached and the fault zone will form a continuous structure with unusually thick damage zones at breached overlap locations. However, the same sedimentary succession may be divided into larger-scale layers, each consisting of predominantly shale or sand. Larger faults may respond to this scale of heterogeneity to form vertical overlaps that affect the sealing potential of these larger faults in a similar, upscaled fashion.

9.2. Implications for reservoir communication

Uncertainties related to the interpretation of structural rotations along and adjacent to fault surfaces and within large-scale overlap zones can be substantial, even in areas of good seismic data quality. The observations described in this article help to reduce such uncertainties by providing some useful relationships and rules that can be applied during seismic interpretation.

In addition to seismic-scale fault structures, smaller subseismic layer rotations significantly influence reservoir performance. Since overlap zones are often located within the shaly layers in sandstone-shale sequences, layer thickness could control the frequency and size of overlap structures in many reservoir settings. Normal rotation in vertical overlap zones (and normal drag in general) reduces the effective throw on a fault, while reverse rotation increases the throw. In this sense, normal rotation is likely to increase

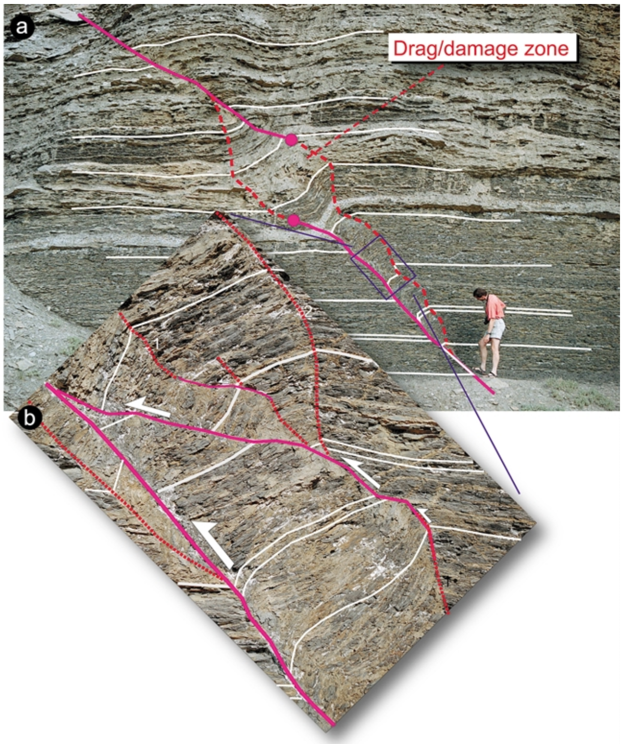

Fig. 14. (a) Reverse faults forming a restraining overlap zone near the NE termination of the San Rafael Swell, Utah. The boundary of the damage zone is marked with a red, dashed line. (b) Close-up of the complex internal structure of the zone.

