GEOLOGIC NOTE

Fault linkage and graben stepovers in the Canyonlands (Utah) and the North Sea Viking Graben, with implications for hydrocarbon migration and accumulation

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ABSTRACT

Segmented graben systems develop stepovers that have important implications in the exploration of oil and gas in extensional tectonic basins. We have compared and modeled a representative stepover between grabens in Canyonlands, Utah, and the North Sea Viking Graben and, despite their different structural settings, found striking similarities that pertain to other graben systems. In both cases, the stepovers represent relatively high parts within the graben systems that are likely to be among the first to be filled with hydrocarbons generated in deeper parts of the grabens. Furthermore, the relay ramps and smaller fault offsets in stepovers ease hydrocarbon migration and allow stepovers to act as preferred migration routes from deep graben kitchens to structurally higher traps in the basin. Graben stepovers and their related structures should be paid special attention during exploration because they may represent hydrocarbon accumulations complementary to larger traps along the graben flanks. These observations explain the location of the Kvitebjørn, Valemon, and Huldra fields in a stepover structure of the Viking Graben and encourage increased focus on similar graben stepovers in the Viking Graben and other graben systems.

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INTRODUCTION

Large-scale lateral shifts or steps in graben axes (Figure 1) are well known from many continental rift systems, such as the East African rift system (Rosendahl et al., 1986; Morley et al., 1990; Nelson et al., 1992), the Oslo rift (Sundvoll and Larsen, 1994), the Rheine rift (Ziegler, 1992), the Suez rift (Bosworth, 1995), and the Rio Grande rift (Mack and Seager, 1995), as well as from mid-ocean rift systems (e.g., Sempéré et al., 1993). In the well-explored Late Jurassic North Sea passive rift system, the Viking Graben defines the central rift graben between latitudes 60 and 62° (Figure 2). The Viking Graben is segmented in a consistent right-stepping sense (Figures 3, 4). Some of the largest North Sea offshore oil fields (e.g., the Statfjord, Gullfaks, Snorre, and Oseberg fields) are located on the flanks of the Viking Graben, and several smaller hydrocarbon-filled structures have recently been discovered in the same area. Although the giant oil and gas fields are located on the elevated rift margins, several smaller fields and plays are found in areas of overlapping graben segments. The coincidence between graben transfer zones or stepovers and hydrocarbon accumulations is intriguing and far from coincidental: we suggest that these accumulations are related to specific structural characteristics of graben stepovers. Although various structural characteristics of graben stepover structures and rift accommodation zones have been discussed in several previous works (e.g., Rosendahl, 1987; Morley et al., 1990), we will focus here on structural parallels between graben stepovers in the Viking Graben and a geometrically similar graben system in the Canyonlands, Utah. Based on the comparison between the exceptionally well-exposed Canyonlands example and the larger-scale Viking Graben, along with calculations of graben-related topography and boundary-fault propagation, we discuss the implications of graben segmentation to petroleum exploration.

RELAY STRUCTURES AND GRABEN SEGMENTATION

Faults grow from smaller-scale structures by accumulation of slip through seismic activity and aseismic creep (e.g., Cowie et al., 2007). During the evolution of fault populations, individual faults interact and overlap, forming relay structures (e.g., Larsen, 1988; Childs et al., 1995). A relay structure, also referred to as a stepover, is the site of displacement transfer between two faults. Where displacement is transferred by means of ductile folding of the stratigraphy between the overlapping normal

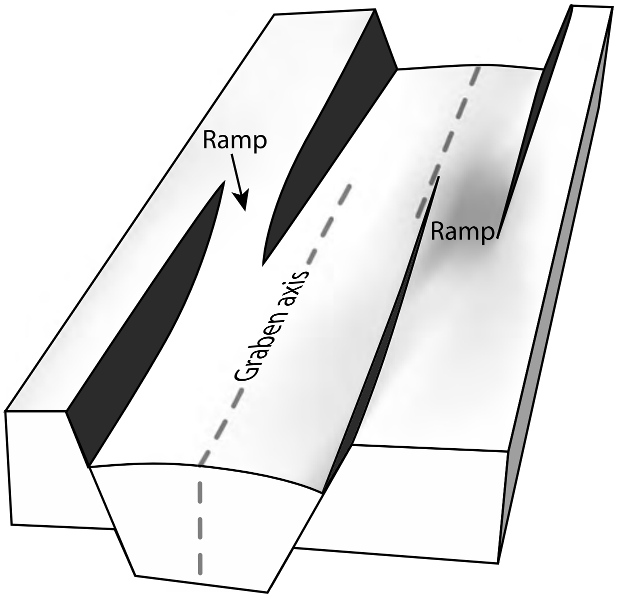


Figure 1. Concept of a graben stepover, with associated relay ramps and shift in graben axes.

fault tips (e.g., Willemse, 1997), the area is defined as a relay ramp (e.g., Peacock and Sanderson, 1994). Relay ramps may accumulate strain until the rocks in the ramp fail in shear (Crider and Pollard, 1998). At this point, the two fault segments become physically connected by the formation of one or more through-going faults (Soliva and Benedicto, 2004). The resulting structure is referred to as a breached relay ramp (Childs et al., 1995).

Relay ramps are formed and destroyed (breached) continually throughout the growth history of a fault population. Furthermore, they form at a wide range of scales, from centimeter-scale structures observable in hand sample to map-scale structures up to 100 km wide (Peacock et al., 2000; Soliva and Benedicto, 2004). Relay structures in the form of relay ramps may negatively influence the sealing capacity of faults and have a positive effect on communication across faults during migration as well as production of water and hydrocarbons (Bense and Balen, 2004; Rotevatn et al., 2007, 2009a, b).

Graben systems also evolve through fault interaction and linkage, except that they contain two sets of oppositely dipping faults. Hence, where a shift in the axis of a simple graben exists, two oppositely dipping relay ramps form (Figure 1). One of the best exposed examples of laterally stepping or echelon grabens and associated relay ramps is found in the grabens area of Canyonlands National Park in southeast Utah, an example that can be scaled up to fit the larger scale Viking Graben of the northern North Sea. We refer to areas where grabens shift perpendicular to their strike direction as graben stepovers in this article.

