Strike-slip reactivation of segmented normal faults: Implications for basin structure and fluid flow

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Abstract
Reverse reactivation of normal faults, also termed “inversion”, has been extensively studied, whereas little is known about the strike-slip reactivation of normal faults. At the same time, recognizing strike-slip reactivation of normal faults in sedimentary basins is critical, as it may alter and impact basin physiography, accommodation and sediment supply and dispersal. Motivated by this, we present a study of a reactivated normal fault zone in the Liassic limestones and shales of Somerset, UK, to elucidate the effects of strike-slip reactivation of normal faults, and the inherent deformation of relay zones that separate the original normal fault segments. The fault zone, initially extensional, exhibits a series of relay zones between right-stepping segments, with the steps between the segments having subsequently become contractional due to sinistral strike-slip movement. The relay zones have therefore been steepened and are cut by a series of connecting faults with reverse and strike-slip components. The studied fault zone, and comparison with larger-scale natural examples, leads us to conclude that the relays turned contractional steps are associated with (a) complex fault and fracture networks that accommodate shortening, (b) anomalously high numbers of fractures and faults, (c) layer-parallel slip and (d) folding and uplift. Comparison with published statistics from global relay zones shows that whereas the reactivated relay zones feature aspect ratios similar to those of unreactivated relay zones, bed dips within reactivated relay zones are significantly steeper than unreactivated relay zones. Given the potential of reactivated relay zones to form areas of local uplift, they may affect basin structure and may also form potential traps for hydrocarbon or other fluids. The elevated faulting and fracturing, on the other hand, means reactivated relays are also likely loci for enhanced up-fault flow.

Keywords
fault segmentation, reactivation, relay zone, restraining steps, strike-slip

1 | INTRODUCTION

Normal fault systems are a critical element of extensional sedimentary basins, being the primary controls on basin boundaries, geometry, physiography, accommodation, sediment routing and fluid flow (e.g. Ebinger, Deino, Tesha, Becker, & Ring, 1993; Gawthorpe & Leeder, 2000; Henstra, Gawthorpe, Helland-Hansen, Ravnås, & Rotevatn, 2017; Henstra et al., 2016). Over the past several decades, there has been considerable research into the development...
of normal faults and extensional sedimentary basins (e.g. Anderson, 1951; Bosworth, 1985; Cartwright, Trudgill, & Mansfield, 1995; Childs, Watterson, & Walsh, 1995; Gibbs, 1984; Jackson, Bell, Rotevatn, & Tvedt, 2017; Jackson & Rotevatn, 2013; Rotevatn & Jackson, 2014; Walsh, Bailey, Childs, Nicol, & Bonson, 2003; Walsh, Nicol, & Childs, 2002; Walsh & Watterson, 1987). This research has taught us that (a) normal fault systems are fundamentally and universally segmented (e.g. Cartwright et al., 1995; Fossen & Rotevatn, 2016; Hayward & Ebinger, 1996; Peacock, 2002; Peacock & Sanderson, 1991; Walsh et al., 2003), and (b) are associated with relay zones (Figure 1a, b), between stepping normal fault segments (e.g. Childs et al., 1995, 2017; Faulds & Varga, 1998; Gawthorpe & Hurst, 1993; Morley, Nelson, Patton, & Munn, 1990; Peacock & Sanderson, 1994; Rotevatn, Fossen, Hesthammer, Aas, & Howell, 2007; Rotevatn, Tveranger, Howell, & Fossen, 2009).

