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The role of pressure solution seam and joint assemblages in the formation of strike-slip and thrust faults in a compressive tectonic setting; The Variscan of south-western Ireland

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ABSTRACT

The Ross Sandstone in County Clare, Ireland, was deformed by an approximately north-south compression during the end-Carboniferous Variscan orogeny. The initial assemblage consists of mutually abutting orthogonal arrays of 170° oriented set 1 joints/veins (JVs) and approximately 75° oriented set 1 pressure solution seams (PSSs) formed under the same stress conditions. Orientations of splay JVs and PSSs (set 2) suggest a clockwise remote stress rotation of about 35° responsible for the contemporaneous shearing of the set 1 arrays. Among these nearly orthogonal strike-slip faults, the prominent set is sub-parallel to set 1 JVs. These faults are formed by the linkage of en-echelon segments with broad damage zones responsible for right-lateral offsets of hundreds of meters. Thrust faults with up to 30 m of offset initiate within shale horizons and follow either the PSSs in the sandstones or high-angle shales within tilted sequences. Within the large thrust fault zones, compartmentalised blocks of rocks are bounded by thrust faults segments with various dip angles. Strike-slip and thrust faults are contemporaneous and owe their existence to initial weaknesses in the form of JVs and PSSs rather than by switching relative stress magnitudes and orientations associated with Andersonian models of faults and related stress orientations.

1. Introduction

The coastal exposures of the Carboniferous Ross Sandstone in western Ireland have been of great interest for the study of deep water successions and turbidite channel architecture (Rider, 1974; Pulham, 1989; Elliott, 2000; Martinsen et al., 2003; Pringle et al., 2003; Strachan and Alsop, 2006; Pyles, 2008; Pyles and Jennette, 2009). However, the detailed structural evolution of the Irish Variscan deformation within this formation is relatively overlooked. This location provides exceptionally well exposed arrays of opening mode structures such as joints or veins (since opening mode structures with and without fill exist, we will refer to them collectively as JVs), and closing mode structures in the form of pressure solution seams (PSSs). We refer to the initial assemblage of JVs and PSSs formed by these two basic failure modes in this paper as 'fundamental structures'. Complex structures exist at the geological map scale such as strike-slip faults and thrust-cored folds in various stages of development. In this study we focus on the initiation and development of strike-slip faults by shearing of the initial JVs and PSSs and the formation of thrust faults by exploiting weak shale horizons and strike-parallel PSSs in the adjacent sandstone intervals.

Development of faults from the shearing of initial structural elements with either opening or closing modes in a wide range of structural settings has been extensively reported. The assemblage of structures around a sheared discontinuity allows inferences about the local stress state to be inferred (Rispoli, 1981). Segall and Pollard (1983), Martel and Pollard (1989) and Martel (1990) have described strike-slip faults formed by shearing of thermal fractures in granitic rocks. Myers and Aydin (2004) and Flodin and Aydin (2004) reported strike-slip faulting from shearing of joints formed by an earlier episode of deformation in sandstone. Willemse et al. (1997) and Graham-Wall et al. (2006) elucidated strike-slip faulting from a combination of veins and PSSs in carbonate rocks. Perhaps, the closest analogues to the development of strike-slip and thrust faults in the clastic rocks of the Irish Variscan are those described by Florez-Nino et al. (2005) and Gonzales and Aydin (2008) from the Andean foreland in Bolivia and Chile, respectively. These authors reported thrust faults being confined within shale-dominated horizons and strike-slip faults taking place within the stiffer sandstone and conglomerate units. In

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both cases, the strike-slip faults formed by reactivation of the cross joints initially perpendicular to structural trends of the fold and thrust belts.

In all these cases and a few others which dealt with normal faults (Graham et al., 2003; Agosta and Aydin, 2006), the basic mechanism was determined to be shearing of the initial structural elements, JVs and/or PSSs (set 1 structures) resulting in the formation of splay JVs and/or PSSs (set 2 structures). The shearing of these splays can result in higher order structures. Although splay fractures are called by different names (wing crack, tail cracks, and horsetail structures) the mechanism and the resulting fracture geometry are the same (de Joussineau et al., 2007).

Gonzales and Aydin (2008) reported that through-going strike-slip fault zones with larger slip magnitudes are slightly oblique to the initial joint orientation due to the linkage of stepping segments. The strike-slip faults can continue to grow to form a linked network of fault zones (Peacock, 1991; Peacock and Sanderson, 1995) with deformation being eventually concentrated on the largest faults (de Joussineau and Aydin, 2007).

As with strike-slip faults, thrust faults can be viewed as the linkage of initially isolated fault segments to form a larger, through-going structure (Eisenstadt and de Paor, 1987; Aydin, 1988; Ellis and Dunlap, 1988; Nicol et al., 2002; Davis et al., 2005). Fault segmentation can be enhanced in heterogeneous rock sequences if differences in rock properties exist across layer interfaces. This acts to pin thrust tip-lines in mechanically weak layers that are adjacent to strong layers (Nicol et al., 2002). Eventually thrust faults cut across the stiff layers above (Boyer and Elliott, 1982) forming flats and ramps and producing thrust related folds (Suppe, 1985). However the details of how a thrust propagates through the stiffer units and the architecture of thrust fault zones and related dip domains are less well understood. In this study, we document the role of PSSs and JVs in incipient thrust faults that sole into shale horizons and transect stiffer units. Through the associated folding, the resulting fault zones have highly complex internal architectures which would be difficult to elucidate without understanding the underlying mechanisms.

This investigation is of the development of faults from PSS and JV assemblages within a region of fold and thrust tectonics. We describe the deformation mechanism and the evolution of damage networks by mapping structures at progressive stages of their development. This study has three objectives: (1) To determine the relative timing, orientation, distribution, interaction and dynamic significance of PSSs and JVs during the initial tectonic episode. (2) To produce a chronological reconstruction of the shearing of fundamental structures to elucidate the evolution of fracture patterns, relative timing, sense and magnitude of shearing responsible for the formation of strike-slip faults. (3) To conceptualise the role of shale horizons, PSSs and JVs in the initiation and growth of thrust faults and as part of their internal architecture. This provides a better insight into both the nature and the degree of deformation associated with the Irish Variscan orogeny within Ireland.

The understanding of coeval PSS and JV formation in naturally deformed sandstone/siltstone turbidites, along with their shearing leading to the initiation and development of faults, has implications for fluid flow in analogous systems. For example, sandstones of similar age to the Ross Sandstone form potential hydrocarbon reservoirs in the subsurface offshore from the west coast of Ireland (Croker, 1995; Johnston et al., 2001; Martinsen et al., 2003). Studies on fold-thrust belt structural assemblages in carbonates emphasise that fractures and faults can act as high permeability networks through an otherwise low permeability host rock (Agosta and Aydin, 2006; Graham-Wall et al., 2006). This information is relevant to fluid migration through the rock during the period of deformation as well as at the present time (Braithwaite, 1989; Bjorlykke and Hoeg, 1997; Gibson, 1998; Aydin, 2000).

2. Geological setting

The formation of Pangaea at the end of the Carboniferous is marked by a roughly east-west oriented fold-thrust belt through Europe (where it is known as the Variscan orogenic zone), northern Africa and North America. In Ireland, the Variscan nearly north-south shortening was responsible for approximately east-west oriented structural fabrics apparent in the surface geological map of the study area (Fig. 1). The lack of Variscan structural trends in the north of Ireland indicates that the structures in County Clare represent the northern-most surface extent of the orogeny. A good summary of various structures present in the Irish and British Variscan is presented by Sanderson (1984) who advocated a thick-skinned model of tectonic deformation based on gravity data and the magnitude of shortening. However, the nature of the Variscan deformation deep in the crust has been debated. O'Reilly et al. (1996) stated that Variscan fabrics are not present in the deeper crust suggesting a 'thin-skinned' mode of crustal deformation. Cooper et al. (1986) also proposed a thin-skinned model. These authors used balanced 2D cross sections to explain the Irish Variscan deformation history as a progression of layer-parallel shortening, buckling and thrusting, though a thorough mechanical assessment of structural evolution within their study is not evident.

The structures of interest occur in the Ross Sandstone Formation located in County Clare, on the west coast of Ireland (Figs. 1 and 2). This formation is predominantly composed of deep water turbiditic sandstones and siltstones with occasional shaly intervals. The Ross Sandstone is part of the infill of the Shannon Basin which formed at the end of the Devonian crustal extension (Collinson et al., 1991). The base of the Namurian succession is comprised of the laterally equivalent Clare Shale Formation and Ross Sandstone Formation (Fig. 1). These formations are overlain by the Gull Island siltstones/sandstones representing of slumped continental shelf and unstable slope deposits, and the Central Clare Group deltaic cyclothems representing of delta progradation (Rider, 1974; Gill, 1979). The Ross Sandstone is only exposed at its type section on the Loop Head peninsula as it thins rapidly both to the north and to the south (Rider, 1974). Dating of the Ross Sandstone using goniatites of age H_2 to R_1 place it in the mid-Namurian (Hodson, 1954; Rider, 1974). The broader area of south-west Ireland displays confirmatory evidence in the form of approximately east-west trending thrust-cored folds (Fig. 4) of approximately north-south shortening during the Variscan Orogeny at the end of the Carboniferous (Coller, 1984; O'Reilly et al., 1996).