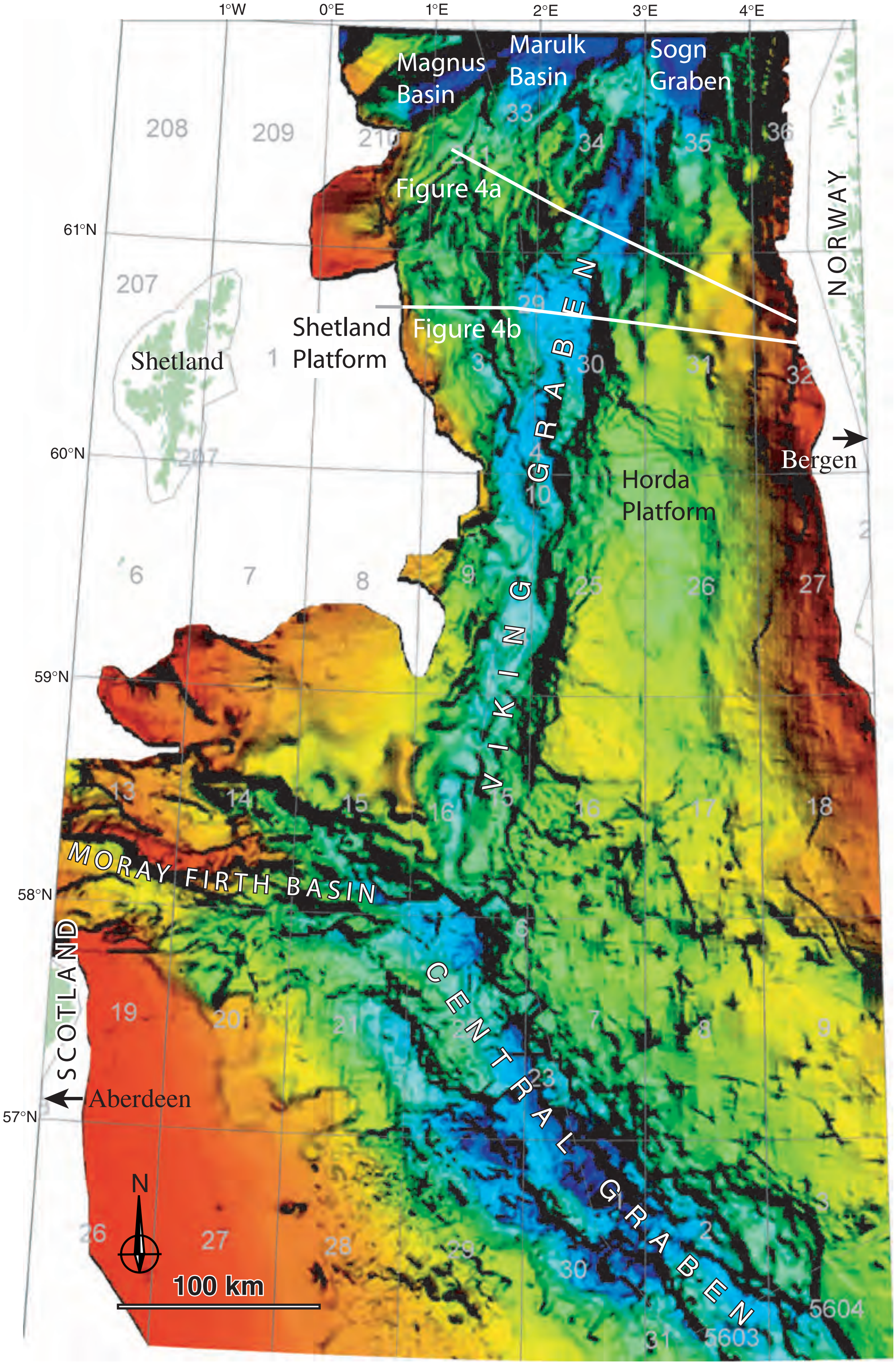
SEGMENTED VIKING GRABEN

The Viking Graben forms the central graben and the structurally lowest part of the North Sea rift system, extending about 500 km (311 mi) from the triple junction with the Central Graben and the Moray Firth Basin in the south to the Sogn Graben in the north (Figure 2). The North Sea rift system has experienced two main phases of rifting; one during the Late Permian to Early Triassic and one during the late Middle Jurassic to earliest Cretaceous (e.g., Roberts et al., 1993; Færseth, 1996). The Viking Graben per se is a result of the latter phase; the axis of maximum extension was located farther east during the precursory Permian–Triassic phase (Færseth et al., 1995).

Geometrically, the Viking Graben is irregular in map view, stepping sideways along strike. In the northern part, this is particularly well developed in the form of right-stepping graben segments. Individual segments are about 30 km (18.6 mi) wide and 50–100 km (31–62 mi) long in this area, and the northern segment has been named the Sogn Graben (Figure 3). However, the exact width of the graben segments is not always well constrained because of the complexity of faulting and fault interaction along the graben margins.

In cross section, the Viking Graben ranges from almost symmetric (Figure 4b) to asymmetric with a faulted rollover structure on the east side (Figure 4a). Graben-bounding faults show Late Jurassic offsets up to approximately 3 km (2 mi) and are clearly curved in map view. The Late Jurassic extension across the Viking Graben is estimated to be 40–50% (Roberts et al., 1993; Odinsen et al., 2000).

Figure 2. North Sea rift system and location of the Viking Graben relative to Norway, Scotland, and the triple junction with the Central Graben and the Moray Firth Basin. The mapped surface is the base Cretaceous, and cool colors indicate deep depths. Modified from Evans et al. (2003). Reprinted by permission of the Geological Society (London).



VIKING GRABEN STEPOVERS

We will pay particular attention to the two graben stepovers in the northern part of the Viking Graben. These zones, here called the Huldra-Kvitebjørn and Viking-Sogn Graben stepovers, are areas where the graben axis has been offset laterally by an amount corresponding to the width of the graben segments