There has also been considerable interest in the reverse reactivation of normal fault systems (commonly termed “positive inversion” or simply “inversion”; e.g. Buchanan & Buchanan, 1995; McClay, 1989; Williams, Powell, & Cooper, 1989). The typical geometries that are produced during reverse reactivation of normal fault systems are therefore relatively well known from nature and experiments, including, for example, (a) inversion anticlines (e.g. Morley, Back, van Rensbergen, Crevello, & Lambiase, 2003; Tavani, Mencos, Bausà, & Muñoz, 2011; Yamada & McClay, 2004); (b) inversion thrust faults (e.g. McClay & Buchanan, 1992), (c) thrust ramps (e.g. McClay, 1989), (d) folding of the original fault(s) (e.g. Allen, Alsop, & Zhemchuzhnikov, 2001) and (e) uplift or up-thrusting of hanging-wall wedges of synextensional “growth” strata (e.g. Panien, Schreurs, & Pfiffner, 2005; Roberts, 1989). Although these are considered typical “inversion structures”, a wider range of geometries are possible during reverse reactivation of normal fault systems, depending on (a) the cross-sectional and along-strike geometry of the original normal fault system (e.g. Buchanan & McClay, 1991) and (b) the timing and magnitude of reverse reactivation (e.g. Brun & Nalpas, 1996; McClay, 1989).

There has, however, been very limited work on the strike-slip reactivation of normal faults (Figure 1d–f), that is, where a phase of normal-sense dip-parallel slip is succeeded by a reactivation phase of strike-parallel slip. Note that strike-slip reactivation of normal faults, where the slip vector during reactivation is parallel to the strike of the original normal fault, is different from both (a) single-phase oblique extension (e.g. Brune, Popov, & Sobolev, 2012; Clifton & Schlische, 2001), and (b) multi-phase extension where an initial orthogonal extension phase is succeeded by a phase of oblique extension on the first-phase faults (e.g. Henstra, Rotevatn, Gawthorpe, & Ravnås, 2015; Henza, Withjack, & Schlische, 2010). Although strike-slip reactivation is reported in the literature (e.g. Aris, Coiffait, & Guiraud, 1998; Balaguru, Nichols, & Hall, 2003; Ducea, Kidder, Chesley, & Saleebey, 2009; Faure, Tremblay, Malo, & Angelier, 2006; Firth et al., 2015; Hartz & Andresen, 1995; Jankowski & Probulski, 2011; Kim, 1996; Turner, Liu, & Cosgrove, 2011), detailed descriptions of the strike-slip reactivation of normal faults (Van Noten et al., 2013) and the associated effects of reactivation on along-strike transfer zones (Barton, Evans, Bristow, Freshney, & Kirby, 1998; Kelly, McGurk, Peacock, & Sanderson, 1999; Zampieri &

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**FIGURE 1** Schematic diagrams of the main map-view fault geometries described in this study. (a) A transfer zone between two stepping subparallel normal faults of any relative dip direction (e.g. Morley et al., 1990). (b) A relay ramp, between two stepping subparallel normal faults with the same dip direction (e.g. Larsen, 1988). (c) A breached relay, where the stepping faults are linked by a connecting fault (e.g. Peacock & Sanderson, 1991). (d) A contractional step between two right-stepping sinistral faults. (e) An extensional step between two left-stepping sinistral faults. (f) A relay ramp reactivated as a contractual step.
Massironi, 2007) are scarce. Thus, an understanding of key features and typical structures produced during strike-slip reactivation of normal faults is currently lacking.

Motivated by this, we here aim to elucidate the effects of strike-slip reactivation of normal faults, and the inherent effects on relay zones that separate normal fault segments. We also identify typical structures formed during strike-slip reactivation of normal faults, and the key geologic factors governing their formation. Furthermore, we discuss the possible effects of such reactivation on fluid flow along and around such faults, and how such reactivation may be identified on seismic data. Note that we separate between two separate scenarios when normal faults are reactivated in strike-slip: When the reactivating strike-slip shear sense is identical to the stepping direction of the original extensional fault system (same-sense strike-slip reactivation), the original relay zones become extensional steps (e.g. right-lateral strike-slip reactivation of a right-stepping normal fault system). When the reactivating strike-slip shear sense is opposite to that of the stepping direction of the original extensional fault system (opposite-sense strike-slip reactivation), the original relay zones become contractional steps (e.g. left-lateral strike-slip reactivation of a right-stepping normal fault system). In this study we focus on the latter scenario, that is, reactivation of normal fault systems that turns relay ramps into contractional steps.