3. Field observations

Large scale structures of the Loop Head peninsula such as large folds and faults were mapped at a scale of 1:10,000 onto topographic base-maps in order to establish the Variscan structural trends and to form a framework for subsequent detailed mapping.

The large scale fold and fault structures on a sandstone platform, which we will refer to as the 'Ross platform', were mapped at a scale of 1:5000 (Fig. 2b; location 1). This platform is located near an antiform eroded from the base known as the 'Bridges of Ross' found on the coast near the village of Ross. It provides exceptionally exposed examples of pressure solution seams, joints and quartz-filled veins, folds, strike-slip and thrust faults with offsets ranging from millimetres to tens of metres, which are the focus of the present study. This location provides an opportunity to collect high quality data including the orientations, distributions, cross-cutting and abutting relationships. The developmental stages of younger shearing deformation and various fault sets can be observed. Fracture damage networks around medium-offset strike-slip faults

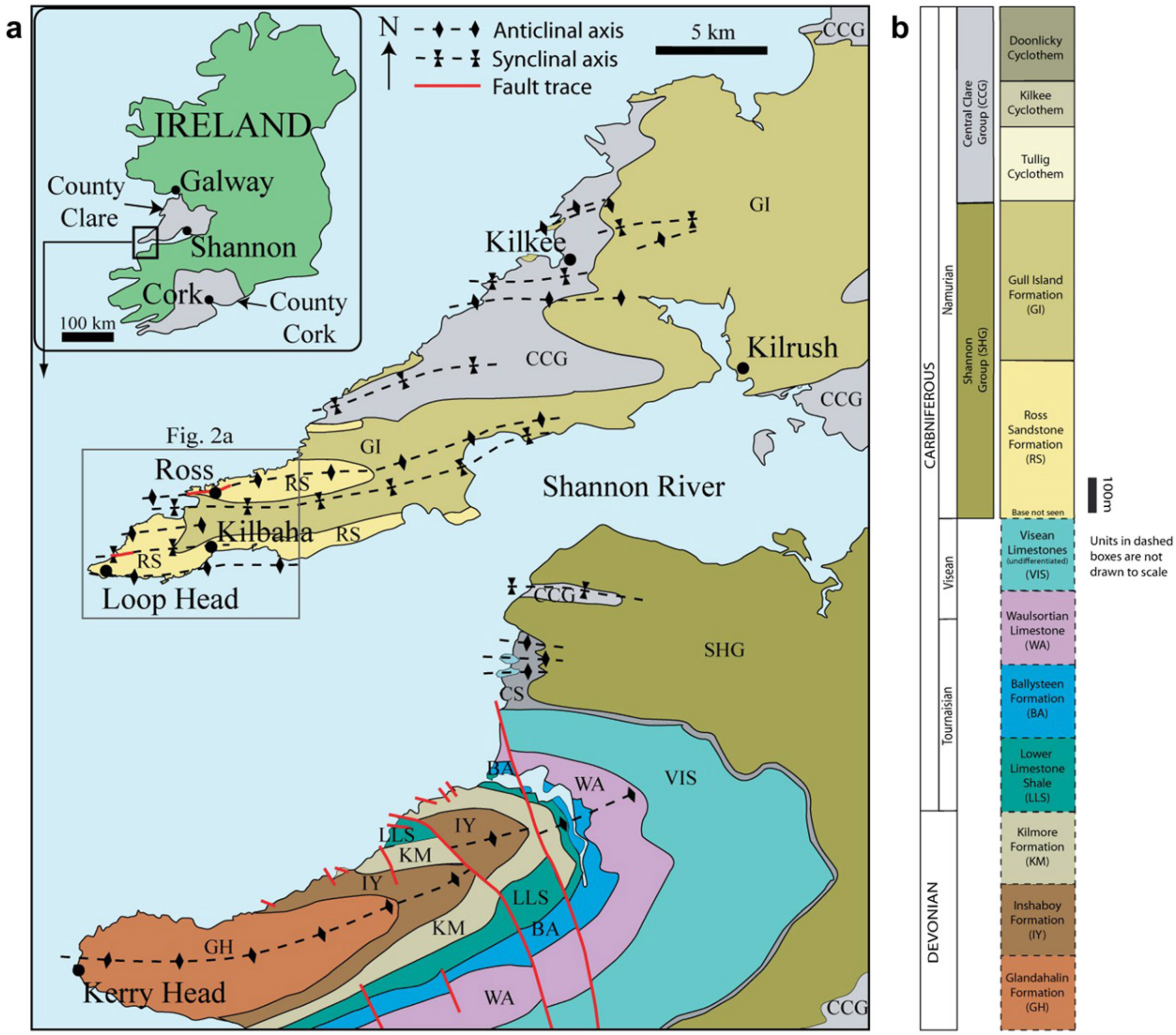

Fig. 1. Geological units with major fold axes and thrust fault traces within County Clare (a) modified from Sleeman and Pracht (1999) with inset to show location of the Loop Head peninsula within County Clare, Ireland. Geological column to accompany the map (b).

were also mapped within the Ross Sandstone but are located to the east of Kilbaha (Fig. 2a; location 2). We also present maps to show the orientation and distribution of larger-offset en-echelon strike-slip faults taken from a platform to the south-west of the Ross platform (Fig. 2a; location 3). This particular location is only accessible at low tide.

The outcrop scale structures were identified in the field and detailed maps were made directly onto photographs and photomosaics which were then digitally traced using Adobe Illustrator. These maps document structural arrays (of a single fracture type), assemblages (of multiple fracture types) and zones of structures found within the Ross Sandstone outcrops. Detailed maps of strike-slip fault arrays and thrust-cored folds were made using an array of measuring tapes and a compass to record distances between, and orientations of, structures and lithological boundaries.

3.1. Joint/vein and pressure solution seam assemblages

Two types of fundamental structures are ubiquitously present forming arrays at a high-angle to bedding: opening mode joints and veins (JVs), and closing mode pressure solution seams (PSSs). This assemblage of what we will refer to as set 1 JVs (JV1s) and set 1 PSSs (PSS1s) forms an orthogonal network (Fig. 3). The JV1s frequently abut against the PSS1s but there are also instances of the opposite abutting relationships indicating their essentially contemporaneous development.

The JVs in the Ross location can easily be identified by quartz infilling and typical plumose morphology when their surfaces are exposed (Fig. 4a). JV1s are at a high-angle to bedding and have an average orientation of 170° (Fig. 5a). Although JVs are strata-bound, the vertical continuity of the larger composite JVs crossing many layers as previously conceptualised by Helgeson and Aydin (1991) are often on the scale of many meters.

Although bed-parallel PSSs are also present in the Ross Sandstone, it is the high-angle PSSs (PSS1s) that are of interest in this study as they are the most pervasive. They are also easily distinguished from depositional structures such as thin clay lenses that are not necessarily formed by the pressure solution process. The high-angle PSSs are characterised by the colour contrast of the residue with respect to the host rock (Fig. 4b), strike-parallel orientation and sinuous form. PSS1 trace orientation measurements were taken over a length of seam to capture their sinuosity. An average orientation of approximately 75° was measured (Fig. 5a) has a greater error (on the order of ±10°) than that of the