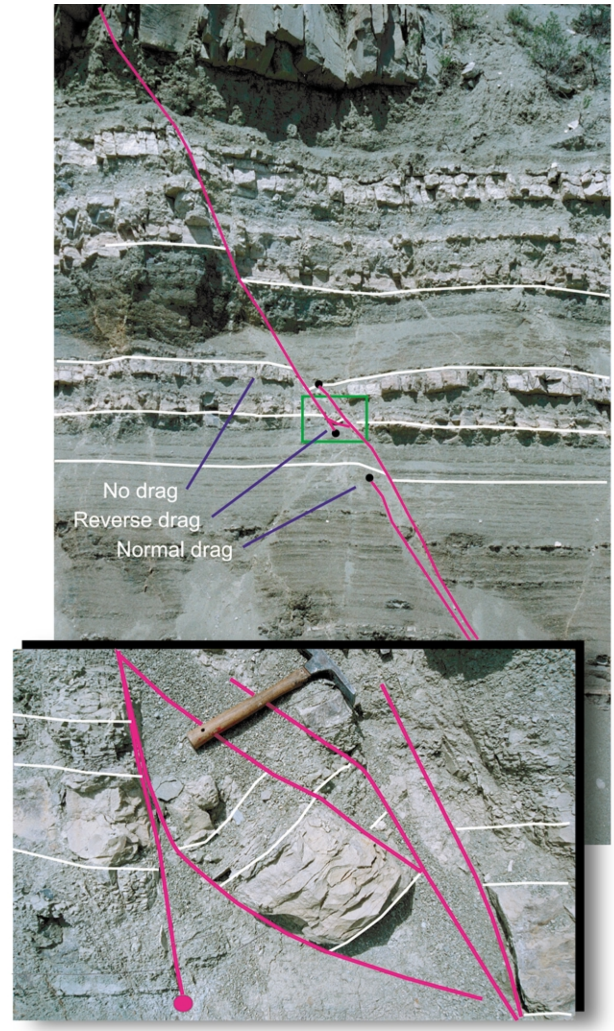

Fig. 15. Restraining overlap zone in Eocene marls and calcareous sandstones of the Eocene Green River Formation, Utah. Reverse rotation within the zone is consistent with that anticipated from Fig. 1(j) and (k) and run E (Fig. 9), and is probably controlled by curved fault tips. A smaller, releasing overlap zone below shows the opposite sense of rotation (normal drag).

reservoir communication for a single-layer reservoir model, while its effect on multi-layer reservoirs is harder to predict. On an exploration scale, the reduction of discontinuous offset along larger faults by normal drag related to releasing overlap structures may cause leakage across faults that might otherwise appear to be sealing. However, normal rotation in vertical releasing overlap zones also has a higher potential for clay smear, such as shown in Fig. 11. This is particularly true if the overlap zone is

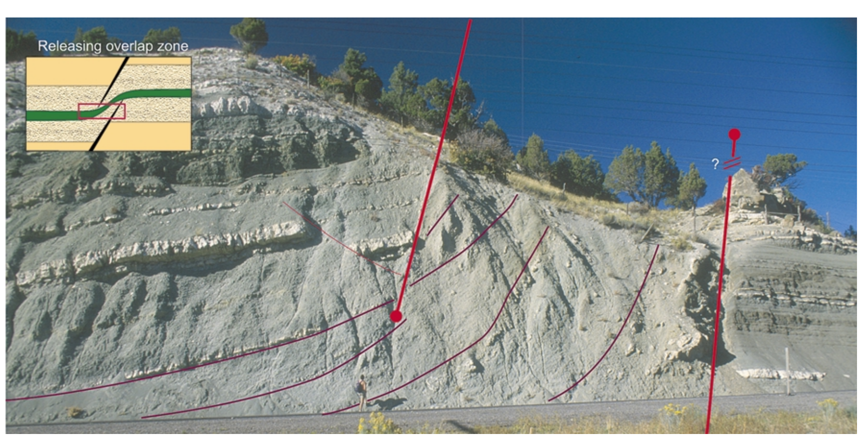

Fig. 16. Fault zone showing some tens of meters of throw in the Mill Fork area. The observations and experiments described in this article allow us, with some confidence, to interpret this structure as a releasing overlap zone, as indicated from the inset figure.

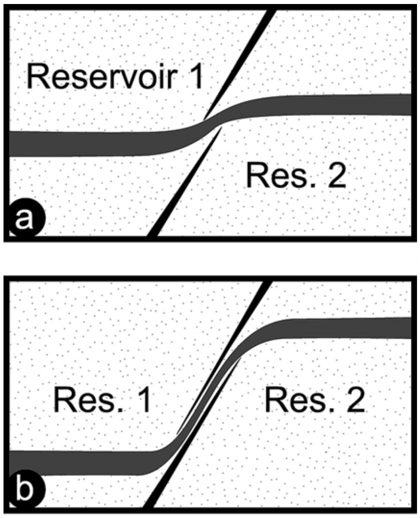

Fig. 17. A simple model where two fault tips approach and overlap to form a narrow releasing overlap zone. In shale-sandstone sequences, overlaps of this kind tend to form at shale layers, which may then be smeared along the zone as offset accumulates.