To address the above-stated goals, we investigate a spectacularly well-exposed outcrop example of a normal fault zone (throw 8–20 m) reactivated in strike-slip in the Liassic limestones and shales at Lilstock on the Somerset coast, UK (Figure 2), and discuss the findings in light of other, larger-scale examples. The fault zone exhibits a series of relay zones that separate right-stepping segments, with the steps between the segments having subsequently become contractional due to sinistral strike-slip reactivation (Figure 1f). The fault zone was mapped using a base map constructed from merged photographs taken using an unmanned aerial vehicle (UAV or drone) flown at ~20 m above the exposure. The merged image is available as Supporting Information Figure S1 for this study.

Understanding and recognizing strike-slip reactivation of normal faults in sedimentary basins is critically important as it may alter and influence the way in which faults control basin physiography, accommodation as well as sediment supply and dispersal (see, e.g. Kristensen et al., 2018). Furthermore, the results of this work have economic implications, as advances in the understanding of normal faults reactivated in strike-slip may lead to improvements of our understanding of fluid flow, fluid retention and leakage, and trap-forming mechanisms relevant for, for example, petroleum exploration, subsurface carbon storage, groundwater aquifer management and extraction of geothermal energy.

2 | TERMINOLOGY

The terminology used in this study is defined in Biddle and Christie-Blick (1985), Peacock, Knipe, and Sanderson (2000a,b) and Peacock, Nixon, Rotevatn, Sanderson, and Zuluaga (2016), with Figure 1 illustrating some of the geometries described. Whereas transfer zone is used by Dahlstrom (1970) for the structures that conserve shortening, or allow a regular change in shortening, between over-stepping thrust faults, the term is generally used for an area of deformation and bed rotation between two normal faults that overstep in map view (e.g. Morley, 1995). Morley et al. (1990, their Figure 1) describe synthetic transfer zones and conjugate transfer zones, in which the overstepping faults dip in the same and opposite directions respectively (Figure 1a). A relay ramp (synthetic transfer zone of Morley et al., 1990) is an area of reoriented bedding between two normal faults that overstep in map view and that have the same dip direction (Figure 1b; e.g. Huggins, Wattersen, Walsh, & Childs, 1995; Larsen, 1988; Peacock & Sanderson, 1991). If a relay ramp is breached by one or more connecting faults (Figure 1c), it is termed a breached relay. The term relay zone encompasses both relay ramps (Figure 1b) and breached relays (Figure 1c; e.g. Peacock et al., 2016).

3 | OUTCROP EXAMPLE OF A NORMAL FAULT ZONE REACTIVATED IN STRIKE-SLIP AT LILSTOCK, SOMERSET, UK

3.1 | Geological background

Mapping has been carried out on a fault zone on Lilstock Beach, Somerset, UK (Figures 2 and 3). The fault zone occurs in wave-cut platform exposures of Liassic limestones and shales (e.g. Whittaker & Green, 1983). Peacock and Sanderson (1999) show that the deformation at Lilstock involves the following:

- 060° striking veins, and possibly normal faults, are locally developed and indicate approximate 150°–330° extension.
- Normal faults and calcite veins strike at about 095° and indicate approximate north-south extension. Oblique fibres in the veins indicate sinistral transtension, consistent with NNW-SSE-directed extension. This event may be consistent with approximate NW-SE extension in the Wessex Basin from the Permian to the Cretaceous, described by Chadwick (1986) and by Lake and Karner (1987). Nucleation, growth and normal slip on the studied fault system can likely be attributed to this stage of deformation.
Approximate east-west contraction is indicated by conjugate arrays of veins and pull-aparts (described by Peacock & Sanderson, 1995), and by sinistral shear on some of the 095° striking normal faults. Sinistral reactivation of the studied fault system is likely related to this stage of deformation.