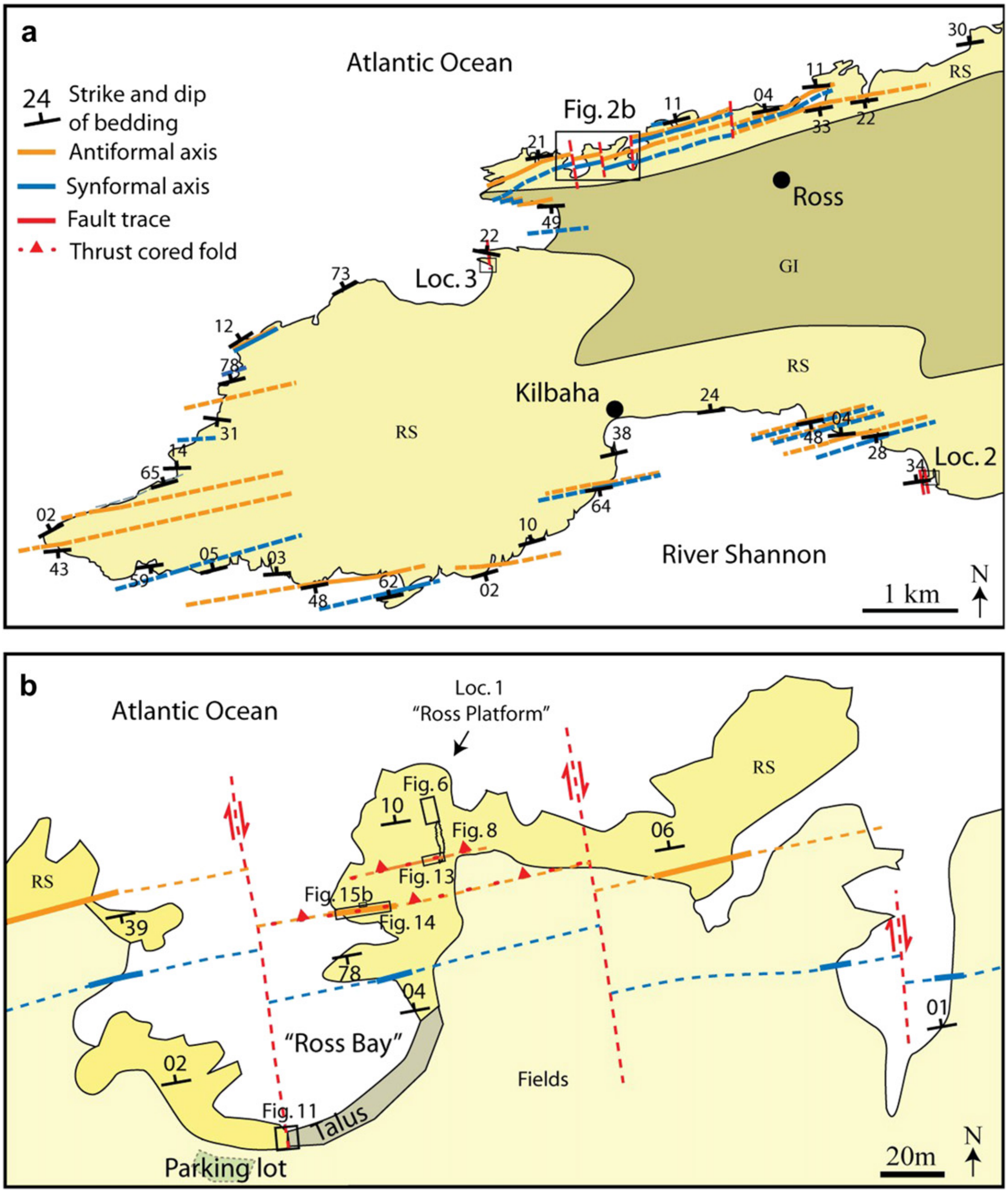

Fig. 2. Mapped regional scale fold and fault traces as observed on the Loop Head Peninsula (a) and the Ross platform near the Bridges of Ross location (b) within County Clare. The geological boundaries are adapted from Pyles (2008).

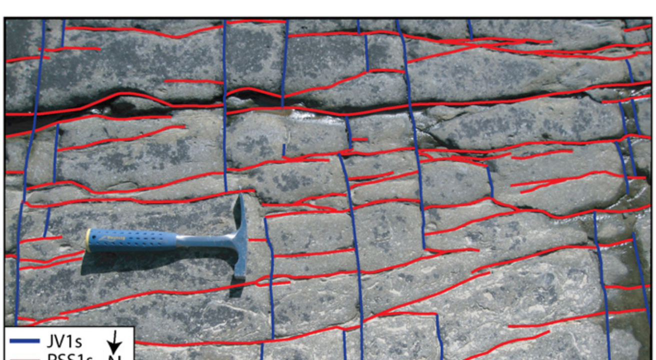

Fig. 3. Orthogonal JVs and PSSs in the Ross Sandstone at the Kilbaha location. Interbutting relationships suggest contemporaneous formation of these structures.

straighter JVs. Similar PSSs to those we describe here found in clastic rocks exposed near Cork city in the south of Ireland were detailed by Nenna and Aydin (2011) and reported by other workers who referred to the PSSs as cleavages (Dolan, 1984; Sanderson, 1984; Trayner and Cooper, 1984; Cooper et al., 1986; Meere, 1995).

3.2. Strike-slip faults

In various locations on the Ross platform (Fig. 2b, location 1), sheared versions of the fundamental structures are observed along with unsheared ones (Fig. 6). Some JV1s and PSS1s were determined to have right- and left-lateral shearing based on measured offsets and splays, which we refer to as set 2 JVs (JV2s) and PSSs (PSS2s) respectively. The average orientation of the JV2s is 25°. The PSS2s have an average orientation of 115° (Fig. 5b). These

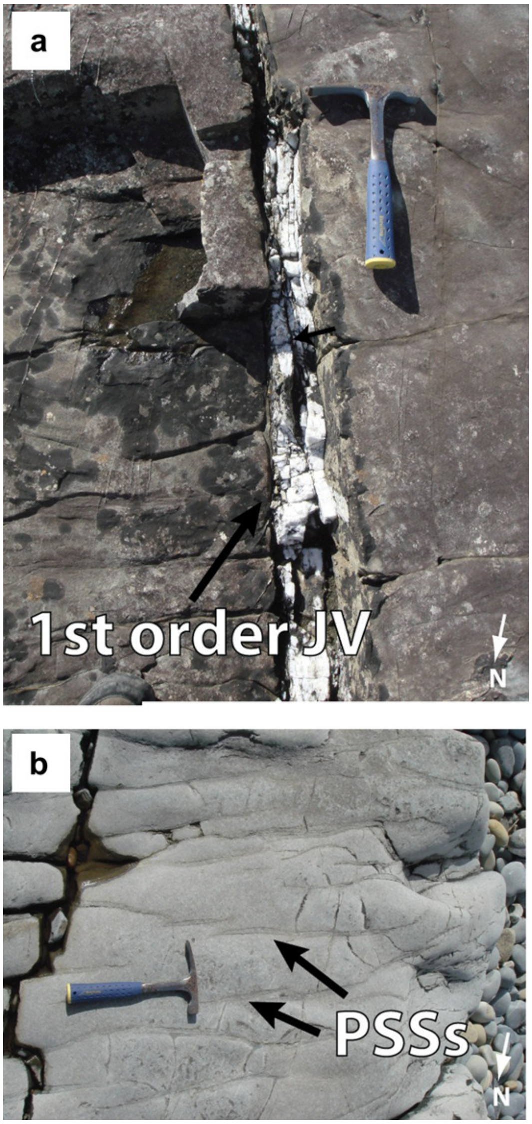

Fig. 4. Image of a JV with multiple slip surfaces (a) suggesting slip continued to occur after vein deposition. Exposed PSS traces (b) are identified by their sinuous trace and colour contrast against the host rock (hammer shown for scale).

measurements were taken on straight sections away from the tips of the set 1 structures in order to avoid recording any inconsistent intermediate orientations where the set 2 structures initially curve away from the set 1 ones.

On the Ross platform we mapped an echelon array of JV1s with an associated set of JV2s at an acute angle to them (Fig. 6), indicating that right-lateral slip has taken place. A maximum shear displacement of about 40 cm was calculated for this particular sheared JV1 using the presence of sub-horizontal slickenlines on the exposed vein surfaces and the apparent vertical offset of the inclined beds. Multiple slip surfaces with striations within the vein material show that episodic slip occurred after the vein material was deposited (Fig. 4a). Some of the individual PSS1s in this same location have also undergone left-lateral shearing to produce set 2 closing mode splays. In addition, a series of pull-aparts with multiple quartz veins occurs between overlapping sheared PSS1s along the extensions of the JV2 system. One of these shows 2 cm of left-lateral shear across this particular PSS1 as estimated from the combined widths of the quartz veins within the pull-apart (Fig. 7). The most intriguing phenomenon is that the shearing of JV1s and PSS1s was contemporaneous based on evidence from the detailed maps showing the interaction of the two shear systems: occurrence of quartz veins along the extension of set 2 (splay) JVs within the pull-aparts at step-overs between the sheared PSS1 segments (Fig. 8). This indicates that the shearing of the JVs and the formation of their splays coincided with the shearing of the PSSs and their pull-apart veins.

We have already referred to small offset strike-slip faults with right- and left-lateral displacements along most JV1s and PSS1s, respectively. On the Ross platform the right-lateral shearing of JV1s is greater in magnitude and distribution frequency than the left-lateral component along the PSS1s. In what follows we document progressively larger strike-slip faults and their internal architecture.

A series of sub-parallel right-lateral faults each with offset in the order of 30 cm to 2.5 m are observed at location 2 (Fig. 9a). Zones of fractured rock around the slip planes are formed from extensive splays (both opening and closing mode) between adjacent sheared PSS1s and JV1s, as seen on a mapped example that accommodates approximately 90 cm of offset (Fig. 9b). The majority of the offset occurs along one or more slip surfaces that are sub-parallel to the JV1s, but no obvious fault core is observed. This is true also of the strike-slip faults observed at location 3, where the observed offsets reach up to 8.7 m. Larger-offset right-lateral fault arrays were observed and mapped using a measuring tape and compass technique (Fig. 10). The faults have left stepping en-echelon arrangements with individual segments having maximum offsets in the range of 0.6–8.7 m. Average orientations of strike-slip faults were made by taking an average orientation through each en-echelon set (Fig. 5c). For strike-slip faults with only a few metres of offset, only closely spaced fault segments are linked by damaged rock produced by shearing of the JV1s and PSS1s, so the average orientation of the sets of linked right-lateral strike-slip faults are close to that of the original JV1s.