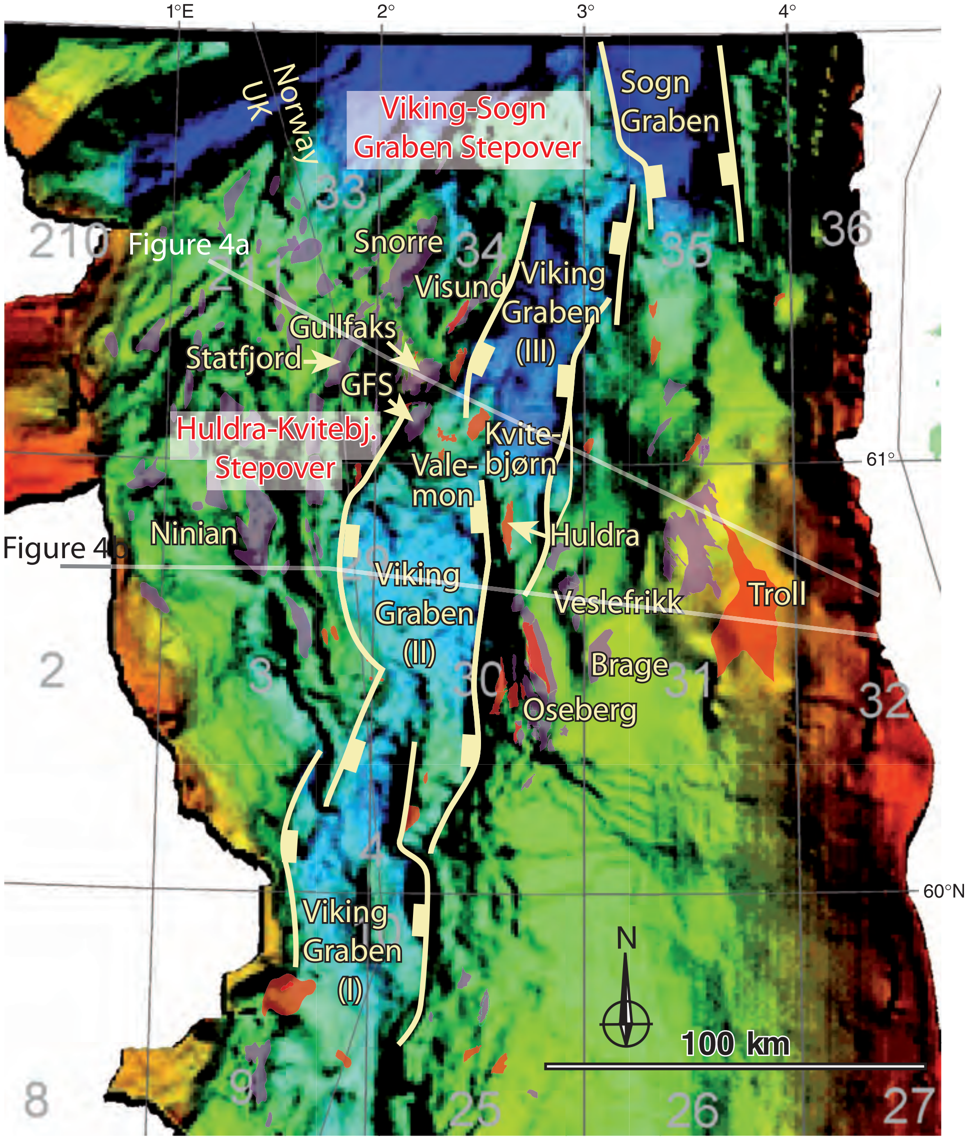


Figure 3. Detail of Figure 2, showing the northern part of the Viking Graben and the segments discussed in the text. GFS = Gullfaks Sør field.

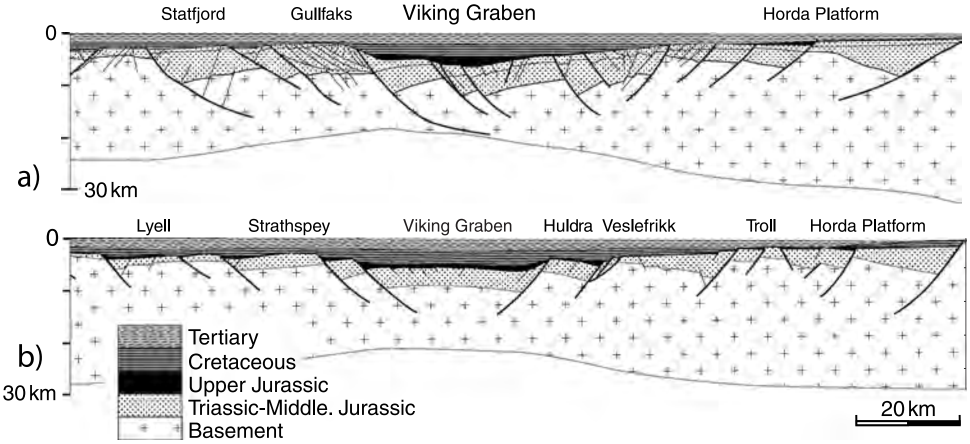


Figure 4. Profiles across the Viking Graben, modified from Odinsen et al. (2000). See Figure 3 for the location.

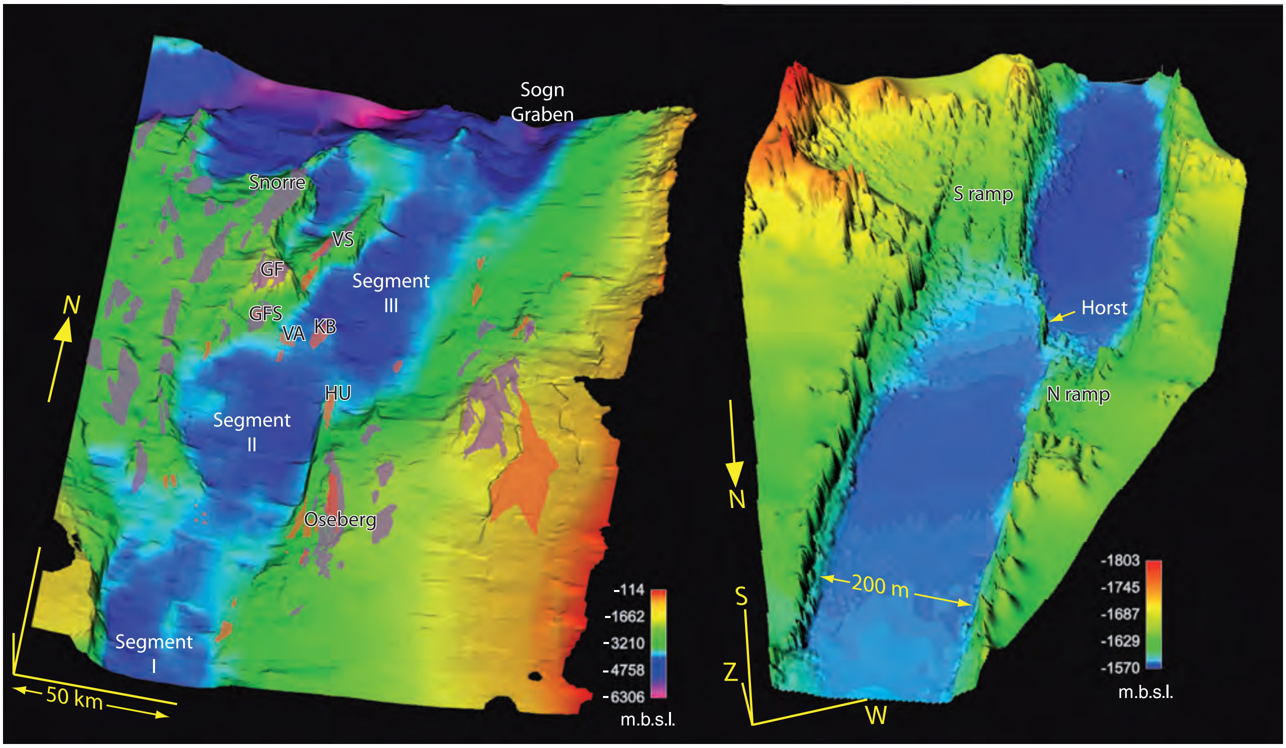


Figure 5. Northern part of the right-stepping Viking Graben system (left), illustrated at the base Cretaceous level, shown together with the Devils Lane stepover (Canyonlands, right; see Figure 6 for the location). Note high areas and relay ramps at graben stepovers. GF = Gullfaks field (360 million Sm^3 [12.7 billion Sft^3] recoverable oil, 24 billion Sm^3 [847 billion Sft^3] recoverable gas); GFS = Gullfaks Sør field (48 million Sm^3 [1.7 billion Sft^3] oil, 46 billion Sm^3 [1.6 trillion Sft^3] gas); HU = Huldra field (5 million Sm^3 [176 million Sft^3] oil, 16 billion Sm^3 [565 billion Sft^3] gas); KB = Kvitebjørn field (27 million Sm^3 [953 million Sft^3] oil, 74 billion Sm^3 [2.6 trillion Sft^3] gas); VS = Visund field (29 million Sm^3 [1.02 billion Sft^3] oil, 47 billion Sm^3 [1.6 trillion Sft^3] gas); VA = Valemon (at least 50 million Sm^3 [1.8 billion Sft^3] oil equivalents). m.b.s.l. = meters below sea level.