Dextral reactivation occurred on some of the 095° striking normal faults. Calcite veins developed striking at approximately 150°, with reactivation of some 100° striking veins. Van Hoorn (1987) describes late Jurassic to early Cretaceous dextral strike-slip movement on east-west structures further west in the Bristol Channel Basin.

Approximate north-south contraction is indicated by east-west thrusts, strike-slip faults conjugate about north-south, veins striking approximately north-south, and by east-west striking stylolites. This event is probably related to contraction during the Alpine Orogeny (Dart, McClay, & Hollings, 1995). Approximate north-south contraction during the late Cretaceous to middle Tertiary is also described in the Wessex Basin by Chadwick (1993).

The joints post-date the faulting events because the joints abut the faults and they are not mineral filled (Rawnsley, Peacock, Rives, & Petit, 1998).

### 3.2 Present-day fault geometry and segmentation

The Liassic of Somerset consists of a sequence of limestone and shale beds (e.g. Whittaker & Green, 1983), the thicknesses of which may be used to identify the separation between originally adjoined points or horizons in the
hanging-wall and footwall of a fault, and thereby to measure the displacement, throw or heave (e.g. Kelly et al., 1999). The studied fault zone at Lilstock is E-striking, S-dipping and is exposed for ~310 m along strike, with the eastern end in the cliff and the western end disappearing under a cover of sand (Figure 3a). The exposed fault zone is comprised of five main right-stepping segments from east to west (Figure 3a): (a) Segment A is poorly exposed (and thus not shown in Figure 3a) over a few metres and terminates eastward into a cliff; (b) Segment B also terminates eastward immediately before the same cliff and is poorly exposed over a distance of ~74 m; (c) Segment C is ~110 m long and its western end is well exposed; (d) Segment D is ~74 m long and is well exposed along its entire length and (e) Segment E is well exposed over ~95 m, but disappears under a cover of sand to the west.

All of segments A through E are separated by steeply dipping breached relays (Figure 3a), which we from here on will refer to as relay zones. Fault segments A and B are separated by a relay zone with a length (fault overlap) of 30 m, maximum width (distance between the two bounding faults) 10 m and a maximum dip of relay bedding of 33°. The relay zone separating fault segments B and C (Figure 3a) is 31 m long and up to 8 m wide, with a maximum relay bed dip of 41°. The best exposed relay zone (Figure 3b) separates segments C and D and is approximately 58 m long, with a width of up to 11 m; bedding within the relay zone exhibits a maximum dip of 48°. Fault segments D and E are separated by a relay zone (Figure 3a) with length 68 m, maximum width 12 m and maximum relay bed dips of 39°.

Whereas relay zones in extensional fault systems typically feature a down-stepping relief-reducing geometry, the relay zones in the study area exhibit some positive relief and therefore are localized structural highs in the studied fault system (Figure 4a,b). Internally, the ramps are characterized by: (a) steepening of the bedding to dips of up to approximately 45° (Figure 4b); (b) strike-slip faults that are antithetic to the strike-slip displacement on the reactivated normal faults (Figure 3b); (c) strike-slip faults that are synthetic to the strike-slip displacement on the reactivated