Mapped fold hinge lines have an apparent right-lateral offset of about 20 m across the Ross Bay (Fig. 2b). This large offset is distributed amongst a zone of sub-parallel north-south fault segments through the bay, and the wave platform (Fig. 11). Maximum observed offsets of these faults are right-lateral and on the order of 0.1–12.6 m.

Though we have not observed fault zones accommodating offsets larger than 20 m in the Ross area, faults with similar orientations in the same lithologies south of the River Shannon have apparent strike-slip offsets of more than 100s of metres (Fig. 1). These faults appear to be formed by the shearing of existing JVs and PSSs, and grew by linkage of progressively larger segments although too few fault cores are exposed to characterise their internal architecture and growth mechanism. However it is clear that the smaller sized right-lateral faults in the vicinity of these large mapped faults exposed on the wave platform are similar to those observed in the Ross location. The orientations of these map-scale strike-slip faults are between 160° and 110°, though there may be errors due to the poor quality of inland exposures. The angular difference between these large offset strike-slip faults and the smaller ones described previously is interpreted by the larger-offset faults having a larger damage network and incorporating more distal en-echelon fault segments than smaller offset faults.

3.3. Thrust faults

Thrust faults at different stages of development have been observed at the core of folds within the Ross Sandstone (location 1). We note that more, mostly inaccessible, examples exist throughout the region. Though both reverse and thrust faults are present in the area, for simplicity we will refer to them both as thrust faults regardless of the dip-angle of the fault plane.

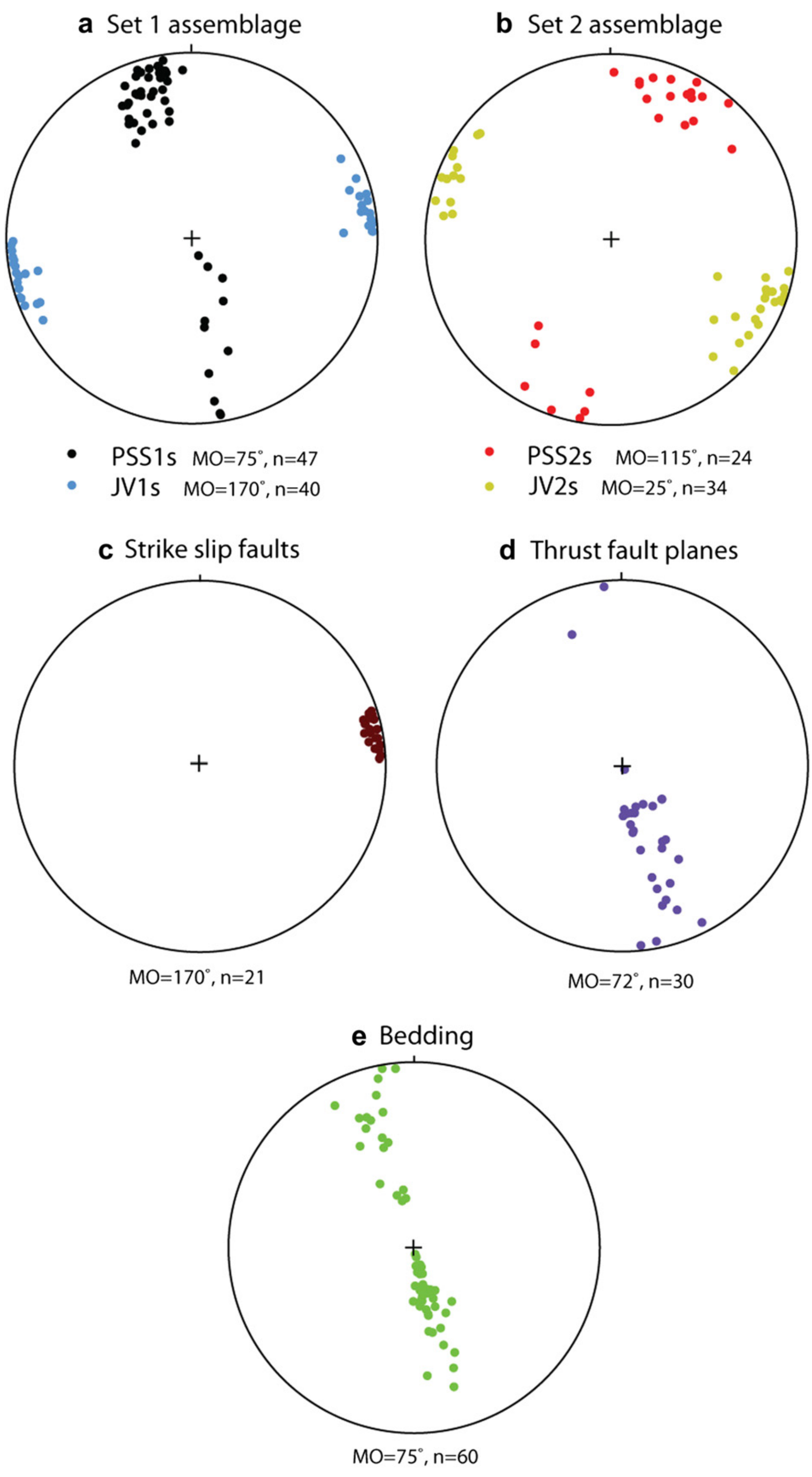

Fig. 5. Equal area, lower hemisphere stereonets to show the poles-to-planes of PSSs, JVs, strike-slip faults, thrust faults and bedding in the Ross and Kilbaha lotions. MO is the mean orientation of a structure set and n is the number of data points.

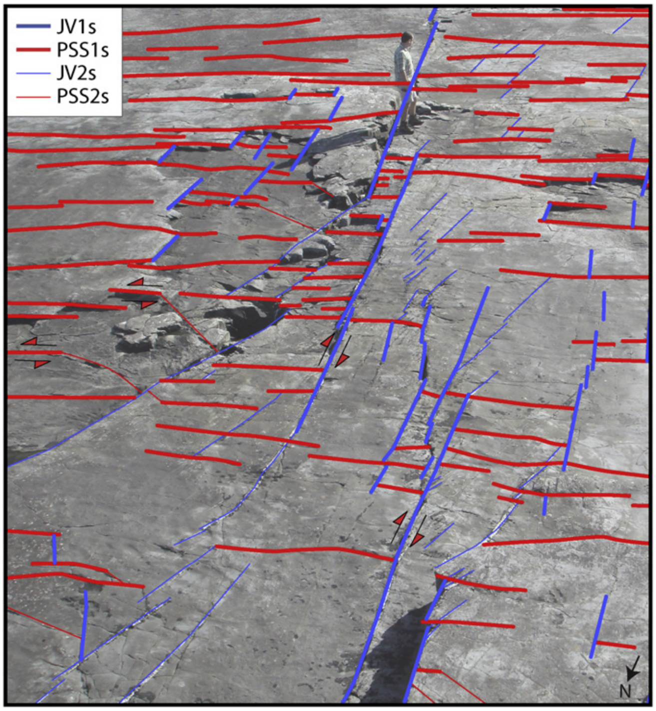

Fig. 6. Mapped photograph to show unsheared JV1s and PSS1s, and sheared ones that have produced JV2s and PSS2s as splays.

One of the smallest thrust faults among many others observed on the Ross platform has an offset in the order of a centimetre and cuts through the apex of a small fold (Fig. 12). The fault merges into or possibly initiates from a thin shale layer. Displacement occurs along strike-parallel PSS1s in the sandstone units with associated bed-parallel slip and crenulation in the adjacent shale unit that suggests the shale deformed independently from the adjacent sandstone.

Faults with approximately 1 m of displacement are observed where bedding is folded in such a way that the shale layers occur at a high dip-angle in the fault zones (Fig. 13). An example of such a fault was mapped both in cross section and along its trace in map view. The fault is composed of several segments that originate from,

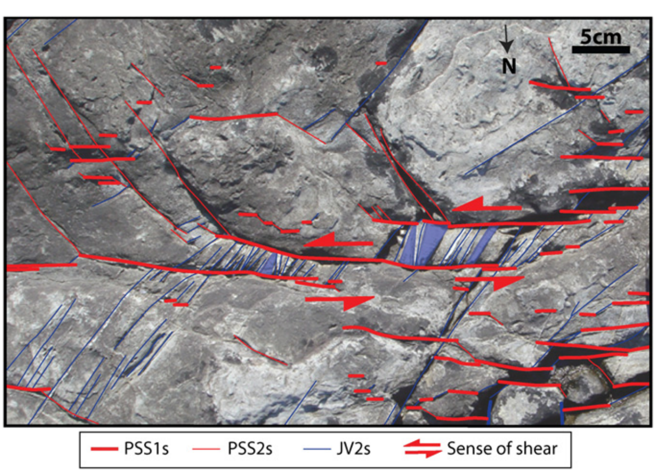

Fig. 7. Mapped image to show PSS1s with pull-aparts as evidence of left-lateral shearing. The JV2s within the pull-aparts have a quartz infill. JV1s are present in this locality, but are not present in this image.