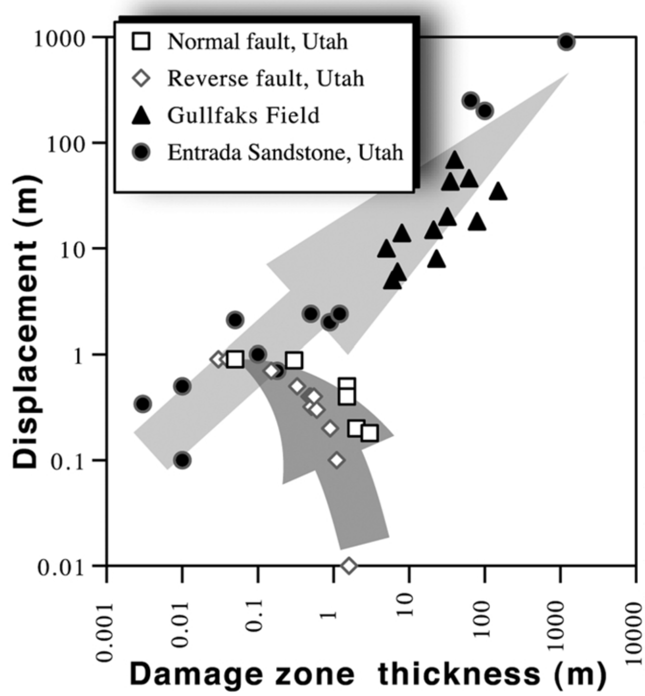

Fig. 18. Plot of damage zone thickness against displacement as measured along two faults with overlap structures from the Colorado Plateau, Utah. The lower, twisted arrow points from the areas of fault overlaps, showing how the damage zones thin away from the fault even though displacement increases. The general trend (long arrow) is illustrated by other faults from the Entrada Sandstone (Utah) and from the North Sea.

narrow and the degree of overlap is large, such as shown in Fig. 17. Here, reservoirs 1 and 2 appear to be juxtaposed, but the presence of smearing (rotation) of the associated clay layer in the overlap zone will hinder communication. This model is similar to that presented by Lehner and Pilaar (1997).

It is shown that overlap zones are often localized within ductile shale or clay layers between sand layers. This relationship is important, as it increases the likelihood of clay or shale smear through the model indicated in Fig. 17. Another important factor is that releasing vertical overlaps appear to be more common than restraining overlaps in extensional settings. About 75% of our own observations are releasing overlaps, and a review of published examples of vertical overlap zones (cf. examples shown in Childs et al., 1996, Koledoye et al., 2000, Mansfield and Cartwright, 1996, Peacock and Zhang, 1993) strengthens this impression. Hence, clay or shale smearing through the mechanism shown in Fig. 17 is likely to predominate and should be considered during reservoir modeling of sandstone-shale sequences. However, if a considerable number of faults affect the given shale layer, it is unlikely that they all developed narrow vertical releasing overlap structures. Some are likely to cut through the impermeable layer and cause communication.

As pointed out by various authors (Childs et al., 1996), fault overlap structures form and become destroyed continuously during the deformation history of an extensional basin. Besides abnormal layer orientations along the faults, this process also results in a marked increase in damage zone thickness at locations where an overlap zone is or has been located (Fig. 18). In rocks where deformation bands or other micro-faults involve significant permeability reductions, a wider and denser damage zone may partly compensate for smaller offsets on individual faults. If the damage zone consist of low-permeable micro-faults or deformation bands, a wide zone with many such fractures will lower the permeability across the fault in the overlap region.

9.3. Concluding remarks

Vertical overlap structures may often be overlooked in most reservoir development plans and models. We are not at a stage where quantitative guidelines can be given as to how the presence and effect of such structures can be incorporated in reservoir models. However, we urge seismic interpreters and structural geologists alike to be aware of their presence as seismic data are interpreted and reservoir models are evaluated. Knowledge of the relationships between drag or layer rotation and the type of fault geometry discussed in this work can help to interpret such structures and predict their influence on reservoir performance. The effect of such structures should be considered in cases where reservoir performance differs from that modeled. Our current knowledge indicates that releasing zones where layers are rotated in a normal sense are more common in clastic reservoir settings than restraining zones. Hopefully, focus on this issue will help increase our understanding of these important structures in the future.

Acknowledgements

The authors thank Norsk Hydro ASA for permission to publish the seismic examples. Peter Bentham and David G. Roberts are thanked for very constructive and useful comments.

References

Antonellini, A., & Aydin, A. (1994). Effect of faulting on fluid flow in porous sandstone: Petrophysical properties. *American Association of Petroleum Geologists Bulletin*, *78*, 181–201.

Chapman, T. J., & Meneilly, A. W. (1990). Fault displacement analysis in the seismic exploration. *First Break*, *8*, 11–22.

Childs, C., Nicol, A., Walsh, J. J., & Watterson, J. (1996). Growth of vertically segmented normal faults. *Journal of Structural Geology*, *18*, 1389–1397.

Childs, C., Walsh, J. J., & Watterson, J. (1997). Complexity in fault zone structure and implications for fault seal prediction. In P. Møller-Pedersen & A. G. Koestler (Eds.), *Hydrocarbon seals: Importance for exploration and production*. *NPF Special Publication*, *Vol. 7* (pp. 61–72). Amsterdam: Elsevier.

