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, lead us to conclude that the relays-turned-contractional-steps are associated with (i) complex fault and fracture networks that accommodate shortening, (ii) anomalously high numbers of fractures and faults, (iii) layer parallel slip and (iv) 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; relay zone; reactivation; strike-slip; restraining steps

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 et al., 1993; Gawthorpe & Leeder, 2000; Henstra et al., 2016, 2017). Over the past several decades, there has been considerable research into the development of normal faults and extensional sedimentary basins (e.g. Anderson, 1951; Gibbs, 1984; Bosworth, 1985; Walsh & Watterson, 1987; Cartwright et al., 1995; Childs et al. 1995; Walsh et al. 2002, 2003; Jackson & Rotevatn, 2013; Rotevatn & Jackson, 2014; Jackson et al., 2017). This research has taught us that (i) normal fault systems are fundamentally and universally segmented (e.g. Peacock & Sanderson 1991; Cartwright et al., 1995; Hayward & Ebinger 1996; Peacock 2002; Walsh et al., 2003; Fossen & Rotevatn, 2016), and (ii) are associated with *transfer zones*, or *relay zones* (Fig. 1A-B), between stepping normal fault segments (e.g. Morley et al., 1990; Gawthorpe & Hurst, 1993; Peacock & Sanderson, 1994; Childs et al., 1995; Faulds & Varga, 1998; Rotevatn et al., 2007, 2009; Childs et al., 2017).

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 et al., 1989). The typical geometries that are produced during reverse reactivation of normal fault systems are therefore relatively well known from nature and experiments, including e.g. (i) inversion anticlines (e.g. Morley et al. 2003; Yamada & McClay 2004; Tavani et al., 2011); (ii) inversion thrust faults (e.g. McClay & Buchanan, 1992), (iii) thrust-ramps (e.g. McClay 1989), (iv) folding of the original fault(s) (e.g. Allen et al., 2001), and (v) uplift or upthrusting of hanging-wall wedges of syn-extensional "growth" strata (e.g. Roberts 1989; Panien et al., 2005). Although these are considered typical "inversion structures", a wider range of geometries are possible during reverse reactivation of normal fault systems, depending on (i) the cross-sectional and along-strike geometry of the original normal fault system (e.g. Buchanan & McClay, 1991) and (ii) the timing and magnitude of reverse reactivation (e.g. McClay 1989; Brun & Nalpas, 1996).

There has, however, been very limited work on the *strike-slip* reactivation of normal faults (Fig. 1D-F), i.e. 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 i) single-phase oblique extension (e.g. Clifton & Schlische, 2001; Brune et al., 2012), and ii) multi-phase extension where an initial orthogonal extension phase is succeeded by a phase of oblique extension on the first-phase faults (e.g. Henza et al., 2010; Henstra et al., 2015). Although strike-slip reactivation is reported in the literature (e.g. Hartz & Andresen, 1995; Kim, 1996; Aris et al., 1998; Balaguru et al., 2003; Faure et al., 2006; Ducea et al., 2009; Jankowski & Probulski, 2011; Turner et al., 2011; Firth et al., 2015), 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 et al., 1998;

Kelly et al., 1999; Zampieri & 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 paper we focus on the latter scenario, i.e. 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 (Fig. 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 (Fig. 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 supplementary material for this paper.

Understanding and recognizing strike-slip reactivation of normal faults in sedimentary basins is critically important since 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 has economic implications, since 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 e.g. petroleum exploration, subsurface carbon storage, groundwater aquifer management and extraction of geothermal energy.

2. Terminology

The terminology used in this paper is defined in Peacock et al. (2000, 2016) and Biddle & Christie-Blick (1985), with Figure 1 illustrating some of the geometries described. While *transfer zone* is *used* by Dahlstrom (1970) for the structures that conserve shortening, or allow a regular change in shortening, between overstepping 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 Fig. 1) describe *synthetic transfer zones* and *conjugate transfer zones*, in which the overstepping faults dip in the same and opposite directions respectively (Fig. 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 (Fig. 1B; e.g. Larsen, 1988; Peacock & Sanderson, 1991; Huggins et al., 1995). If a relay ramp is breached by one or more *connecting faults* (Fig. 1C), it is termed a *breached relay*. The term *relay zone* encompasses both relay ramps (Fig. 1B) and breached relays (Fig. 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 (Figs. 2 and 3). The fault zone occurs in wavecut platform exposures of Liassic limestones and shales (e.g. Whittaker & Green, 1983). Peacock & Sanderson (1999) show that the deformation at Lilstock involves the following:

1. 060° striking veins, and possibly normal faults, are locally developed and indicate approximate 150°-330° extension.
2. 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 & Karner (1987). Nucleation, growth and normal slip on the studied fault system can likely be attributed to this stage of deformation.
3. 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.
4. 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.

5. 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 et al., 1995). Approximate north-south contraction during the late Cretaceous to middle Tertiary is also described in the Wessex Basin by Chadwick (1993).
6. The joints post-date the faulting events, because the joints abut the faults and they are not mineral-filled (Rawnsley et al., 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 (Fig. 3A). The exposed fault zone is comprised of five main right-stepping segments from east to west (Fig. 3A): (i) **Segment A** is poorly-exposed (and thus not shown in Fig. 3A) over a few metres and terminates eastward into a cliff; (ii) **Segment B** also terminates eastwards immediately before the same cliff and is poorly-exposed over a distance of ~ 74 m; (iii) Segment **C** is ~ 110 m long and its western end is well-exposed; (iv) **Segment D** is ~ 74 m long and is well-exposed along its entire length; (v) **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 (Fig. 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 33º. The relay zone separating fault segments B and C (Fig. 3A) is 31 m long and up to 8 m wide, with a maximum relay bed dip of 41º. The best exposed relay zone (Fig. 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 48º. Fault segments D and E are separated by a relay zone (Fig. 3A) with length 68 m, maximum width 12 m, and maximum relay bed dips of 39º.