(~35 km [22 mi]) (Figures 3, 4). Although the map shown in Figure 3 presents a simplified picture of the complex pattern of faulting in this region, it illustrates some striking features that are important. One is that the depth of the grabens varies systematically within each graben segment, from deep in the central parts of the segments to remarkably shallow within the stepovers (Figure 5). Another is that hydrocarbon fields (Huldra and Kvitebjørn fields) are located in the highest parts within the Huldra-Kvitebjørn stepover, and several major oil fields (Gullfaks area and Oseberg-Veslefrikk area) are located immediately next to them. Furthermore, several relay structures are located in the graben stepovers, connecting the graben area with the hydrocarbon-filled highs in the vicinity of the stepovers. We find that these features are characteristic of many graben stepover zones, and we will explore them more closely by means of a well-exposed Canyonlands example.

CANYONLANDS GRABENS

The grabens area is located in the Needles district of Canyonlands National Park, Utah. In this area, several grabens have formed, and are still developing, in a 12-km (7-mi)-wide and 25-km (15-mi)-long area on the east side of the Colorado River (McGill and Stromquist 1979; Moore and Schultz, 1999; Trudgill, 2002; Furuya et al., 2007). The graben system, which on a large scale shows an arcuate shape, is developed in an approximately 460-m (1509-ft)-thick sequence of Carboniferous to Permian sandstones and subordinate limestones belonging to the Cutler, Rico, and Hermosa formations.

The sandstones rest on Pennsylvanian evaporite deposits (Paradox Formation) that outcrop along the base of this particular section of the Colorado River canyon.

The sedimentary strata in the grabens area dip very gently (~4°) toward the Colorado River canyon, and the graben system forms in response to a slow, gravity-driven translation of the sandstones and limestones toward the canyon incised by the Colorado River (McGill and Stromquist, 1979; Schultz-Ela and Walsh, 2002). Hence, the graben formation initiated after the Colorado River had eroded through the Carboniferous–Permian sandstones and into the underlying salt, a process that initiated during the late Cenozoic uplift of the Colorado Plateau.

Mechanically, the grabens form by faulting of preexisting joint sets that are extensively developed in this part of the Colorado Plateau. The joints, which are thought to have formed during the uplift and cooling history of the sedimentary rocks, are steeply dipping and in this area have accumulated shear displacements up to several hundred meters (up to 600–700 ft). During normal faulting, the grabens descended into the underlying salt, and these vertical movements are tied to dissolution and lateral flow of the underlying salt. In map view, the graben-bounding normal faults interact, and several outstanding exposures of graben stepovers and associated relay structures are found in the grabens area (Trudgill and Cartwright, 1994; Moore and Schultz, 1999).

The petrophysical properties of the Canyonlands faults are somewhat different from those found in the North Sea and most other reservoirs because of their near-surface formation by faulting of preexisting joints in well-lithified sandstones. This resulted in faults and joints that not only transmit but also vertically conduct fluid flow. In reservoirs such as those of the North Sea, where uplift is scarce or absent and where faulting occurred in unfractured sediments and sedimentary rocks, faults tend to represent tabular zones of reduced permeability that are more likely to influence fluid flow. In this article, we will focus on geometrical instead of petrophysical attributes between the Viking Graben and Canyonlands grabens, focusing on a particularly well-exposed stepover zone located in the Devils Lane graben of the Canyonlands area, given that the differences in fault properties are secondary to their geometric similarities and structural behavior.

DEVILS LANE

Devils Lane represents one of several asymmetric north-south–trending Canyonlands grabens with the main fault located on the west side of the graben. The east side is a gentle rollover structure affected

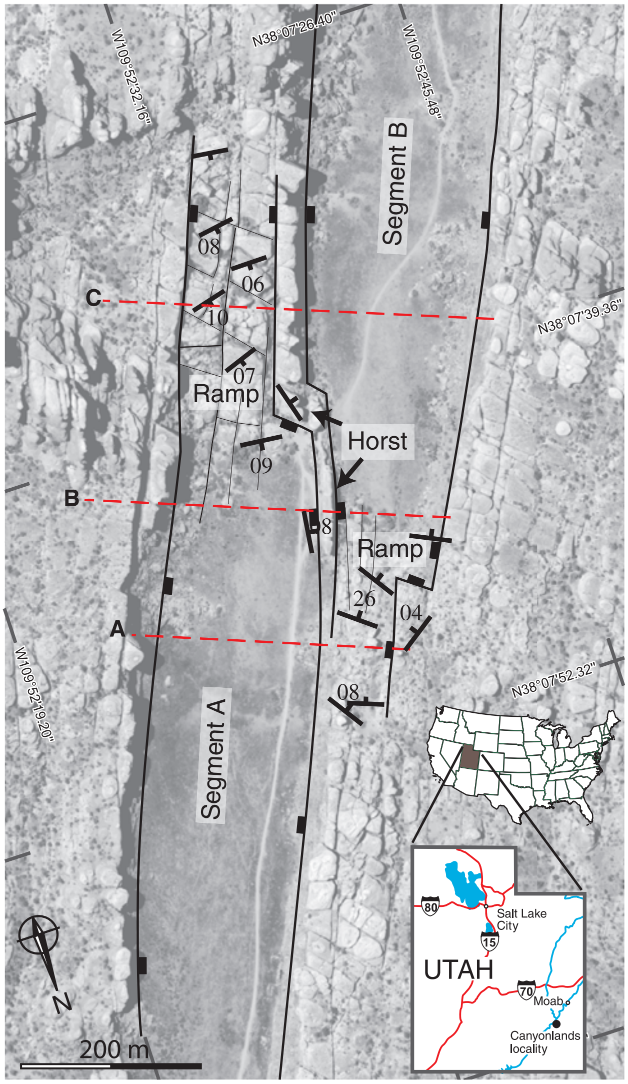
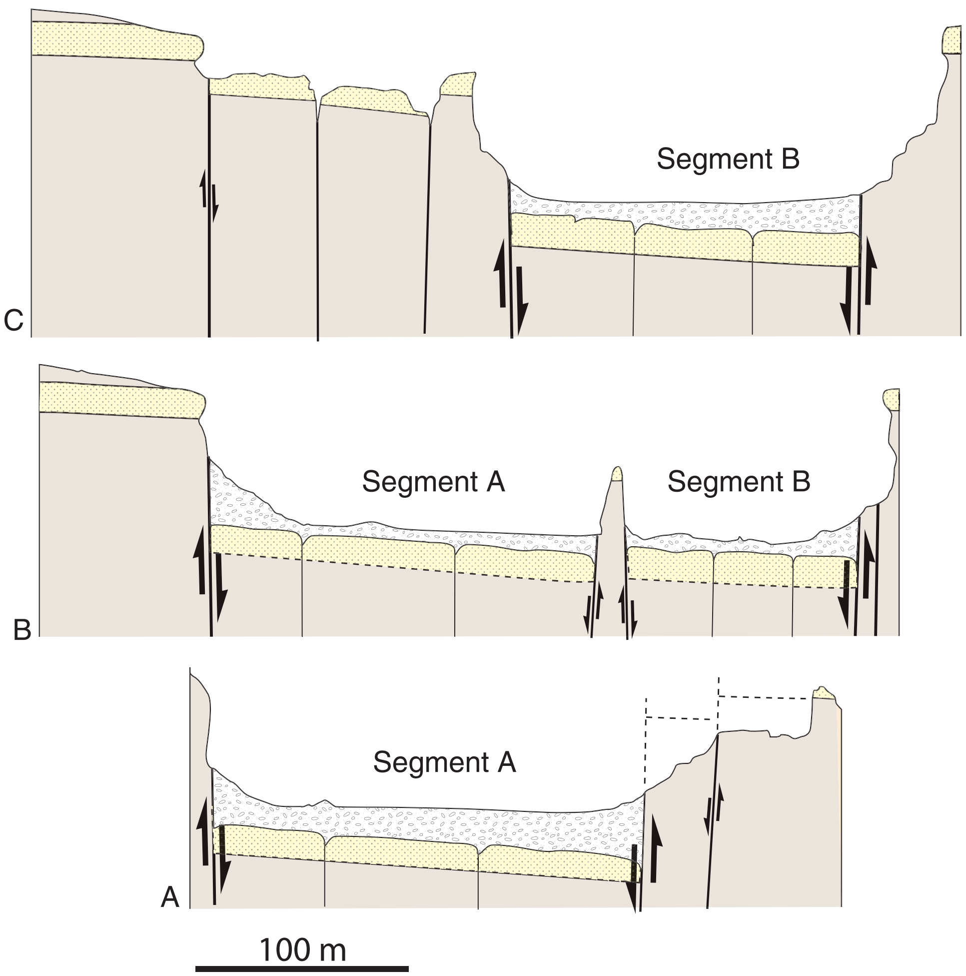