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**FIGURE 3** (a) Map of the reactivated normal fault zone at Lilstock, Somerset. Segments B through D are shown; Segment A falls outside the area shown in this image but is poorly exposed. Lower hemisphere stereonets show the orientation of (i) beds at distance from the fault zone, (ii) beds within the relay zones, (iii) normal faults reactivated as sinistral strike-slip faults and (iv) normal faults elsewhere in the broader study area (mostly outside the area shown in this figure) that are not reactivated by strike-slip reactivation. (b) One of the reactivated relay ramps along the fault system shown in (a). The location is shown in (a). Both figures were made using merged images taken from an UAV.
FIGURE 4  Field photographs showing evidence for strike-slip reactivation of the fault zone at Lilstock. (a) View westwards along the fault showing steepened relay zones. (b) Close-up view towards the west showing the steepened beds of one of the relay zones. (c) E-W striking left-stepping calcite veins linked to form a sinistral strike-slip fault in the east of the fault zone. (d) Slickenside lineations with evidence of strike-slip dominated (sinistral) displacement during reactivation. (e) Folding and thrusting in the footwall of a normal fault in the east of the fault zone (view towards the west). Note that the thrust detaches downdip in the dark shale-dominated unit where deformation is accommodated as layer-parallel slip. (f) Crenulation cleavage in shale in a fold in the east of the fault zone. The locations of (a) and (b) are shown in Figure 3b. The photographs showing structural detail (c), (e) and (f) were taken within and around the reactivated relay zone shown in Figure 3b. Photograph (d) was taken along Segment D, which is shown in Figure 3a
normal faults; (d) calcite veins indicating sinistral transtension (Figure 4c); (e) locally developed fold-thrust structures (Figure 4e); (f) layer-parallel slip (Figure 4e) and (g) locally developed crenulation cleavage in shale beds (Figure 4f).

3.3 | Evidence for normal slip and subsequent strike-slip reactivation

Stratigraphic cross-fault correlation suggests a net throw of between ~8 m and ~20 m down to the south, showing that the fault has a normal displacement. Other evidence for normal displacement includes E-W striking calcite veins and normal faults in the footwall (Figure 5).

The initial observation that led us to hypothesize that the fault system had been reactivated in strike-slip was that the relay zones between the right-stepping segments appeared over-steepened (Figures 3b and 4a). In fact, the relay zones are much steeper than is typical of relay zones in Liassic rocks elsewhere on the Somerset coast, and for relay zones in general (e.g. Fossen & Rotevatn, 2016; Peacock & Sanderson, 1991, 1994; see Section 5 for full discussion). We thus tentatively interpreted the steep relay zone dips as a result of local contraction due to sinistral strike-slip reactivation of the normal fault system (see Figure 1f). The following lines of evidence offer independent support for strike-slip reactivation:

- Fault lineations (slicken-sides) indicate approximate strike-slip displacements (Figure 4d);
- Left-stepping vein arrays that strike approximately E-W in the walls of the fault zone also indicate sinistral strike-slip deformation (Figure 4c);
- The network of faults and other structures within the steepened relay zones (Figure 3b and 4) also indicates contractional deformation, including fold-thrust structures (Figure 4e) and crenulation cleavage (Figure 4f). Localized contraction within the relay zones is consistent with sinistral strike-slip reactivation.

Reliable offset markers to determine the magnitude of strike-slip displacement are scarce or absent; however, based on the sum of field observations we estimate that strike-slip displacement falls in the range 1–5 m.
4 | DISCUSSION

4.1 Typical geometries and effects associated with strike-slip reactivation of normal faults

Strike-slip reactivation of normal fault zones means that any irregularity along that original fault zone will take on a new role as a locus for localized (oblique) contraction or extension. The highest-order and most prominent irregularities in the along-strike geometry of a segmented normal fault zone are the relay zones that separate adjacent segments. In the following we discuss the field observations made herein and draw parallels to published larger-scale examples and scaling relations, to draw out typical effects and geometries associated with strike-slip reactivation of normal faults, and particularly the effect of reactivation of relay zones. In the case of the example presented in Figure 3, where a right-stepping normal fault zone is reactivated as a sinistral strike-slip fault, such relay zones become sites of localized contraction (as would the dextral strike-slip reactivation of a left-stepping normal fault system) (Figure 6). This, being the case-in-point, will form the main focus for the discussion.