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 localised structural highs in the studied fault system (Fig. 4A and B). Internally, the ramps are characterised by: (i) steepening of the bedding to dips of up to approximately 45° (Fig. 4B); (ii) strike-slip faults that are antithetic to the strike-slip displacement on the reactivated normal faults (Fig. 3B); (iii) strike-slip faults that are synthetic to the strike-slip displacement on the reactivated normal faults; (iv) calcite veins indicating sinistral transtension (Fig. 4C); (v) locally-developed fold-thrust structures (Fig. 4E), (vi) layer-parallel slip (Fig. 4E), and; (e) locally-developed crenulation cleavage in shale beds (Fig. 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 (Fig. 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 (Figs. 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. Peacock & Sanderson 1991, 1994; Fossen & Rotevatn 2016; 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 Fig. 1F). The following lines of evidence offer independent support for strike-slip reactivation:

(i) fault lineations (slickensides) indicate approximate strike-slip displacements (Fig. 4C).

(ii) left-stepping vein arrays that strike approximately E-W in the walls of the fault zone also indicate sinistral strike-slip deformation (Fig. 4B)

(iii) the network of faults and other structures within the steepened relay zones (Fig. 3B and 6A) also indicates contractional deformation, including fold-thrust structures (Fig. 4E) and crenulation cleavage (Fig. 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 we estimate that strike-slip displacement falls in the range of 1-5 m.

4. Discussion

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

Strike-slip reactivation of normal fault zones mean that any irregularity along that original fault zone will take on a new role as a locus for localised (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 Fig. 3, where a right-stepping normal fault zone is reactivated as a sinistral strike-slip fault, such relay zones become sites of localised contraction (as would the dextral strike-slip reactivation of a left-stepping normal fault system) (Fig. 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. Rotevatn et al., 2007; Bastesen & Rotevatn, 2012; Dimmen et al., 2017), as well as a wide variety of fault orientations due to fault interaction and stress perturbation in the relay zones (e.g. Crider & Pollard, 1998; Kattenhorn et al., 2000). 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 (intra-ramp strike-slip faults and thrusts) have 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 & 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 characterised 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 & 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. Larsen 1988; Peacock & Sanderson, 1991, 1994; Fossen & Rotevatn, 2016). 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 (Fig. 4E) and crenulation cleavage (Fig. 4F). Similarly, in a study of a km-scale similarly reactivated fault system in the Italian Alps, Zampieri & Massironi (2007) show that relay zones are associated with increased and higher-amplitude folding compared to non-reactivated relay zones (Fig. 7).

The relay zones in the studied fault systems represent local structural highs. While relay zones in extensional fault systems represent a downward stair-stepping structure from the footwall to the hangingwall (e.g. Larsen, 1988; Peacock & Sanderson 1991, 1994), localised shortening of the relay zones means they may form local structural highs along strike of the reactivated fault system. The localised shortening is responsible for a tendency to turn the former relay zones into positive structures due to folding, tilting and thrusting, much like is seen at restraining bends and steps along primary strike-slip faults (e.g. Sylvester, 1988; McClay & Bonora, 2001; Cunningham & Mann, 2007; Dooley & Scheurs, 2012). On the plate-boundary scale, a relevant example for comparison is the Sulaiman-Kirthar arcuate fold-thrust belt in Pakistan (Fig. 8). This originated as a 100s-km-scale transfer zone in a Mesozoic rift system between Africa, Madagascar and India (e.g. Scotese, 1991; Haq & Davis, 1997), but underwent sinistral reactivation in Eocene times during the collision between the Indian and Eurasian plates (Dewey et al., 1989; Haq & Davis, 1997), leading the transfer zone to turn into an arcuate fold and thrust belt (Fig. 8).

4.2 Scaling relations and bed dips of reactivated relay zones compared to un-reactivated 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 non-reactivated 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 Mansfield & Cartwright, 2001, Long & Imber, 2011, Fossen & Rotevatn, 2016). As such, aspect ratio appear not to be distinctive for reactivated relay zones when compared to non-reactivated 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 & Sanderson (1991, 1994) show relay zones in the study area between stepping normal faults with dips of up to about only 20º. Figure 10 shows a comparison of the relay zone steepness data from this study and data from Fossen & Rotevatn (2016), who show, based on global outcrop-based data (from Soliva & Benedicto, 2004; Huggins et al., 1995; Xu et al., 2011; Giba et al., 2012; Bastesen & Rotevatn, 2012; Rotevatn & Bastesen, 2014) that unbreached, partly breached and fully breached relay zones have mean bed dips of 7º, 13º and 18º, respectively (the maximum dip reported was for a breached relay, at 32º). The relay zones in the fault zones at Lilstock, however, shows dips of up to about 48º (Figs. 3, 4A and 10). This suggests that relay zone dips higher than 20-30º is atypical for relay zones in normal fault systems, and that relay bed dips in excess of 30-35º is probably 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 localised shortening, may be summarised in two points: Firstly, the relay zones are associated with high fault intensities that are amplified by the strike-slip fault 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 et al., 2010; Rotevatn & Bastesen, 2014; Peacock et al., 2017). Numerous studies have shown similar effects of structural complexity on the loci of fluid flow in non-reactivated normal fault systems (e.g. Davatzes & Aydin, 2003; Gartrell et al., 2004; Dockrill & Shipton, 2010). For example, Rowland & 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 the strike-slip reactivation of normal faults suggests either that (i) strike-slip reactivation of normal faults is uncommon, or (ii) 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:

Clear seismic evidence of normal offset, as well as one or more of the following:

- Seismically identifiable strike-slip offset, although this is generally difficult to pinpoint from seismic reflection data.
- Inversion only of selected faults, particularly at or near relay zones or fault bends
- Relay beds steeper than 30-35º (see Section 5.2 and Fig. 10).
- Areas of uplift (folds, thrust-related features) at relay zones and/or fault bends.
- Evidence for contractional deformation at relay zones.
- Network of faults, within and around relay zones, that accommodate shortening.

4.5 Releasing strike-slip reactivation of normal fault zones

Although the current study focuses on an example where relay zones are turned into sites of localised contraction during strike-slip reactivation, localised 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 localised subsidence, or pull-apart basins, as the transfer zones along normal faults become reactivated as extensional steps by strike-slip deformation (e.g. Richard and Krantz, 1991; Wong and

Munguía, 2006; Zampieri and 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 paper has aimed to elucidate the phenomenon of strike-slip reactivation of segmented normal faults, and specifically opposite-sense strike slip-reactivation, i.e. 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.
- 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 relays-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.