Du, Y., & Aydin, A. (1991). Interaction of multiple cracks and formation of echelon crack arrays. *International Journal of Numerical and Analytical Methods in Geomechanics*, *15*, 205–218.

Færseth, R. B., & Ravnås, R. (1998). Evolution of the Oseberg Fault-Block in context of the northern North Sea structural framework. *Marine and Petroleum Geology*, *15*, 467–490.

Fossen, H., & Hesthammer, J. (1997). Geometric analysis and scaling relations of deformation bands in porous sandstone. *Journal of Structural Geology*, *19*, 1479–1493.

Freeman, B., Yielding, G., & Badley, M. (1990). Fault correlation during seismic interpretation. *First Break*, *8*, 87–95.

Groshong, R. H. (1999). *3-D structural geology*, New York: Springer.

Gupta, A., & Scholtz, C. H. (2000). A model of normal fault interaction based on observations and theory. *Journal of Structural Geology*, *22*, 865–879.

Hesthammer, J., & Fossen, H. (1998). The use of dipmeter data to constrain the structural geology of the Gullfaks Field, northern North Sea. *Marine and Petroleum Geology*, *15*, 549–573.

Hobbs, B. E., Means, W. D., & Williams, P. F. (1976). *An outline of structural geology*, New York: Wiley, pp. 571.

Huggins, P., Watterson, J., Walsh, J. J., & Childs, C. (1995). Relay zone geometry and displacement transfer between normal faults recorded in coal-mine plans. *Journal of Structural Geology*, *17*, 1741–1755.

Koledoye, A. K., Aydin, A., & May, E. (2000). Three-dimensional visualization of normal fault segmentation and its implication for fault growth. *The Leading Edge*, *July*, 692–701.

Larsen, P.-H. (1988). Relay structures in a lower Permian basement-involved extension system, East Greenland. *Journal of Structural Geology*, *10*, 3–8.

Lehner, F. K., & Pilaar, W. F. (1997). In P. Møller-Pedersen & A. G. Koestler (Eds.), *The emplacement of clay smears in synsedimentary normal faults: Inferences from field observations near Frechen, Germany*. *NPF Special Publication*, *7* (pp. 39–50). Amsterdam: Elsevier.

Lia, O., Omre, H., Tjelmeland, H., Holden, L., & Egeland, T. (1997). Uncertainties in reservoir production forecasts. *American Association of Petroleum Geologists Bulletin*, *81*, 775–801.

Mansfield, C. S., & Cartwright, J. A. (1996). High resolution fault displacement mapping from three-dimensional seismic data: Evidence for dip linkage during fault growth. *Journal of Structural Geology*, *18*, 249–263.

Manzocchi, T., Ringrose, P. S., & Underhill, J. R. (1998). In M. P. Coward, H. Johnson & T. S. Daltaban (Eds.), *Flow through fault systems in high porosity sandstones*. *Special Publications*, *127* (pp. 65–82). London: Geological Society.

Nicol, A., Watterson, J., Walsh, J. J., & Childs, C. (1996). The shapes, major axis orientations and displacement patterns of fault surfaces. *Journal of Structural Geology*, *18*, 235–248.

Peacock, D. C. P., & Sanderson, D. J. (1991). Displacements, segment linkage and relay ramps in normal fault zones. *Journal of Structural Geology*, *13*, 721–733.

Peacock, D. C. P., & Zhang, X. (1993). Field examples and numerical modelling of oversteps and bends along normal faults in cross-section. *Tectonophysics*, *234*, 147–167.

Reches, Z., & Eidelman, A. (1995). Drag along faults. *Tectonophysics*, *247*, 145–156.

Schultz R.H., & Fossen, H. (2002). Displacement-length scaling in three dimensions: The importance of aspect ratio and application to deformation bands. *Journal of Structural Geology*, in press.

Trudgill, B., & Cartwright, J. (1994). Relay-ramp forms and normal-fault linkages, Canyonland National Park, Utah. *Geological Society of America Bulletin*, *106*, 1143–1157.

Watterson, J. (1986). Fault dimensions, displacement and growth. *Pure and Applied Geophysics*, *124*, 366–373.

Willemse, E. J. M., Pollard, D. D., & Aydin, A. (1996). Three-dimensional analyses of slip distributions on normal fault arrays with consequences for fault scaling. *Journal of Structural Geology*, *18*, 295–309.