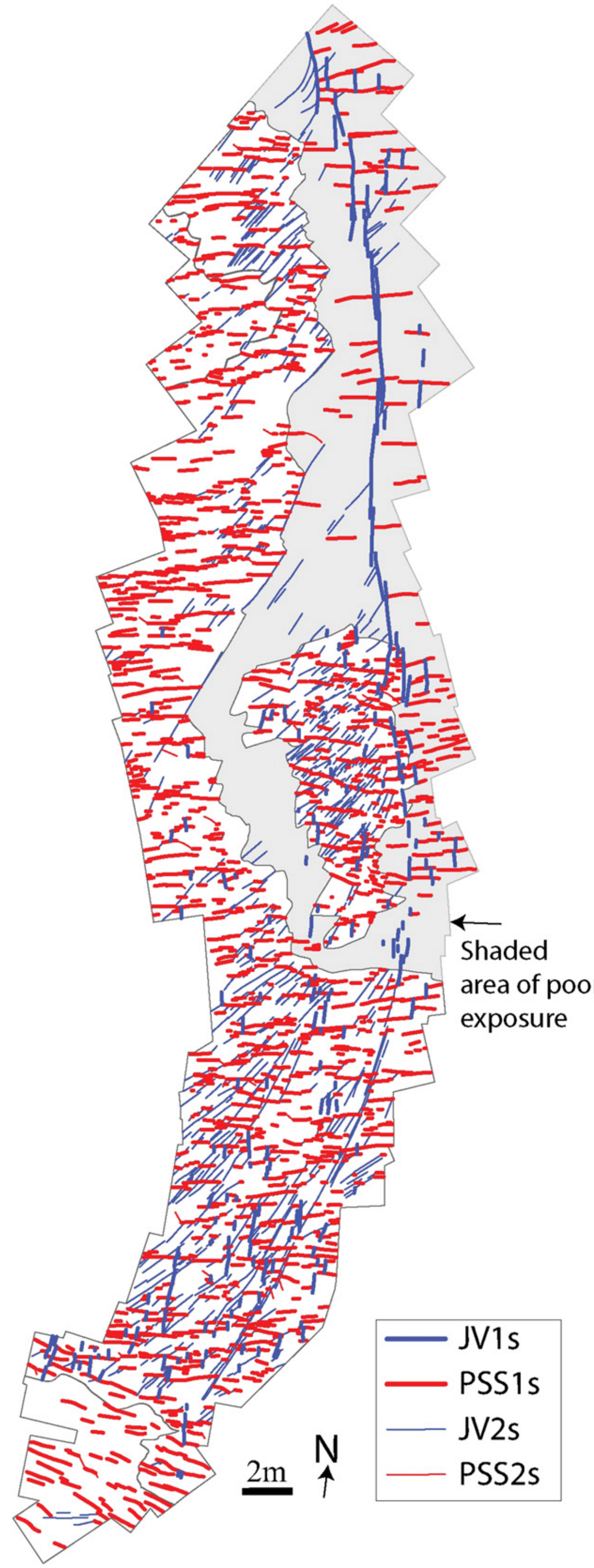

Fig. 8. Detailed map of a sheared PSS1 and JV1 assemblage in the Ross Sandstone. The splays show that the PSS1s have undergone left-lateral slip, and the JV1s have undergone right-lateral slip. PSS2s are much shorter than the other structural elements and are not clearly mapped at this scale.

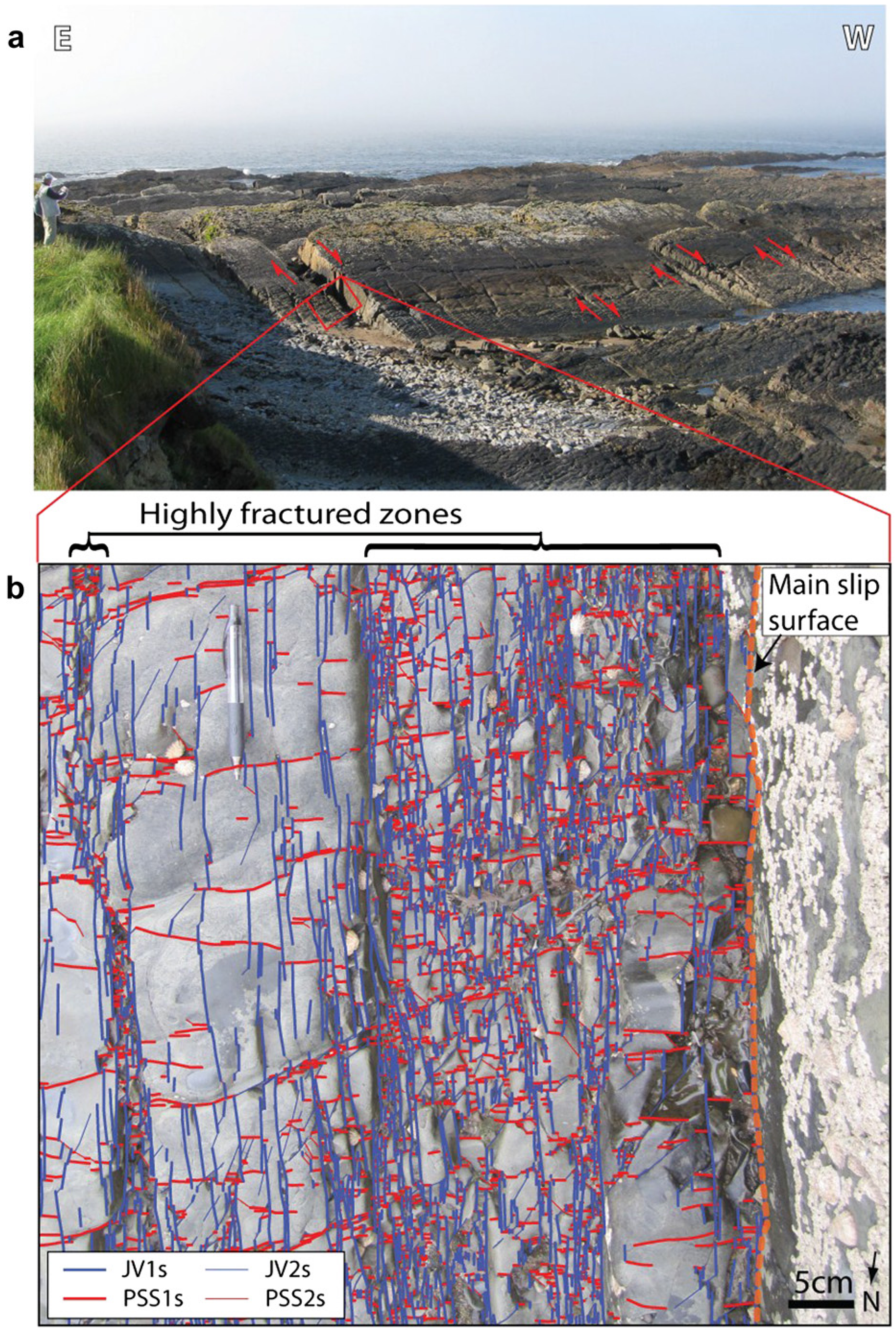

Fig. 9. Array of approximately N-S trending strike-slip faults near Kilbaha (location 2) (a). Mapped photograph (b) of strike-slip fault with about 90 cm of slip. Most of the offset occurs along a single slip surface with no obvious fault rock present.

or terminate into the shale layers and continue through the sand layers along PSSs. Thick vein deposits on the order of a few centimetres are located on the fault planes. They have slickenlines on their surfaces indicating an approximately north-south direction of slip. The JV1s associated with a small scale strike-slip fault system truncate against the thrust fault plane.

A much larger thrust fault with associated tight folds is observed 25 m to the south of the intermediate thrust-cored fold (Fig. 14). This fault penetrates the entire cliff face but the nature of the exposure prevents offset markers being observed in both the hanging wall and footwall. The large amplitude of the folding (on the order of 15–20 m) and the abrupt change in bedding orientation on either side of the fault plane suggests an offset at least equal to the height of the cliff face, about 25–30 m.

The fault strands include bedding plane faults following low-angle and upright shale units on the northern and southern limb of the large scale fold. Highly deformed and extensively veined sandstone lenses are bounded between the sheared shale beds (Fig. 15a). The majority of these veins within the thrust fault zone appear to be strike-parallel and sub-horizontal in some places in contrast to the JV1s or JV2s described earlier (Fig. 15b). The geometry of the fault strands and fractures (JVs and PSSs) and the distribution and variation of the dip domains of fault bounded blocks are extremely complex especially in map view.