Conflicts of interest

A. Rotevatn is an Associate Editor in Basin Research.

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Figure captions

Fig. 1. Schematic diagrams of the main map-view fault geometries described in this paper. (a) A *transfer zone* between two stepping sub-parallel normal faults of any relative dip direction (e.g. Morley et al., 1990). (b) A *relay ramp*, between two stepping sub-parallel 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 contractional step.

Fig. 2. Geological map of Somerset, the Bristol Channel Basin and surrounding areas. The location of the study area at Lilstock is shown. From Engelder and Peacock (2001).

Fig. 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 a UAV.

Fig. 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). (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 detaill (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.

Fig. 5. Field photograph of a south-dipping normal faults and associated E-W striking calcite veins, exposed in the eastern part of the fault zone at Lilstock. These structures indicate initial ~ N-S extension.

Fig. 6. Schematic figure showing the effects of strike-slip reactivation on normal fault zones.

Fig. 7. A km-scale normal fault system reactivated as a sinistral-strike slip fault in the Italian Alps (from Zampieri & Massironi, 2007). Note the (originally extensional) transfer zone to the south, between the Garmonda and Tormeno faults, which has been reactivated as a restraining stepover. See text for full discussion. Note also the releasing stepover to the north, between the Tormeno and Melegnon faults.

Fig. 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 between 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.

Fig. 9. Relay length (fault overlap) vs relay width (fault separation) of the inverted relay zones this study plotted with global data from previous studies. The figure is modified from Fossen & Rotevatn (2016), and the global data are from the same paper and form Mansfield & Cartwright (2001), Long & Imber (2011). F&R16 = Fossen & Rotevatn (2016). Note that the data from the example shown in Fig. 3 (n = 4) plot well within the cloud of points that defines the global trend.

Fig. 10. Distribution of maximum dip of relay zones that are: (a) unbreached; (b) parly breached; (c) strongly breached, and; (d) inverted. The data in (a), (b) and (c) are derived from outcrop examples from Soliva & Benedicto (2004); Huggins et al. (1995); Xu et al. (2011); Rotevatn & Bastesen (2012); Giba et al. (2012), and Bastesen & Rotevatn (2012). Dip is relative to the general (regional) layer orientation. (a), (b) and (c) are modified from Fossen & Rotevatn (2016), whereas (d) presents data from this study.

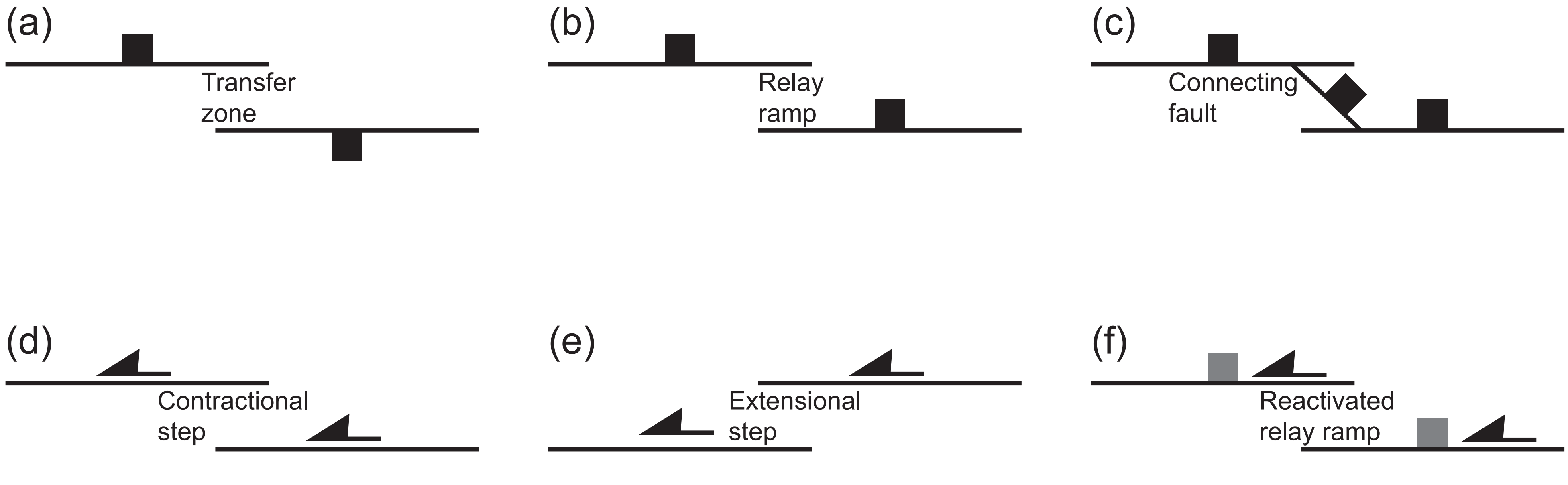

(a)
Transfer
zone
(b)
Relay
ramp
(c)
Connecting
fault
(d)
Contractional
step
(e)
Extensional
step
(f)
Reactivated
relay ramp