Relay zones in normal fault systems are generally known to be zones of high fault (and commonly other fracture type) intensity and connectivity (e.g. Bastesen & Rotevatn, 2012; Dimmen, Rotevatn, Peacock, Nixon, & Nærland, 2017; Rotevatn et al., 2007), as well as a wide variety of fault orientations due to fault interaction and stress perturbation in the relay zones (e.g. Crider & Pollard,
This is the reason why relay zones are often described as areas of enhanced structural “complexity”. When such relay zones are subjected to a second phase of deformation during strike-slip reactivation, such structural “complexity” is bound to increase as new structures grow within the relay zones. Within the relay zones of the fault zone studied herein, growth of structures formed during strike-slip reactivation (intraramp strike-slip faults and thrusts) has led to higher total fault intensities and connectivity than what would have been the case prior to fault reactivation. This finds support also in larger-scale examples; for example, Peacock and Shepherd (1997) describe km-scale faults in the Sydney Basin, Australia. They show that relay zones in a right-stepping normal fault system reactivated in sinistral strike-slip were characterized by sinistral strike-slip faults and thrusts within the relay zones, and concluded that the complex patterns of deformation typically seen in relay zones and transfer zones were generally increased during (strike-slip) reactivation.

Whereas the internal structure of relay zones in normal fault systems is generally dominated by normal-slip faults and extension fractures, the reactivated relay zones shown herein also feature thrust faults and strike-slip faults. This is supported by similar finds in other studies (Peacock & Shepherd, 1997; Zampieri & Massironi, 2007; Zampieri and Massironi 2007) also show that (strike-slip) reactivated relay zones are typified by inversion of pre-existing normal faults and layer-parallel faulting.

Relay zones are also known to be associated with gentle, monoclinal folding of relay beds (e.g. Fossen & Rotevatn, 2016; Larsen, 1988; Peacock & Sanderson, 1991, 1994). In the relay zones of the herein studied fault system, the relay zones have steeper dips than are typical of other relay zones in the area. Also, they include local development of fold-thrust structures.

**FIGURE 8** (a) The Sulaiman-Kirthar arcuate fold and thrust belt in Pakistan. This originated as a 100s-km-scale extensional transfer zone in a Mesozoic rift system among Africa, Madagascar and India, but underwent sinistral reactivation in Eocene times during the collision between the Indian and Eurasian plates, leading the transfer zone to turn into an arcuate fold and thrust belt. (b) Schematic figure illustrating the deformation in the Sulaiman-Kirthar ranges.
Fault systems represent a downward stair reactivated relay zones (Figure 7).

Relay zone dips, however, are much steeper than is typical of relay zones in Liassic rocks elsewhere on the Somerset coast, and for relay zones in general. For example, Peacock and Sanderson (1991, 1994) show relay zones in the study area between stepping normal faults with dips of up to about only 20°. Figure 10 shows a comparison of the relay zone steepness data from this study and data from Fossen and Rotevatn (2016), who show, based on global outcrop-based data (from Bastesen & Rotevatn, 2012; Giba, Walsh, & Nicol, 2012; Huggins et al., 1995; Rotevatn & Bastesen, 2014; Soliva & Benedicto, 2004; Xu, Nieto-Samaniego, Alainz-Álvarez, & Cerca-Martinez, 2011), that unbreached, partly breached and fully breached relay zones have mean bed dips of 7°, 13° and 18° respectively (the maximum dip reported was for a breached relay, at 32°). The relay zones in the fault zones at Lilstock, however, show dips of up to about 48° (Figures 3, 4a and 10). This suggests that relay zone dips higher than 20–30° are atypical for relay zones in normal fault systems, and that relay bed dips in excess of 30–35° probably are diagnostic of relay zones that have been shortened and thus over-steepened. Note that continued strike-slip would likely lead to relay abandonment at some point, after which relay steepening and internal deformation would largely cease. Further studies of other natural examples, or physical analogue experiments, of normal faults reactivated in larger-magnitude strike-slip (e.g. greater than the original normal-sense slip) would be needed to further investigate this.

4.2 Scaling relations and bed dips of reactivated relay zones compared to unreactivated relay zones

The relay zones in this study show similar relationships between relay length (fault overlap) and relay width (fault separation) as do relays zones in nonreactivated normal fault systems. This is shown in Figure 9, where the four reactivated relay zones studied herein show similar aspect ratios as relay zones in normal fault systems globally (see also Fossen & Rotevatn, 2016; Long & Imber, 2011; Mansfield & Cartwright, 2001). As such, aspect ratio appears not to be distinctive for reactivated relay zones when compared to nonreactivated relay zones.