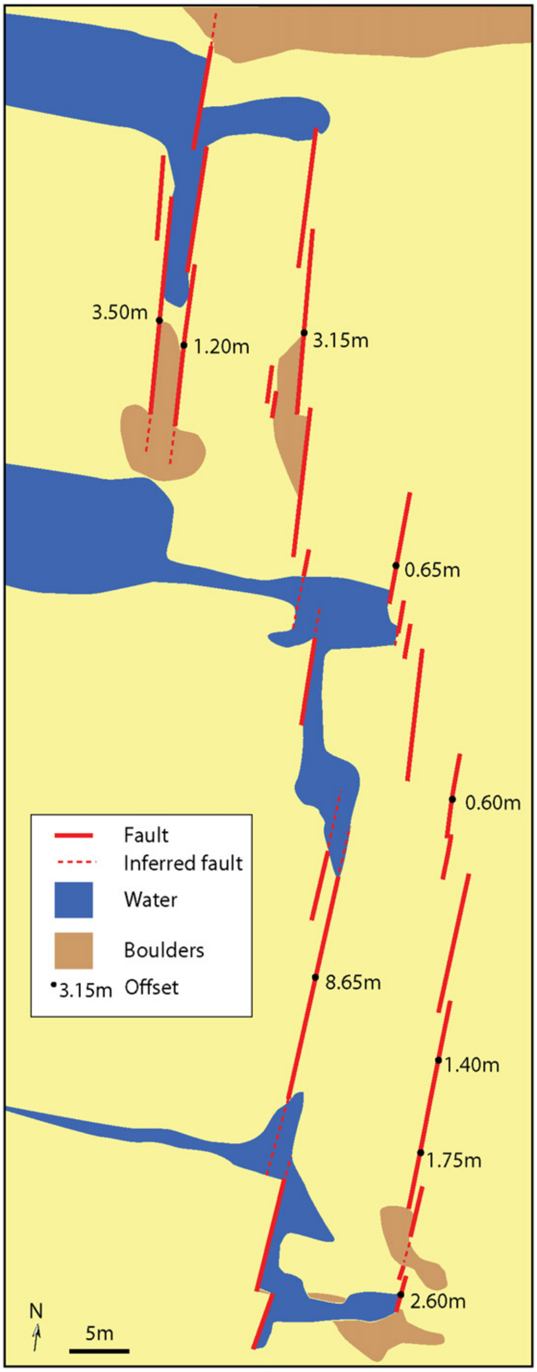

Fig. 10. Map created at location 3 (see Fig. 2a) to show the en-echelon pattern of strike-slip faults. Displayed offsets were found using slickenline and bedding orientation data.

3.4. Folds

The regional overview map (Fig. 1) highlights the presence of broad northeast to east-west trending folds which on the Loop Head peninsula typically have half-wavelengths between 0.9 and 2.6 km. The trends of the folds can vary from approximately 70°–90° even along the same fold. In areas such as the Loop Head coastline around Ross, tight low-amplitude kink-folds are concentrated around thrust faults and have a similar orientation range (Fig. 2). Open folds are also present in this area, but they do not seem to be associated with thrust faulting.

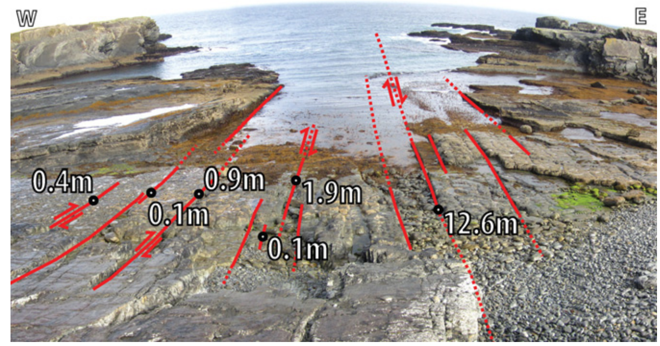

Fig. 11. Distribution of offsets along a zone of strike-slip faults in 'Ross Bay' (Fig. 2b) using bedding and slickenline orientation data. The cumulative offset across the width of the bay is approximately 20m using the apparent strike-slip offset fold axes shown in Fig. 2b. Note that these faults segments are sub-parallel and that their apparent convergence is a perspective artefact of the photograph.

4. Discussion and conceptual model for fracture assemblages and fault evolution

4.1. Joint and PSS assemblages

Most rock units within the Earth's crust are under compression rather than tension due in part to the weight of overlying rock, and in part due to limited processes in the Earth's crust generating regional tensile stresses. Compressive stress conditions generally favour the formation of PSS, but the occurrence of assemblages of both PSS and JV in orogenic belts is also common (Ferket et al., 2000; Graham-Wall et al., 2006). Of these, the JVs perpendicular to the strike of the tilted beds or the PSSs and the trend of the contraction belts (sometimes called strike-perpendicular or cross-fold joints) are often referred to as accommodating orogen-parallel extension (Engelder and Geiser, 1980; Nelson, 1981; Zhao and Jacobi, 1997). However, they do not necessarily indicate remote absolute tensile stress parallel to the structure belts but rather the smaller component of the horizontal compressive principle stress as simulated in triaxial tests by Griggs and Handin (1960).

Pollard and Aydin (1988) reviewed the literature on jointing and concluded that joints initiate at flaws which perturb the stress field. These perturbations may convert a remote compressive stress into a local tensile stress large enough to initiate fracturing. Further examples of local effective tensile stress generation caused by

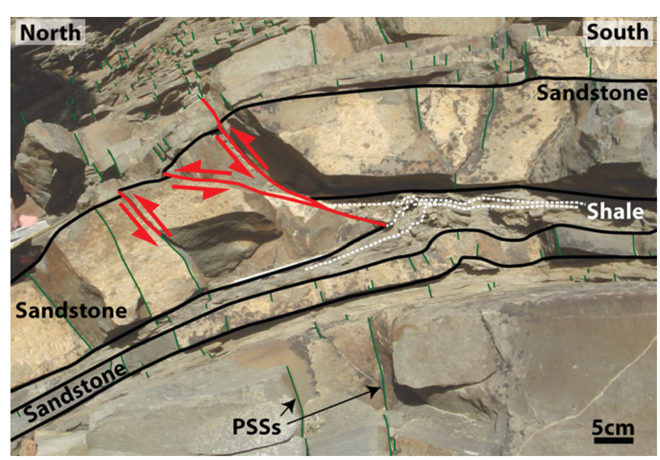

Fig. 12. Mapped photograph of a small scale thrust fault present on a vertical rock face. The maximum apparent offset of this thrust is about 1 cm.

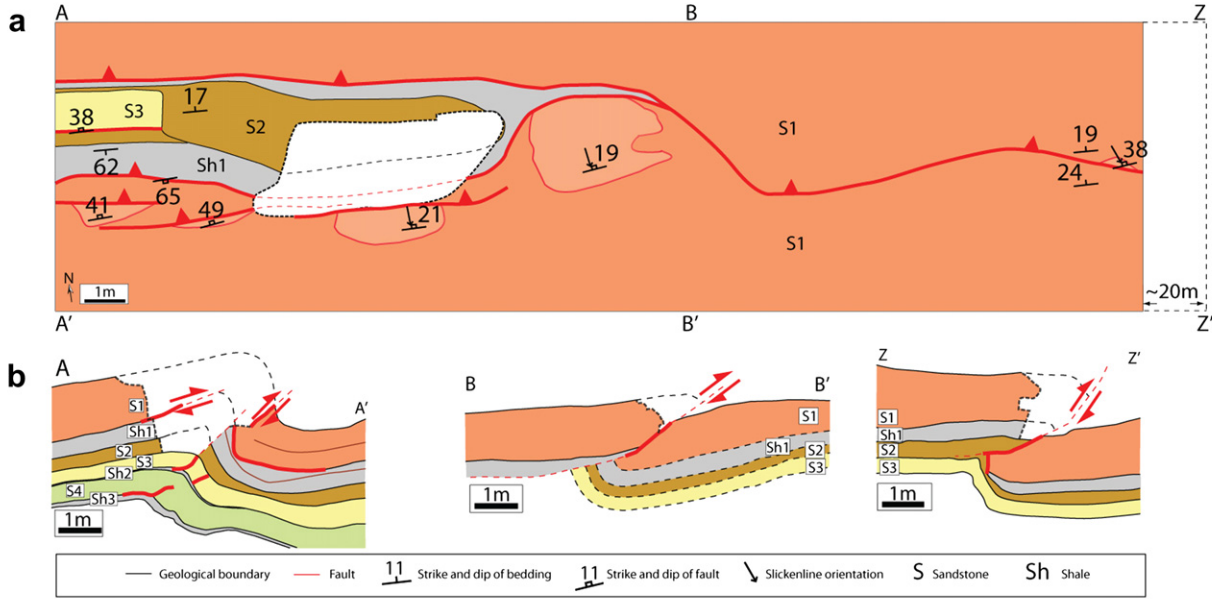

Fig. 13. Map of an intermediate scale thrust fault zone (a). Fault surfaces shown as lighter colours. North-south oriented cross sections showing thrust faults within shale layers in original position and their ascent by following PSSs within the sand layers (b). The maximum apparent offset of this thrust is about 1m.

compressive remote stresses include areas on the crests of folds and in rock units with high pore-fluid pressures (Bessinger et al., 2003). It is also possible that a large degree of volume reduction along the PSSs may produce a local tension that may cause tensile fracturing (Fletcher and Pollard, 1981; Katsman, 2010; Zhou and Aydin, submitted for publication), which we will now discuss further.