Figure 1

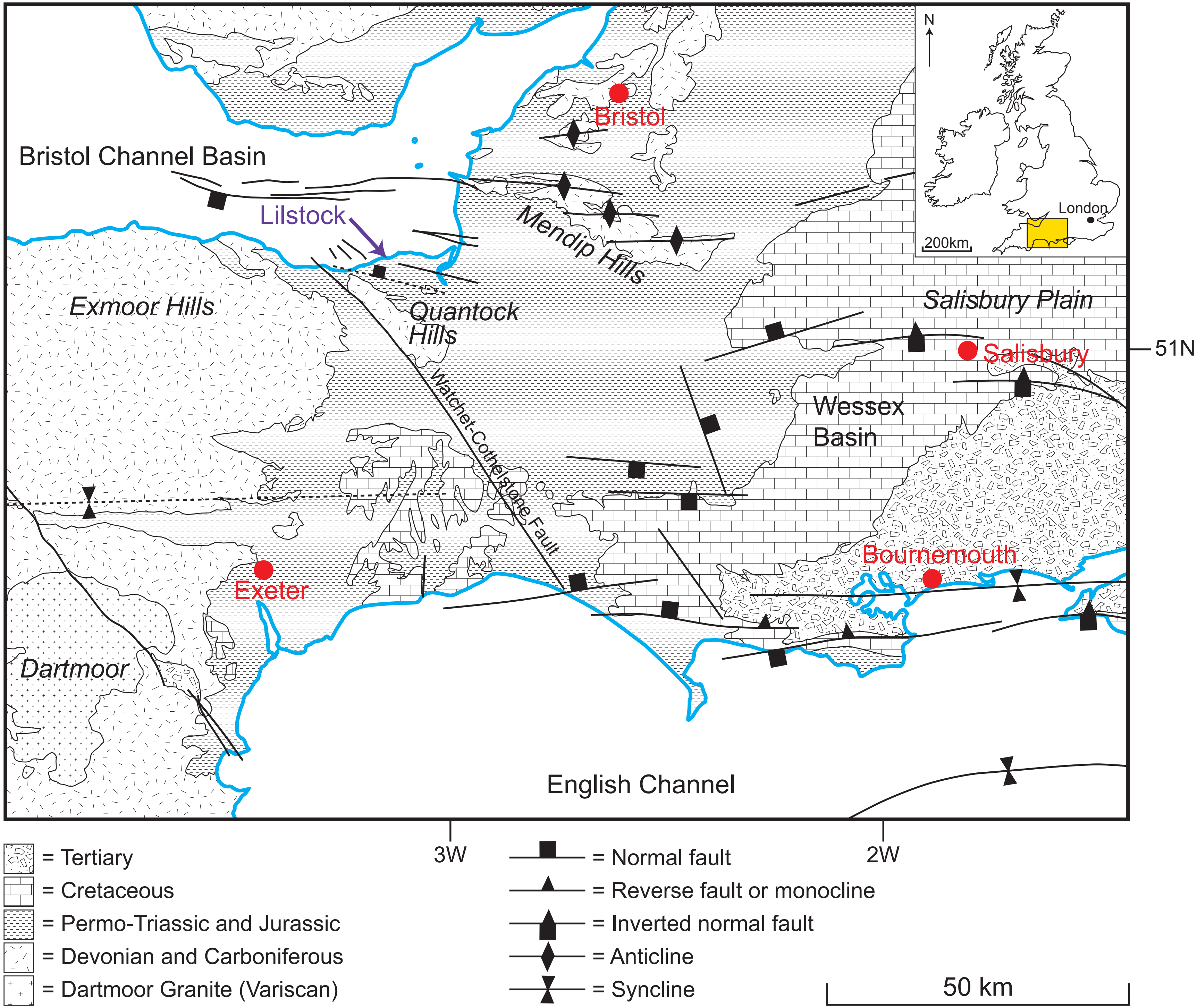

Bristol Channel Basin
Bristol
Lilstock
Mendip Hills
Exmoor Hills
Quantock Hills
Watchet-Cothelstone Fault
Salisbury Plain
Salisbury
51N
Wessex Basin
Bournemouth
Exeter
Dartmoor
English Channel
N
London
200km
3W
2W
= Tertiary
= Cretaceous
= Permo-Triassic and Jurassic
= Devonian and Carboniferous
= Dartmoor Granite (Variscan)
= Normal fault
= Reverse fault or monocline
= Inverted normal fault
= Anticline
= Syncline
50 km