Figure 6. Air photo of the graben stepover in Devils Lane. Note the two oppositely dipping ramps and the high area in the middle of the stepover.

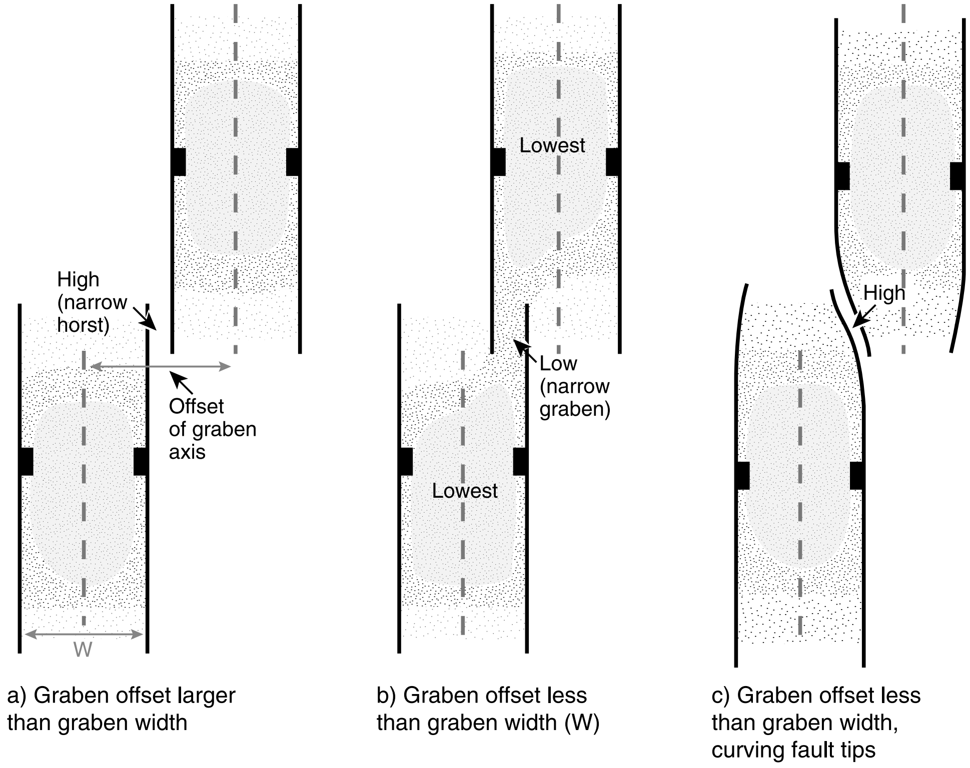
Figure 7. Profiles across the Devils Lane graben system. No vertical exaggeration. See Figure 6 for the locations.



by the opening of a regional set of preexisting north-south–trending joints and subsequent faulting on the same fractures. Geometrically, the similarities to the Viking Graben are striking (Figure 5), although the Canyonlands faults are steeper and controlled by preexisting joint sets (Figures 6, 7). Furthermore, bedding within the intervening fault blocks is less rotated, and the extension is considerably less than in the North Sea example.

The air photo and the corresponding map interpretation shown in Figure 6 reveal several characteristic attributes of the grabens area. First, the shift in graben axis across the stepover is about the width of the graben, i.e., about 200 m (656 ft). This corresponds to the shifts described from the Viking Graben (above). Second, two oppositely dipping ramps in the Devils Lane area are still mostly unbreached but are dissected by joints and minor faults. The ramps are located in the overlap zones between the graben bounding faults: as displacement decreases along one fault into the ramp area, the other picks it up as displacement is transferred across the ramp. The Devils Lane ramps show simple geometries, with subordinate faults and joints controlled by the trends of the preexisting regional joint pattern, but the overall geometry is very similar to that of the Viking Graben.

The fact that displacement along the graben-bounding faults decreases toward the stepover leads to a third characteristic feature, which is the occurrence of a structural high in the stepover between the two graben segments. In the Canyonlands example, this is manifested by a tall fin, or horst, between the two ramps. This striking feature gives the immediate impression of being an anomaly, special to the Devils Lane example. The narrow and dramatic expression of the narrow horst in Devils Lane is partly a function of joint reactivation within this part of the graben system. Yet in qualitative terms, the location of one or more highs



a) Graben offset larger than graben width

b) Graben offset less than graben width (W)

c) Graben offset less than graben width, curving fault tips

Figure 8. Three geometric forms of graben stepovers. Stippled and shaded areas are lows. See the text for discussion.

in a graben stepover is expected to occur also in other examples and settings. In the Viking Graben example, such highs are indeed found and represented by gas and condensate accumulations such as the Kvitebjørn field, the Huldra field, and the Valemon accumulation (Figure 5).