The association of pressure dissolution at high-angle to opening mode fractures has been recognized since the early days of geology

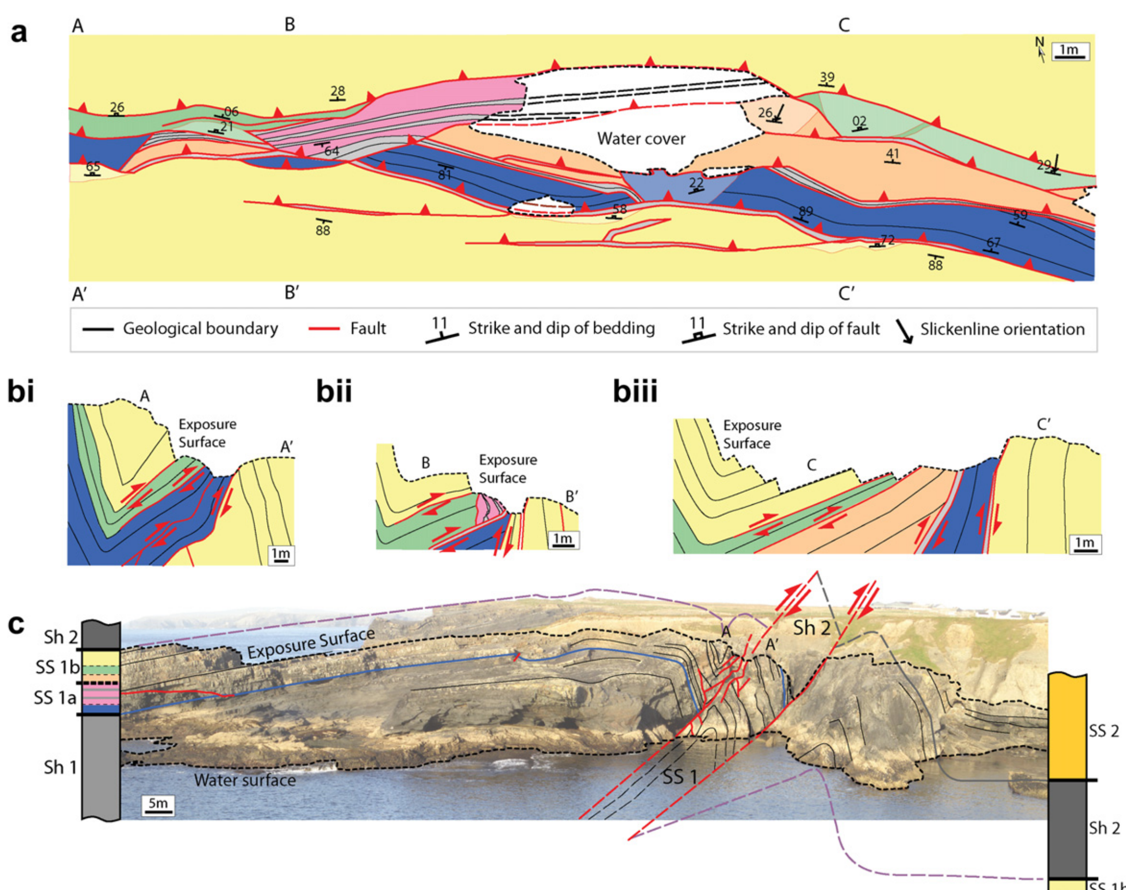

Fig. 14. Map of large scale thrust fault zone (a) with fault surfaces shown as lighter colours. North-south oriented cross sections (b); a photograph showing the details of cross section bii is show in Fig. 15a. Mapped photograph of the Ross outcrop to show 25–30 m apparent vertical offset.

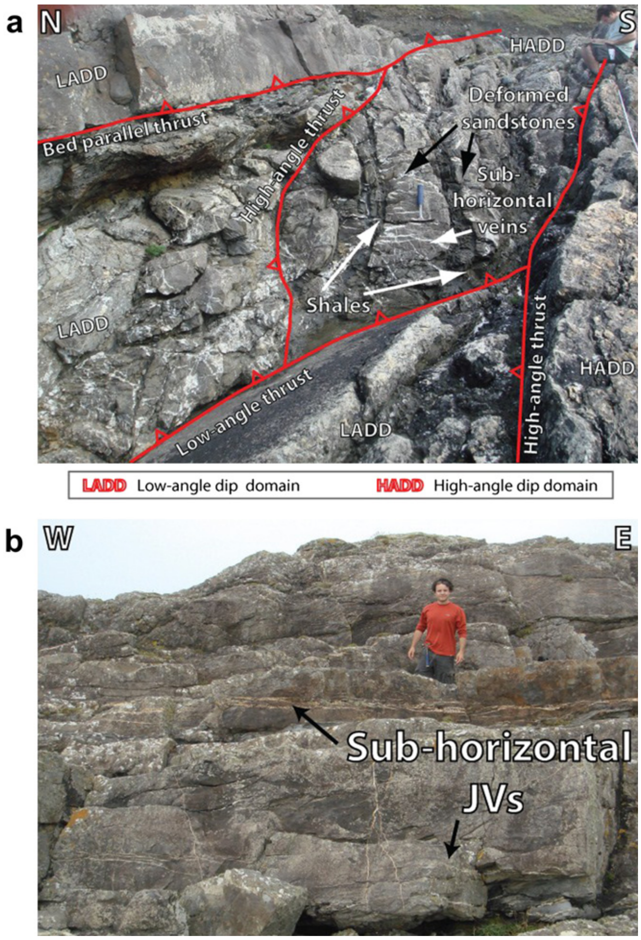

Fig. 15. Annotated photograph (a) to show the relationship between low and high dipping thrusts and the various dip domains between them. This location corresponds with Fig. 14b ii. Steeply dipping beds containing sub-horizontal veins associated with thrust faulting (b). The location is given in Fig. 2b.

(Sorby, 1879). More recently, Gratier et al. (1999) have numerically modelled the stress variation at a contact between two spherical limestone pebbles over time in which a cyclic pattern of elastic behaviour/creep behaviour/failure was envisioned under a constant displacement rate. This model would suggest that grain scale micro-cracks would form at each grain contact within and adjacent to a PSS. At the outcrop scale in the Ross Sandstone the JV1s have spacings on the order of 10 s of centimetres and lengths on the order of metres but their relations to the pressure solution appears to be similar to those at the grain scale. Contemporaneous formation of the JV1s and PSS1s is further supported by their mutually abutting relationship, indicating that the same stress conditions are responsible for the formation of these two opposite modes of structures.

The vein material found in many of the exposed fracture surfaces in the studied locations consists of large well formed prismatic quartz crystals. This material may be sourced from the quartz dissolved from the formation of the PSSs. Though we have not tested this hypothesis in this study, the notion is well supported by experimental studies (Gratz, 1991; Gratier et al., 1999, 2005). These two processes have different time scales; pressure solution creep is slower than brittle fracturing. However, apparently they still interact and enhance each other. Generally, the fractures close to the larger strike-slip faults are filled because the faults are channels for subsurface fluids. Away from the faults, only the joints that are connected to the fluid flow system are filled. Isolated strata-bound joints are left barren.

4.2. Loading conditions required for JV and PSS formation

Based on the presence of bedding-parallel PSSs in the Ross Sandstone (which have not been the focus of this study) the overburden stresses were of sufficient magnitude for quartz dissolution to occur. The geological column for the Shannon basin as observed on the Loop Head peninsula (Fig. 1) suggests that at least 1 km of Namurian sandstones and siltstones overlaid the Ross sandstone at the peak of the Variscan orogeny approximately 300Ma. This is a minimum value as it only takes into account units which are present in situ and are accessible at outcrop but not eroded material. Thermal maturation data compiled by Corcoran and Clayton (2001) show that use of vitrinite reflectance is not sufficient to estimate maximum burial depth of rocks in County Clare. This is due to anomalously high recorded peak temperatures indicative of advective hydrothermal circulation that has overprinted the original geothermal gradients. However, Goodhue and Clayton (1999) suggested the maximum burial depth of late Carboniferous cover units can be constrained between 2 and 4 km based on the extrapolation of the plotted borehole gradients to 'zero coalifcation' as described by Dow (1977). An approximate measure of vertical loading (σ_v) assuming an average density (ρ) of 2500 kg/m^3 for the overburden and a minimum burial depth (h) of 2 km is about 50 MPa (using $\sigma_v = \rho gh$). For a burial depth of 4 km, the vertical stress is approximately 100 MPa.

The PSSs oriented at high-angle to bedding are attributed to the horizontal approximately north-south compression of the Variscan orogeny. Assuming their formation requires the same minimum stresses as the bedding-parallel PSSs, then the most compressive horizontal stress is at least 50–100 MPa and possibly greater based on the intensity of deformation associated with the high-angle PSS array.