Figure 2

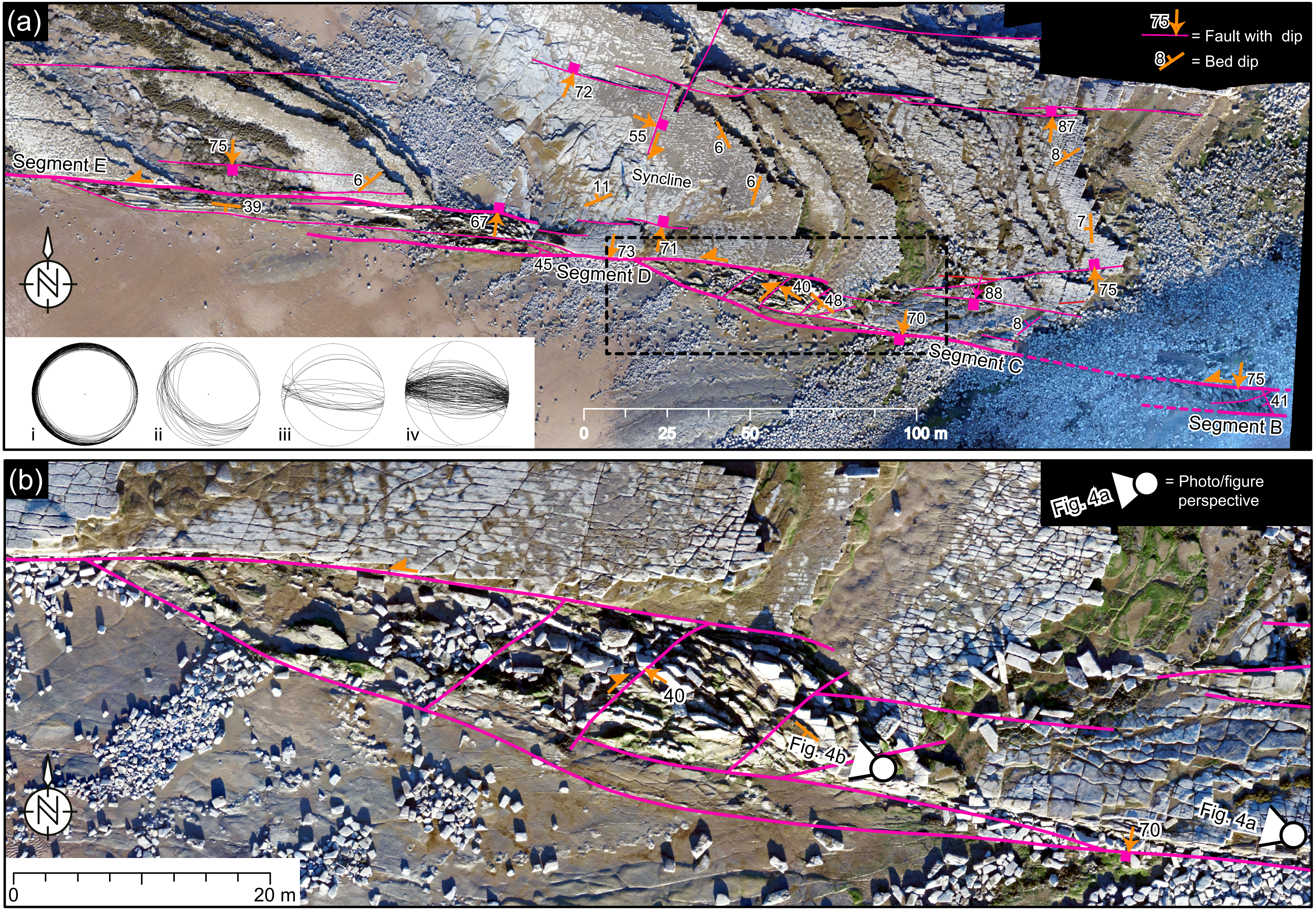

(a)
75 = Fault with dip
8 = Bed dip
Segment E
Segment D
Segment C
Segment B
Syncline
72
55
6
87
8
75
6
39
11
6
67
73
71
7
45
40
48
88
75
70
8