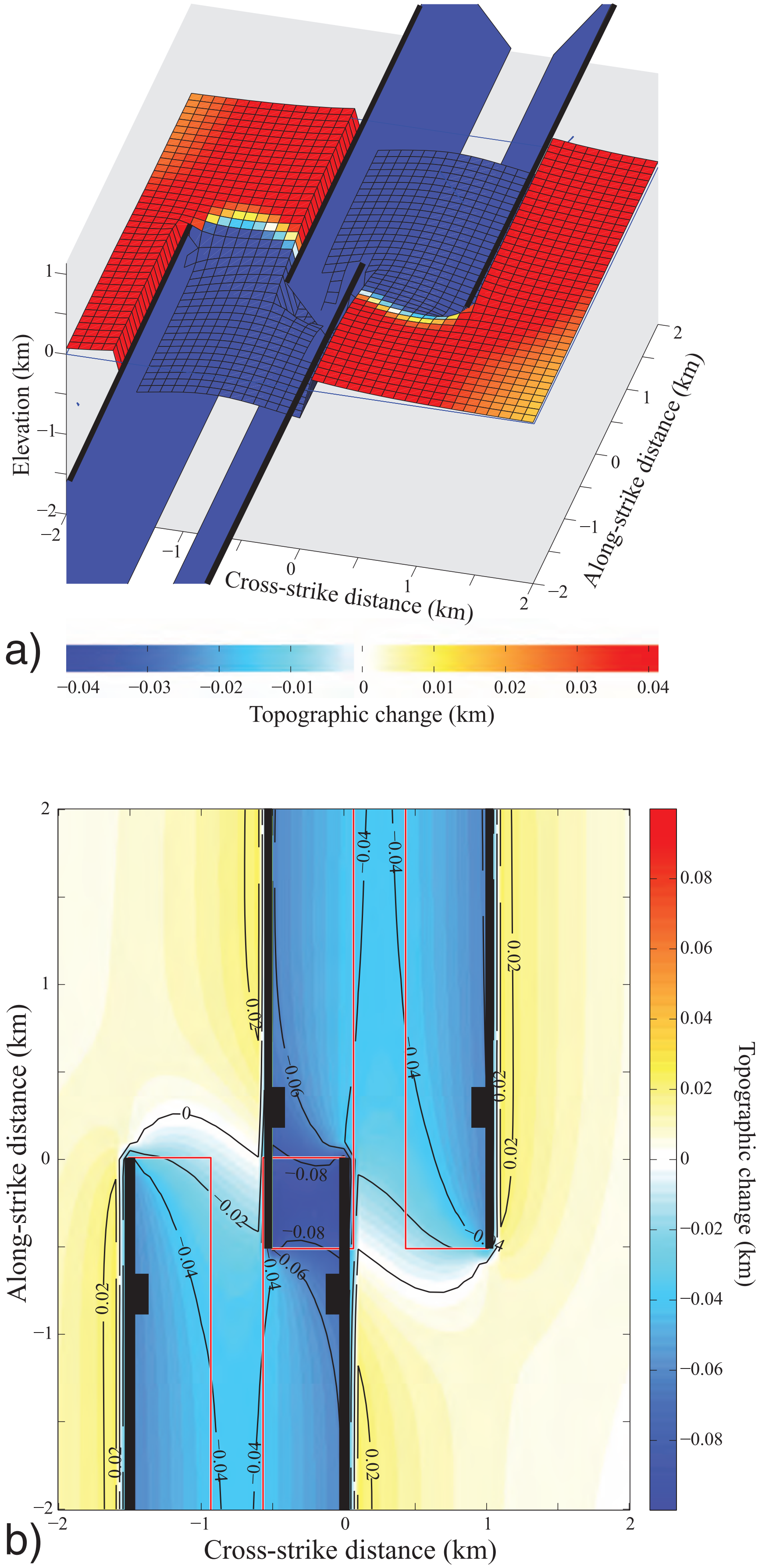
MODELING OF FAULT INTERACTION DURING GRABEN LINKAGE

The narrow horst (fin) in the Devils Lane graben stepover represents an interesting feature in part controlled by the preexisting joint system in the area and in part created during the growth history of the two approaching graben-bounding fault segments (cf. Serra and Nelson, 1988). Similar structural highs are also observed in the linked Viking Graben system. Is there any generality expressed by this structure, predicting qualitatively similar behavior of nonjointed and softer rocks?

A particularly interesting aspect of these positive structures is related to the amount of graben axis offset in map view. If the offset of the graben is larger than the width of the graben itself, then a narrow horst will remain between the two graben segments (Figure 8a). If the graben axis offset is less than the graben width (Figure 8b), then the overlap area will represent a low (narrow graben), although still being the highest part of the graben system. The Canyonlands example represents a case where the offset is less than the graben width, but a narrow horst is still present because of curving fault tips (Figure 8c). We suggest that the interaction between the stress fields around the two mutually approaching fault tips led to the curving of the generally straight fault segments. A similar geometry is indicated in the Viking-Sogn Graben stepover (Figure 3), creating an interesting high structure between oppositely dipping faults.

To explore these questions, we performed numerical modeling by means of COULOMB (Toda et al., 2008), which is a three-dimensional forward mechanical model that calculates the stresses and displacements in an elastic half space due to displacements that are specified along the faults (see Toda et al., 1998; also Schultz and Lin, 2001; Wilkins and Schultz, 2003, for details on the approach and

Figure 9. Predicted topographic changes associated with overlapping graben segments where the graben offset is less than the graben width. (a) Three-dimensional perspective view showing areas of predicted uplift and subsidence. (b) Contour plot of predicted vertical displacements of the ground surface in the graben area. Note that the high subsidence between the two inner faults at the relay ramp is an artifact caused by the constant fault throw assumption used in the model.