The relay bed dips, however, are much steeper than is typical of relay zones in Liassic rocks elsewhere on the Somerset coast, and for relay zones in general. For example, Peacock and Sanderson (1991, 1994) show relay zones in the study area between stepping normal faults with dips of up to about only 20°. Figure 10 shows a comparison of the relay zone steepness data from this study and data from Fossen and Rotevatn (2016), who show, based on global outcrop-based data (from Bastesen & Rotevatn, 2012; Giba, Walsh, & Nicol, 2012; Huggins et al., 1995; Rotevatn & Bastesen, 2014; Soliva & Benedicto, 2004; Xu, Nieto-Samaniego, Alainz-Álvarez, & Cerca-Martinez, 2011), that unbreached, partly breached and fully breached relay zones have mean bed dips of 7°, 13° and 18° respectively (the maximum dip reported was for a breached relay, at 32°). The relay zones in the fault zones at Lilstock, however, show dips of up to about 48° (Figures 3, 4a and 10). This suggests that relay zone dips higher than 20–30° are atypical for relay zones in normal fault systems, and that relay bed dips in excess of 30–35° probably are diagnostic of relay zones that have been shortened and thus over-steepened. Note that continued strike-slip would likely lead to relay abandonment at some point, after which relay steepening and internal deformation would largely cease. Further studies of other natural examples, or physical analogue experiments, of normal faults reactivated in larger-magnitude strike-slip (e.g. greater than the original normal-sense slip) would be needed to further investigate this.

4.3 Implications for fluid flow in sedimentary basins

The main implications for fluid flow in normal fault systems reactivated in strike-slip, where relay zones become zones of localized shortening, may be summarized in two points: Firstly, the relay zones are associated with high fault intensities that are amplified by the strike-slip fault
Unbreached relays (relay ramps)
Mean: 7° ± 3°

Barely breached relays
Mean: 13° ± 5°

Strongly breached relays
Mean: 18° ± 8°

Reactivated relays of this study
Mean: 40° ± 6°
reactivation, which means that the number and connectivity of faults and related fractures in reactivated relay zones are anomalously high. It is therefore likely that reactivated relay zones represent along-strike loci for enhanced up-fault fluid flow (cf. Fossen, Schultz, Rundhovde, Rotevatn, & Buckley, 2010; Peacock, Nixon, Rotevatn, Sanderson, & Zuluaga, 2017; Rotevatn & Bastesen, 2014). Numerous studies have shown similar effects of structural complexity on the loci of fluid flow in nonreactivated normal fault systems (e.g. Davatzes & Aydin, 2003; Dockrill & Shipton, 2010; Gartrell, Zhang, Lisk, & Dewhurst, 2004; Dimmen et al., 2017). For example, Rowland and Sibson (2004) show that steps and transfer zones in a segmented rift system in New Zealand are associated with a concentration of geothermal fields, which they relate to locally enhanced vertical permeability in such zones. Secondly, the reactivated relay zones may represent local structural highs along strike, which means that such locations are associated with structural trap formation where fluids, such as hydrocarbons, may potentially accumulate (cf. Fossen et al., 2010).

### 4.4 Diagnostics of strike-slip reactivation of normal faults from seismic reflection data

Evidence from seismic reflection data is commonly used to identify reverse reactivation of normal faults, including reverse displacements higher up the fault and forced folds above the fault (e.g. Coward, 1996). In contrast, the scarcity of accounts of strike-slip reactivation of normal faults suggests either that (a) strike-slip reactivation of normal faults is uncommon, or (b) that evidence for reactivation may be subtler than structures created by reverse reactivation. There is no evidence-based reason to suspect the former, and given the known challenges associated with the imaging of strike-slip dominated systems from seismic reflection data (McClay & Bonora, 2001), the under-reporting is likely related to difficulties of recognizing strike-slip reactivation from seismic data.