75
41
i
ii
iii
iv
0
25
50
100 m
(b)
Fig. 4a = Photo/figure perspective
40
Fig. 4b
Fig. 4a
70
0
20 m

Figure 3

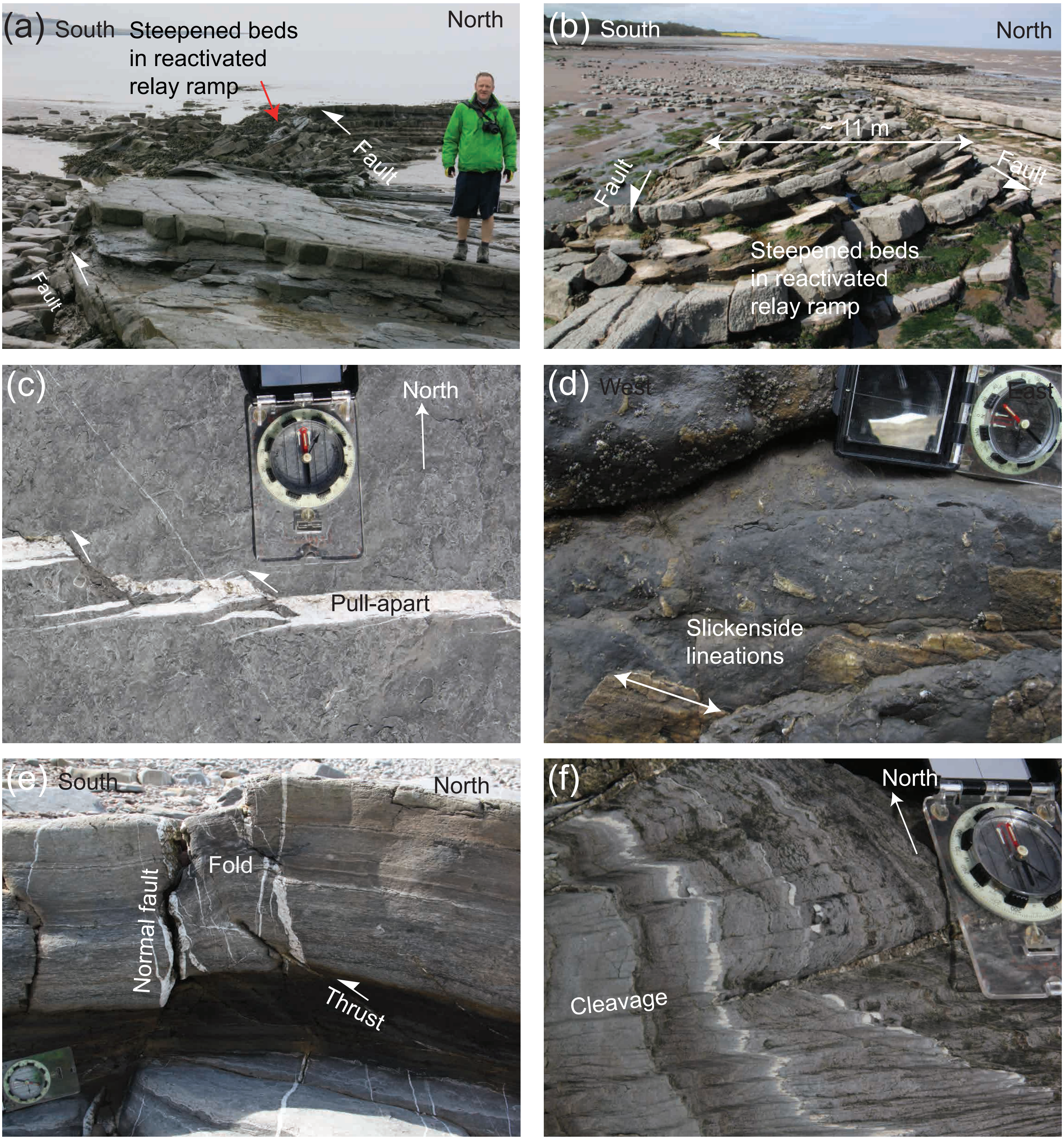
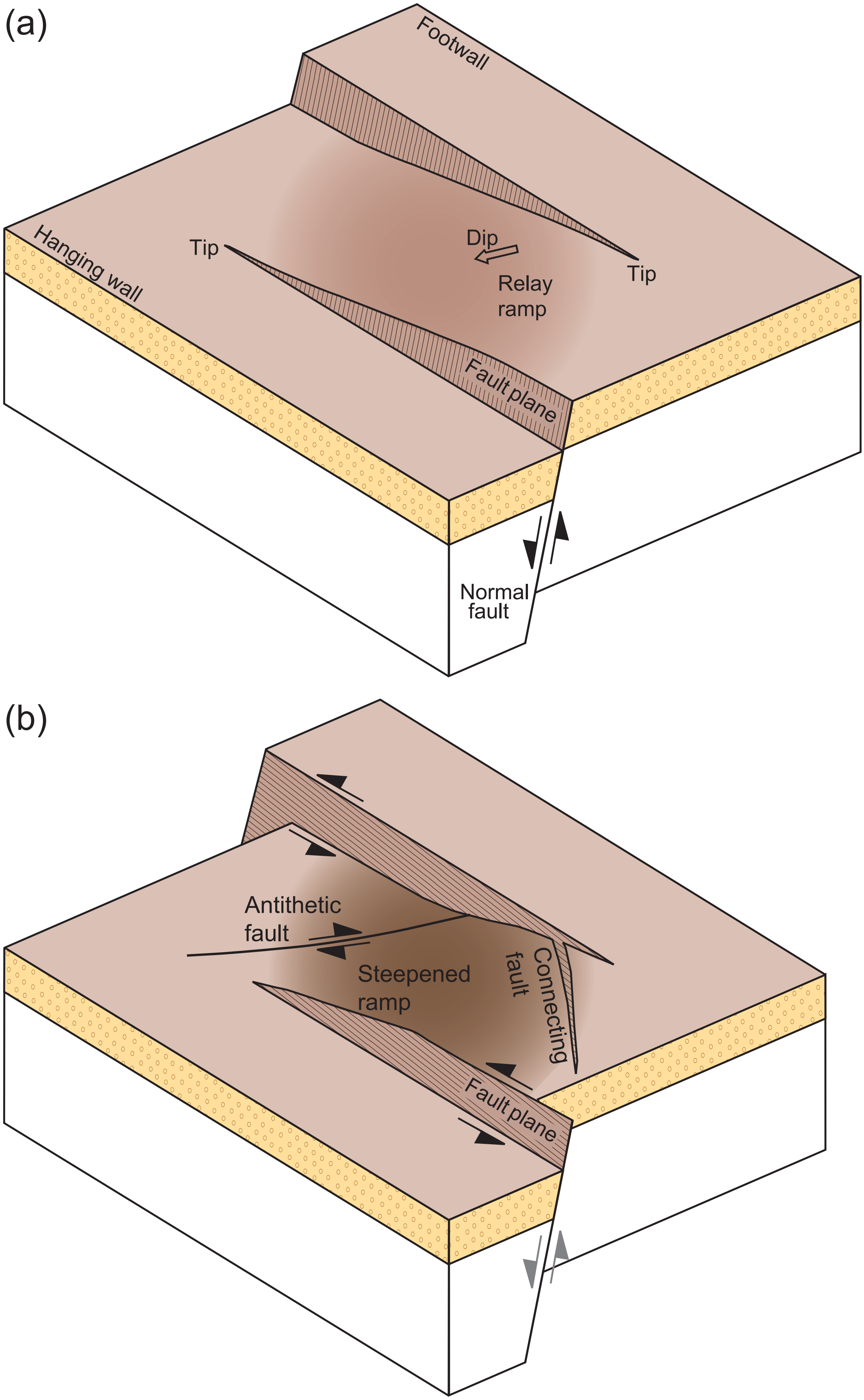