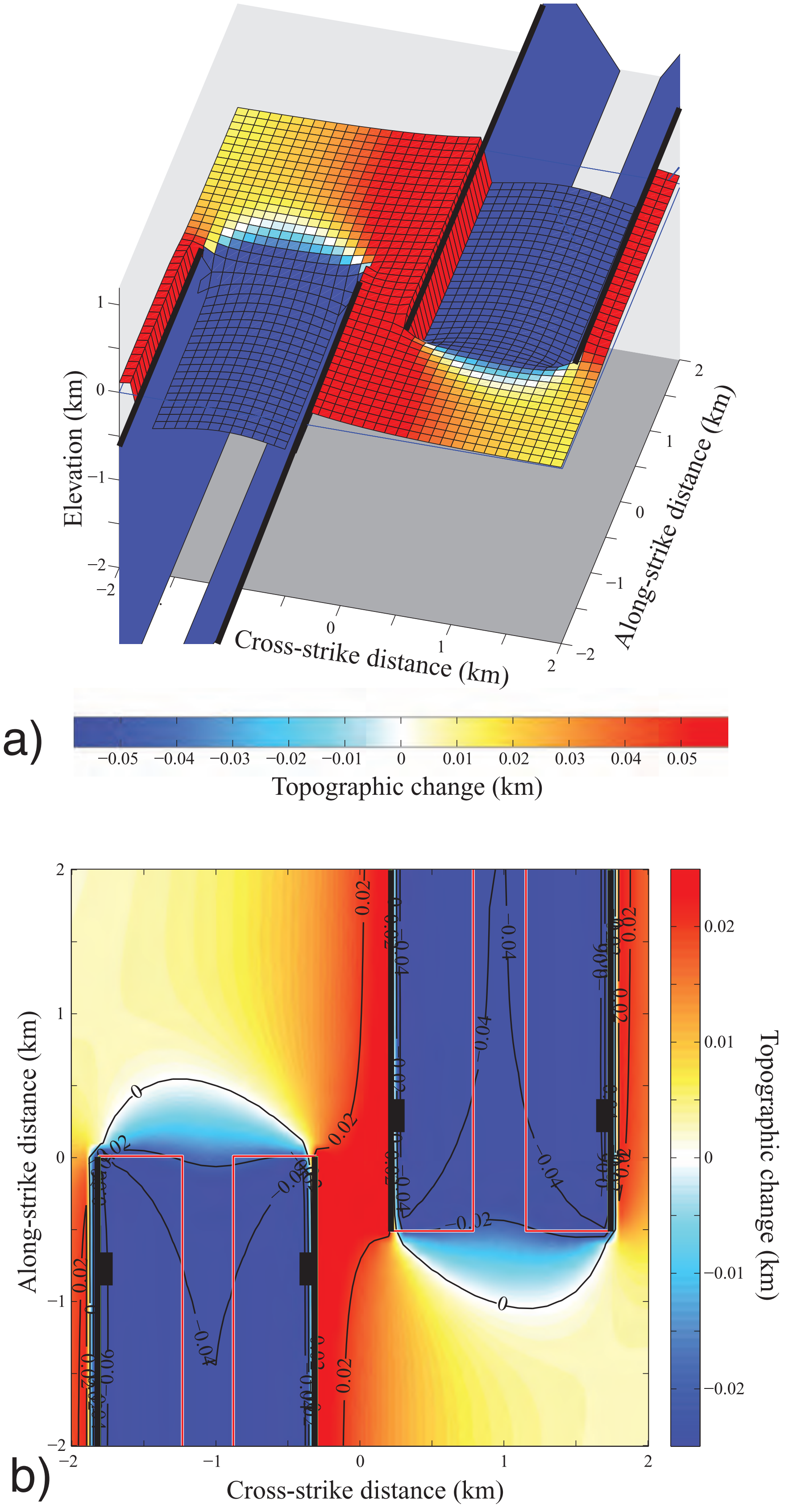
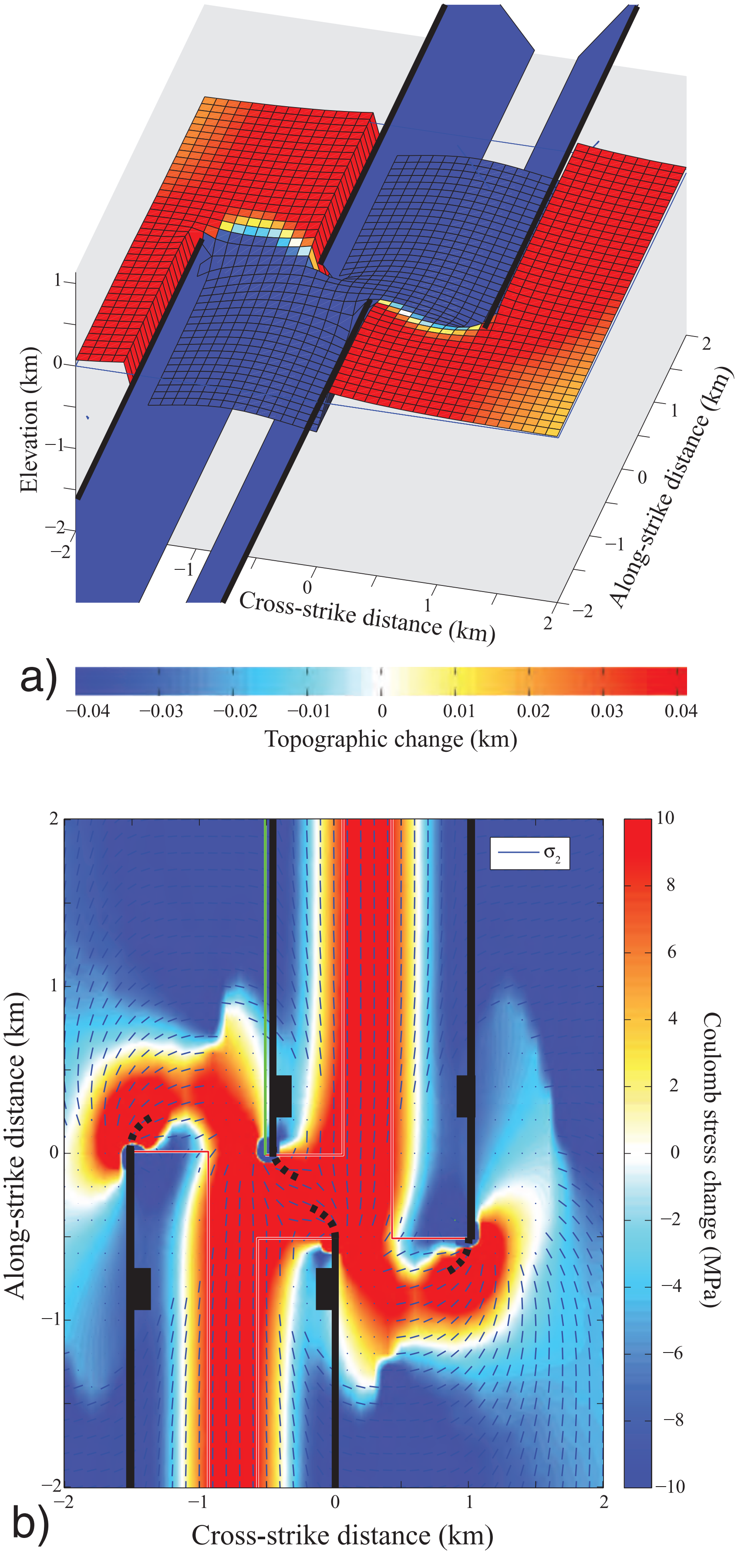


Figure 10. Predicted topographic changes associated with overlapping graben segments where the graben offset exceeds the graben width; panels a and b as in Figure 9. Note the enhanced uplift in the footwall relay ramps.

Figure 11. (a) Predicted topography and (b) Coulomb stress changes associated with grabens growing toward each other with the inner faults having an underlapped geometry. Areas of fault propagation are indicated in panel b by warm colors and in directions of tick marks denoting the local orientations of the intermediate (horizontal) principal stress σ_2. Dashed lines indicate the fault propagation directions in the absence of structural anisotropy.



applications to normal fault and graben systems). Using a mechanical model for fault growth, as done here, provides insight into the development of fault patterns and associated topography beyond that available from analog models (e.g., Hus et al., 2005; Bose and Mitra, 2009). The fault geometries we investigated are shown in Figure 8a and b. Each graben is defined by a pair of inwardly dipping normal faults that are, for this analysis, 4 km (2.5) in length and dipping at 60° down to a depth of 1 km (0.6 mi). A constant displacement of 100 m (328 ft) is applied along each fault, for a ratio of displacement to length of 0.025, in accord with values of other normal faults (e.g., Schultz et al., 2008). The host rock is represented by a Young's modulus of 80 GPa (145,038 psi), a Poisson's ratio of 0.25, and a friction coefficient of 0.6, values that are consistent with those of sedimentary rocks. An observation grid measuring 2 × 2 km (1.24 × 1.24 mi) is placed at the ground surface centered on the graben stepover area with calculations performed at a regular spacing of 100 m (328 ft). Although the specific values of fault dimensions, offsets, dip angles, and host-rock properties affect the results presented below in detail, the conclusions of the analysis are not changed substantially by variations in these values. As a result, our conclusions apply to other graben systems having similar fault geometries and stepover topographies.