We suggest that the following should be taken as suggestive of strike-slip reactivation when investigating normal fault systems using seismic reflection data:

- Seismically identifiable strike-slip offset, as well as one or more of the following:
  - Inversion only of selected faults, particularly at or near relay zones or fault bends
  - Relay beds steeper than 30–35° (see Section 5.2 and Figure 10).
  - Areas of uplift (folds, thrust-related features) at relay zones and/or fault bends.
  - Evidence for contractional deformation at relay zones.
  - Networks of faults, within and around relay zones, that accommodate shortening.

### 4.5 Releasing strike-slip reactivation of normal fault zones

Although this study focuses on an example where relay zones are turned into sites of localized contraction during strike-slip reactivation, localized extension of the original relay zones may also occur. This would be the case where a right-stepping normal fault system is reactivated in dextral strike-slip, or where sinistral reactivation affects a left-stepping normal fault system. Here, relay zones may turn into areas of localized subsidence, or pull-apart basins, as the transfer zones along normal faults become reactivated as extensional steps by strike-slip deformation (e.g. Richard & Krantz, 1991; Wong & Munguía, 2006; Zampieri & Massironi, 2007). This style of strike-slip reactivation of normal faults has not been the focus of this study but will form the focus of future work.

### 5 SUMMARY AND CONCLUSIONS

This study has aimed to elucidate the phenomenon of strike-slip reactivation of segmented normal faults, and specifically opposite-sense strike-slip reactivation, that is, the scenario when the strike-slip reactivation sense of shear (right-or-left lateral) is the opposite of the stepping direction of the original fault system (as in this case, left-lateral strike-slip reactivation of a right-stepping normal fault).

During opposite-sense strike-slip reactivation of a stepping, segmented normal fault zone, the relay zones of the original normal fault system are reactivated as contractional steps, leading to shortening and over-steepening of the relay zones. We reach the following conclusions regarding the overall geometry and structure of the reactivated relays:

- Reactivated relay zones are affected internally by thrusts and strike-slip faults that overprint pre-existing extensional structures.

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**FIGURE 10** Distribution of maximum dip of relay zones that are as follows: (a) unbreached; (b) partly breached; (c) strongly breached and (d) reactivated. The data in (a), (b) and (c) are derived from outcrop examples from Bastesen and Rotevatn (2012), Giba et al. (2012), Huggins et al. (1995), Rotevatn and Bastesen (2012), Soliva and Benedicto (2004) and Xu et al. (2011). Dip is relative to the general (regional) layer orientation. (a), (b) and (c) are modified from Fossen and Rotevatn (2016), whereas (d) presents data from this study.
Complex fault (and other fracture) networks accommodate shortening within the relay zones. The relay zones are therefore typified by anomalously high numbers of fractures and faults, and high fault and fracture connectivities.

Layer-parallel slip accommodating shortening is common.

The reactivated relay zones are associated with more folding of relay beds, and may feature anticlines rather than the monoclines that typify relays unaffected by reactivation.

The reactivated relay zones feature aspect ratios similar to those of relay zones that have not been reactivated.

Due to shortening and associated tilting, bed dips within reactivated relays are significantly steeper than relay zones in unreactivated normal fault systems. The shortening may also lead to localized uplift at the relay-turned contractional steps.

Recognizing strike-slip reactivation of normal fault zones in sedimentary basins may be crucial, as modification of relay zones and the reconfiguration of structural highs and lows along strike has implications for basin physiography, accommodation, sediment supply and dispersal (see, e.g. Kristensen et al., 2018). Furthermore, given their potential to form localized uplifts, relays reactivated as contractional steps may form potential traps for hydrocarbons or other fluids. Conversely, the increased fracturing at reactivated relays may increase the risk of leakage, and means they are likely sites of localized, enhanced up-fault fluid flow. As such they may form loci for geothermal upwelling, ore mineral deposits and fluid rock interactive processes in general.

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CONFLICT OF INTEREST

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