(a) South
Steepened beds in reactivated relay ramp
North
Fault
Fault
(b) South
North
~ 11 m
Fault
Fault
Steepened beds in reactivated relay ramp
(c)
North
Pull-apart
(d) West
East
Slickenside lineations
(e) South
North
Fold
Normal fault
Thrust
(f)
North
Cleavage

Figure 4


Limestone bedding plane
Calcite veins
Normal fault
North
Limestone bedding plane

Figure 5



(a)
Footwall
Hanging wall
Tip
Dip
Tip
Relay
ramp
Fault plane
Normal
fault
(b)
Antithetic
fault
Steepened
ramp
Connecting
fault
Fault plane

Figure 6

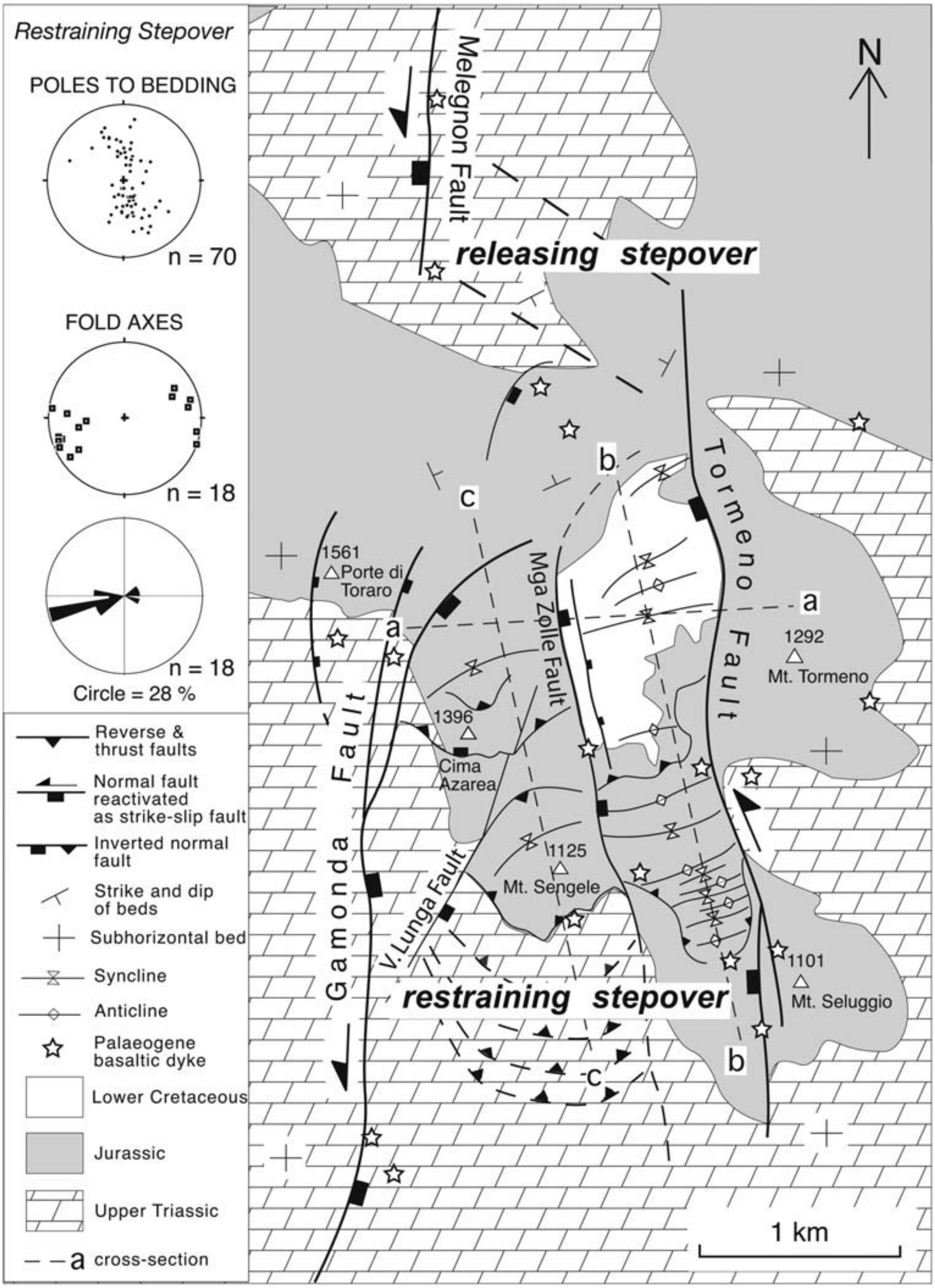
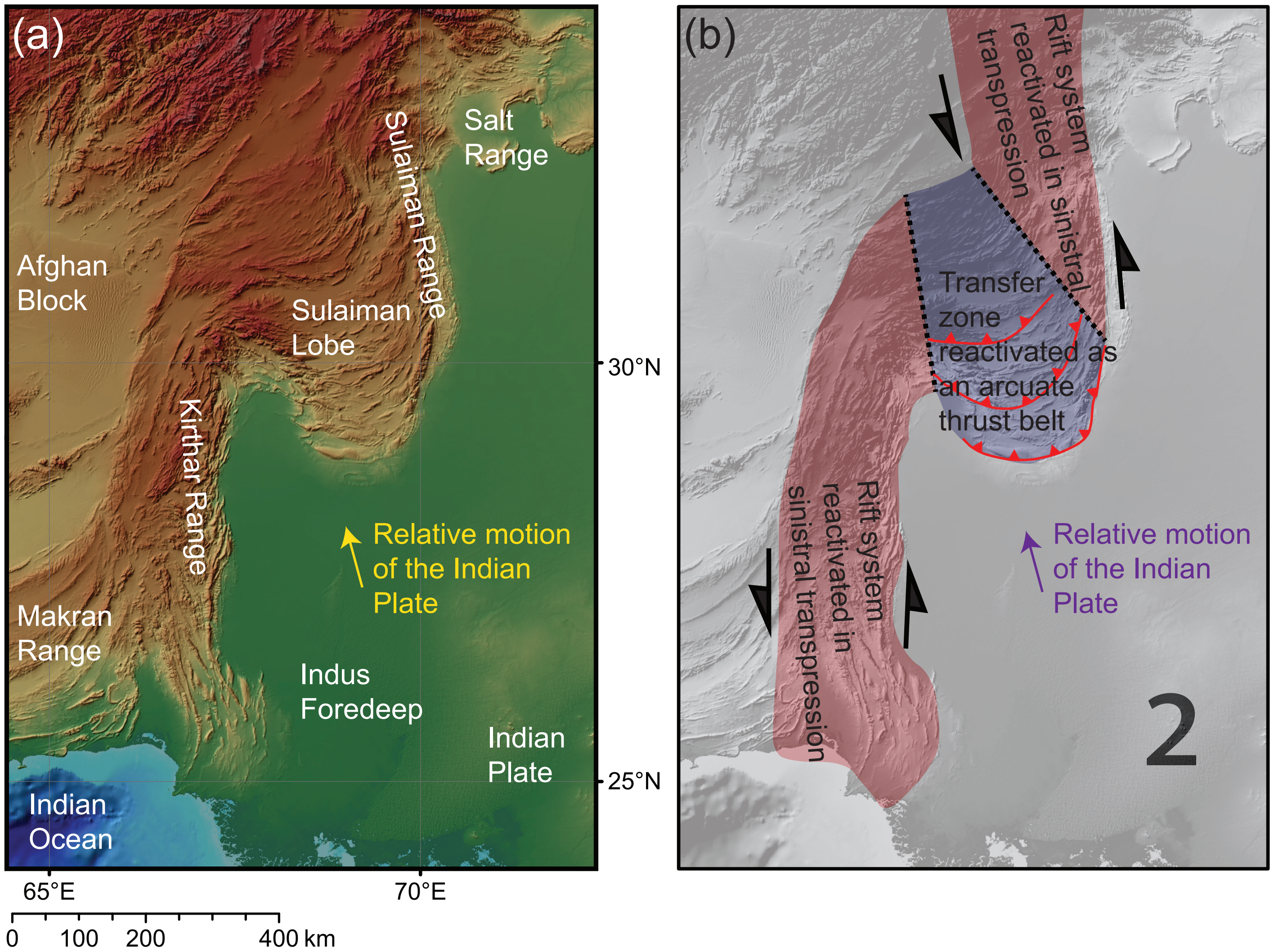
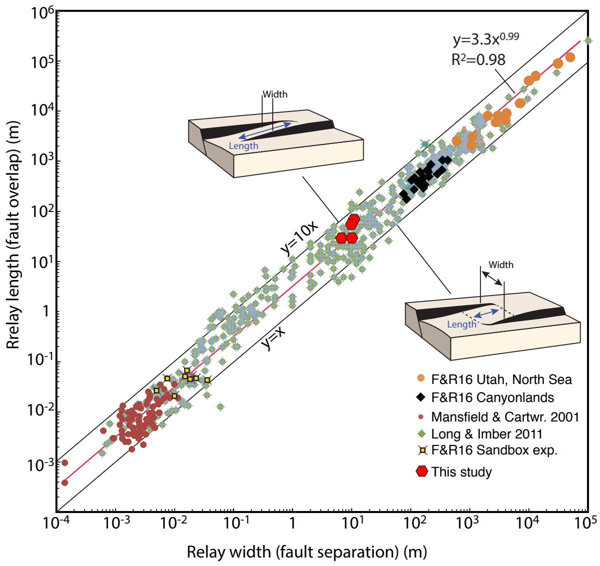