Grabens that have grown into an overlapped geometry can form either the case in Figure 8a, where the graben offset is larger than the graben width, or the case portrayed in Figure 8b, where the offset is less than the graben width. In the last case (Figure 8b), faulting results in subsidence in the central overlap area, and the model predicts a basin in this area (see Figure 9). However, faulting in the first case (Figure 8a) leads to enhanced uplift in the intervening horst (Figure 10). These results suggest that propagation of grabens into overlapped geometries leads to enhanced subsidence or uplift in the relays depending on the initial spacing between the grabens, although the simplifying assumption of constant fault throw exaggerates these effects in the stepovers to some degree.

The cases shown in Figures 9 and 10 assume that the two inner faults outlining the narrow graben in Figure 8b propagate along strike without changing trend. This can occur, for example, when a preexisting fabric or joint set controls the fault propagation direction, as in the case of Canyonlands. Our modeling shows that this behavior can be explained by the stress state in an underlapped stepover (Figure 11a). The orientation of the minimum horizontal stress predicted by the model favors propagation of the inner faults in a counterclockwise sense, producing a graben or horst that is rotated relative to the overall trend of the grabens (Figure 11b). The eye-catching horst segment in the Canyonlands example is not significantly rotated because the faults propagate along preexisting joints and make abrupt steps along them instead of a gradual rotation predicted by the model and shown in Figure 8c. The central fin or horst at Devils Lane graben in Canyonlands can thus be interpreted as the result of propagation of faults with wide spacing and an along-strike anisotropy (i.e., the joint set), whereas the rotated horsts and grabens along the segmented North Sea Viking Graben resulted from fault propagation in strata that lack significant anisotropy, as illustrated in Figure 11b.

DISCUSSION

Some of the characteristics shared between the Canyonlands example and the Viking Graben are of particular importance when it comes to exploration. In principle, three key aspects of linked graben systems exist. One aspect is that the deep parts of the graben segments may be located within the oil window although its flanks are not. Thus, graben systems serve as kitchen areas in many petroleum and gas provinces, including the North Sea. During continued subsidence, the deep parts of a graben system will eventually escape the oil window, in which case, the shallower stepovers may still reside within the oil window. Hence, graben segmentation gives a longer graben source rock residual time within the oil window.

A second aspect concerns the role of relay structures in the graben stepovers with respect to hydrocarbon migration and trapping. In structural settings such as the North Sea, where many large faults are sealing because of the juxtaposition of permeable against nonpermeable units or, in rarer cases, because of shale smear, relay structures provide important migration paths for hydrocarbons from the deep graben parts to structural highs on the flanks. The sealing capacity of faults depends on several factors, of which displacement, together with lithological properties and stratigraphy, is regarded as the most important one (e.g., Yielding et al., 1997). At some critical point, typically near the fault tip, displacement is small enough that the fault changes from sealing to nonsealing. Because faults lose displacement toward graben stepovers and their relay structures, stepovers are likely locations of communication across otherwise sealing faults, even where subseismic structures occur within relay ramps (Rotevatn et al., 2009a). In the context of large-scale graben stepovers such as the Viking Graben, this means that stepovers are locations where hydrocarbons generated in deep parts of the graben system can escape into the surrounding fault blocks and migrate to high structures along the flanks of the graben system. In the northern part of the Viking Graben, migration of hydrocarbons seems to have occurred laterally around or through low-displacement parts of faults (Johannesen et al., 2002), using the pathways generated by graben stepover structures.

Vertical migration of fluids along faults also occurs in basins, and even laterally sealing faults may, intermittently or constantly, conduct fluids in the vertical direction. Because the number of faults and related fractures in graben stepovers is anomalously high, we would expect enhanced vertical migration of hydrocarbons in such settings. This expectation is supported by a study of a segmented rift system in New Zealand by Rowland and Sibson (2004). These authors found a concentration of geothermal fields in stepovers and linked this to enhanced vertical permeability caused by high structural complexity in these zones. Note that the structural complexities found in graben stepovers may cause problems during production, although this depends on a large number of local factors. Combined with deep locations and hence poorer seismic imaging, such complexities may represent a challenge and a call for careful structural mapping.

A third attribute common to the Canyonlands and Viking Graben systems is the location of local structural highs in graben stepovers. These structures, located in the migration route of hydrocarbons from the deep grabens, may accumulate significant amounts of hydrocarbons if the graben system is large, although they will tend to be volumetrically smaller than the shallower, flanking structures. In the Viking Graben example, the Kvitebjørn field is the largest well-explored accumulation located within a graben stepover so far, containing some 27 million Sm^3 (953 million Sft^3) recoverable oil and 74 billion Sm^3 (2.6 trillion Sft^3) recoverable gas.

In general, the observations and mechanical analysis indicate that graben stepovers should be given special attention during regional mapping of rift systems. The likelihood of finding hydrocarbon accumulations in these areas depends, among other things, on the depth of the stepovers. If they are deeply buried, they may represent gas accumulations only, and high temperature and pressure causing compaction and cementation may have reduced the permeability in these areas. Mapping of deep structures such as the Huldra-Kvitebjørn stepover can also be hampered by poor seismic data quality. Nevertheless, the hydrocarbon fields in the Huldra-Kvitebjørn stepover are of significant commercial interest and are also the only locations within the Viking Graben area that are in production. In less mature rift systems, however, stepovers may host the most attractive plays in the region. In general, knowledge of graben stepovers as locally high regions and thus potential sites of hydrocarbon accumulations can help focus exploration onto these areas.

Major grabens in rifts are by nature segmented, but the nature of graben stepovers varies (Nelson et al., 1992). The resulting stepover geometries depend on a large number of variables, such as basement anisotropy, the angle between the stress field and preexisting structures, amount of extension, fault dip, rift asymmetry, and magmatic influence. Although a discussion of different stepover types and their origins is beyond the scope of this work, we note that characteristics found in Canyonlands and the well-studied Viking Graben also pertain to other graben systems, notably those that show some degree of along-strike symmetry. Even some asymmetric rift systems, consisting of linked half grabens, show several of the same characteristics (e.g., Ebinger, 1989). This was explored in detail by Rosendahl (1987), who studied the East African rift system and found local highs in what he referred to as accommodation zones. Although every graben system is unique and deserves special attention, we consider the main concluding points of this work to have general implications for the mapping and exploration of graben systems in rift settings.

CONCLUSIONS

The comparative study of Viking Graben and Canyonlands graben stepover geometries has revealed very similar geometric characteristics that we believe have both local (Viking Graben) and general relevance and implications for hydrocarbon exploration:

1. Graben stepovers can represent positive-relief parts along linked graben systems. This allows for hydrocarbon accumulations in stepovers while the source rock is maturing in the deeper central parts of graben segments. Thus, recognizing the presence of graben stepovers may be an important factor during migration evaluation and basin modeling.
2. Stepovers are places where otherwise sealing faults terminate or lose enough displacement that they lose their sealing properties. Hydrocarbons can more easily escape the graben system here than elsewhere along the system, feeding shallower flanking structures capable of trapping small or large amounts of oil and gas.
3. Local structural traps may occur in graben stepovers, as exemplified by both the grabens area in the Canyonlands National Park and in the Viking Graben. In a large graben system such as the Viking Graben, such positive structures may trap enough hydrocarbons to be of commercial interest.
4. Positive structures within stepovers are most easily formed where the graben axis offset is larger than the graben width, but modeling and observations discussed here show that they can also form where the offset is less than the graben width.

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