Restraining Stepover
POLES TO BEDDING
n = 70
FOLD AXES
n = 18
n = 18
Circle = 28 %
Reverse & thrust faults
Normal fault reactivated as strike-slip fault
Inverted normal fault
Strike and dip of beds
Subhorizontal bed
Syncline
Anticline
Palaeogene basaltic dyke
Lower Cretaceous
Jurassic
Upper Triassic
a cross-section
N
Melegnon Fault
releasing stepover
Tormeno Fault
Gamonda Fault
Mga Zolle Fault
V. Lunga Fault
restraining stepover
1561 Porte di Toraro
1396 Cima Azarea
1125 Mt. Sengele
1292 Mt. Tormeno
1101 Mt. Seluggio
1 km

Figure 7



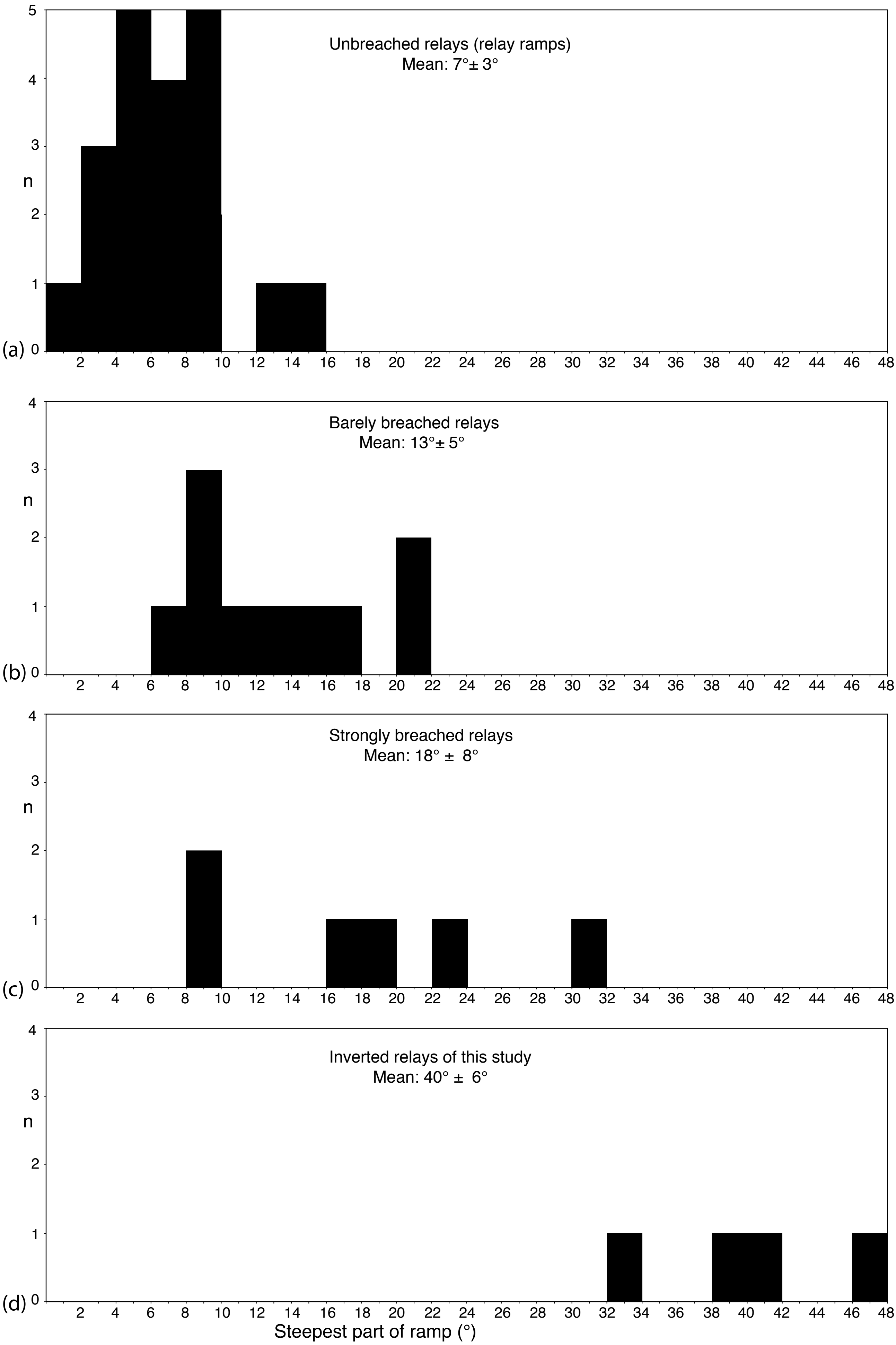
(a)
Salt Range
Sulaiman Range
Afghan Block
Sulaiman Lobe
30°N
Kirthar Range
Relative motion of the Indian Plate
Makran Range
Indus Foredeep
Indian Plate
25°N
Indian Ocean
65°E
70°E
0
100
200
400 km
(b)
Rift system reactivated in sinistral transpression
Transfer zone reactivated as an arcuate thrust belt
Rift system reactivated in sinistral transpression
Relative motion of the Indian Plate
2

Figure 8



y=3.3x^0.99
R²=0.98
Width
Length
Width
Length
y=10x
y=x
F&R16 Utah, North Sea
F&R16 Canyonlands
Mansfield & Cartwr. 2001
Long & Imber 2011
F&R16 Sandbox exp.
This study
Rrelay length (fault overlap) (m)
Relay width (fault separation) (m)

Figure 9



Unbreached relays (relay ramps)
Mean: 7°± 3°
Barely breached relays
Mean: 13°± 5°
Strongly breached relays
Mean: 18° ± 8°
Inverted relays of this study
Mean: 40° ± 6°
n
(a)
(b)
(c)
(d)
Steepest part of ramp (°)

Figure 10