4.3. Strike-slip faulting

The JV1s and PSS1s acted as pre-existing discontinuities along which slip occurred (Willemse et al., 1997; Watkinson and Ward, 2006). Their subsequent shearing is indicative of a rotation of relative remote stress orientation to produce coeval right- and left-lateral strike-slip faults respectively. Given that the JV1s show a greater amount of shear displacement discontinuity relative to the PSS1s, the secondary deformation is likely due to a rotation of the greatest compressive stress to form an acute angle with the orientation of the JV1s. JV2 orientations relative to those of the original JV1s provide some constraint on the angle of rotation of the remote principle stresses responsible for the shearing (Dyer, 1988; Cruikshank and Aydin, 1995). The initial path deviation of the splay from the original fracture plane just beyond the fracture tip is a function of both remote stress orientation and the coefficient of friction (Du and Aydin, 1995; Willemse and Pollard, 1998; Davatzes and Aydin, 2003; Mutlu and Pollard, 2008). de Joussineau et al. (2007) suggest that the relative length of cohesive end zones of the initial fractures make little difference to the splay angles. However, fracture overlap and fracture separation can induce variations in splay angles, explaining the spread of set 2 structure orientations as seen in the stereonet projections (Fig. 5b). We tried to avoid these configurations by taking JV2 measurements on their straightest parts away from the original tips of sheared isolated fractures where the splays curve into a direction parallel to the remote greatest compressive stress (Coterelle and Rice, 1980; Nemat-Nasser and Horii, 1982).

Based on the average JV1 and JV2 orientations on the Ross platform, a clockwise rotation of the principle stresses on the order of 35° is inferred. The difference in average orientation between the PSS1s and PSS2s is about 40°, but the rotation inferred from the JVs is more reliable because their straighter traces allow for measurements with greater certainty. The JV2s in the pull-aparts of the sheared PSS1s are in the path of, and in a similar orientation to the splays of the sheared JV1s. This evidence indicates that the shearing of the JV1s, PSS1s and weak shale horizons (as will be addressed in the 'thrust faulting' section) was likely to have occurred simultaneously under the same remote stress conditions.

Linkage of extensive set 1 and set 2 structures create a zone of damaged rock. The mapped fracture assemblages with increasing amounts of offset allow us to conceptualise the evolution of these faults and their damage zones. The small offset strike-slip faults on the Ross platform show the early stages of rock fragmentation and weakening where both opening- and closing mode set 2 structures originate from, or abut against, the set 1 structures (Fig. 8).

With increased offset, as seen in location 2 in Fig. 2a, the fragmentation is localised in zones where JV1s and PSS1s have significantly lesser spacings than those outside of the zone (Fig. 9). In other places fragmentation is due to the intersection of set 1 and set 2 structure arrays (Fig. 8). Set 2 structures are pervasive within these zones and abut against the set 1 structures to isolate small rock blocks. The orthogonal patterns of fragmentation resulting from these processes are quite regular and appear to be different from the more acute angle patterns reported from other fault zones (for example, Mort and Woodcock, 2008). We infer that only a small amount of slip is distributed amongst the many JV1s within this zone due to the lack of visible offset markers or rotated blocks between fractures. The majority of the slip occurs along a few slip surfaces if not a single one with no obvious fault core observed by the unaided eye. This is in contrast to those faults with comparable offsets in other types of sandstones reported in the literature (Myers and Aydin, 2004; Flodin et al., 2005) but is similar to those in turbidites reported by Gonzales and Aydin (2008). The strike-slip faults seen at larger scales at location 3 (Fig. 2a) contain many segments that consist of the described fragmented zones adjacent to a main slip surface or segment. The segments are in en-echelon patterns each with an offset that contributes to the total offset of the fault zone. With an increasing number of faults within the fault zone, larger total offsets can be accommodated by the segments. The fault zone in the Ross Bay (location 1) accommodates a total slip of about 20 m, and we infer that the largest apparent strike-slip offsets seen on the published geological map in similar orientations as the faults we observe in the studied locations south of the River Shannon (Fig. 1; lower part of the map) are indeed zones of strike-slip fault segments formed from contemporaneous shearing of the original set 1 JV and PSS assemblage. Right-lateral faults south of the River Shannon are described by Diemer et al. (1986) who describe them as 'cross-fractures' that are at high-angle to the east-west fold hinges. These types of faults are also described by Dolan (1984) from northwest Kerry.

4.4. Thrust faulting

The observations from small to intermediate and to large offset thrust faults show that the faults are associated with folds and shales with intervening sandstone layers. We infer that the thrust fault segments originate in the shale layers from bed-parallel slip in the main transport direction. It has been well established that thrust faults localise within shale units in fold and thrust belts and they cut across the intervening stiff units to the next shale horizon (Rich, 1934; Boyer and Elliott, 1982) forming flats and ramps sections that eventually lead to duplexes and ramp-related fault bend folds (Suppe, 1985). The flexural slip across the shale layers or lamina relative to the overlying sandstone is also well known (Behzadi and Dubey, 1980; Olmacher and Aydin, 1995; Cooke and Pollard, 1997; Couples and Lewis, 1999). The slip propagates upwards through the sandstone layers along PSS1s (Fig. 12). The thrust faults with progressively greater offsets occur where folding is more pronounced and the shales at steeply dipping southern limbs of the folds are noticeably sheared, indicating that the development of folding and thrusting are interconnected. Dolan (1984) observed thrust-faulted sandstones in northwest Kerry, south of the River Shannon that are remarkably similar. The presence of thick vein material on the slip planes with slickenlines indicates that the vein material was deposited before the cessation of the thrust faulting. The total offset is distributed among several fault segments or strands that are related to slip along bedding in the shale layers, detachment of sandstone layer interfaces or reactivation and linkage of fold-axis parallel PSSs in the sandstone layers. These dip-slip faults with dip angles from 0° to 90° compartmentalise rocks into various dip domains within the fold and thrust zone. With increasing offset, in-situ high dip-angle shales in the folds are entrained into the anastomosing and discontinuous fault segments and compartmentalise heavily veined sandstone bodies between them (Fig. 15a). Note that these veins concentrated within the fold-thrust zone are primarily in a sub-horizontal orientation and most of them are likely to have formed after the tilting of the beds (Fig. 15b). The JV2s we described earlier are observed to connect veins along thrust fault planes (Fig. 16a) from which we infer that the thrust and strike-slip events overlapped in time and space.

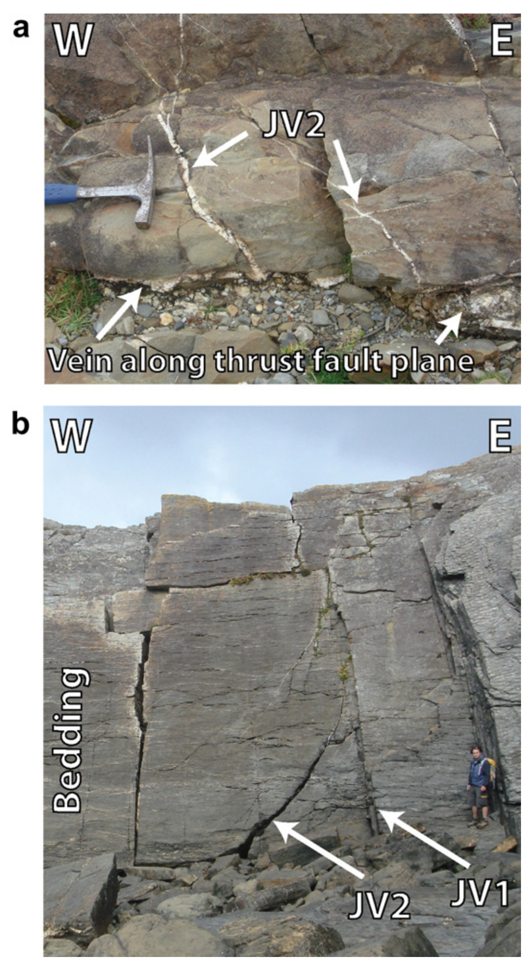

Fig. 16. Photographs to show JV2s connecting to a vein along a thrust fault plane from the location shown in Fig. 13 (a) and folding and strike-slip faulting where the orientation relationships between JV1s, JV2s and bedding are maintained even where beds are steeply dipping (b).

Johnson (1977) suggests that thrust faults may act as triggers for the initiation of kink-folding by introducing an initial localised slope to a horizontal multilayered rock unit. Under horizontal compression, the multilayer yields at this irregularity provided the interfaces between the layers have a relatively low strength, so that slip between layers can occur. This suggests strain is largely confined to the kink-folds during deformation and is evidenced in the shales of south-western Ireland where slickenlines are pervasive in foliations on the short, steeply dipping limbs but not as much on the long, gently dipping limbs of the folds (Dewey, 1965). The remote stress ratio required to initiate slippage is a function of the frictional and cohesive strength of interfaces and the initial slope of the layers locally. The slippage allows for the growth of the kink-fold and in this case it will be unstable as an increase in angle requires a lower remote stress ratio for slip to occur (Johnson, 1977).

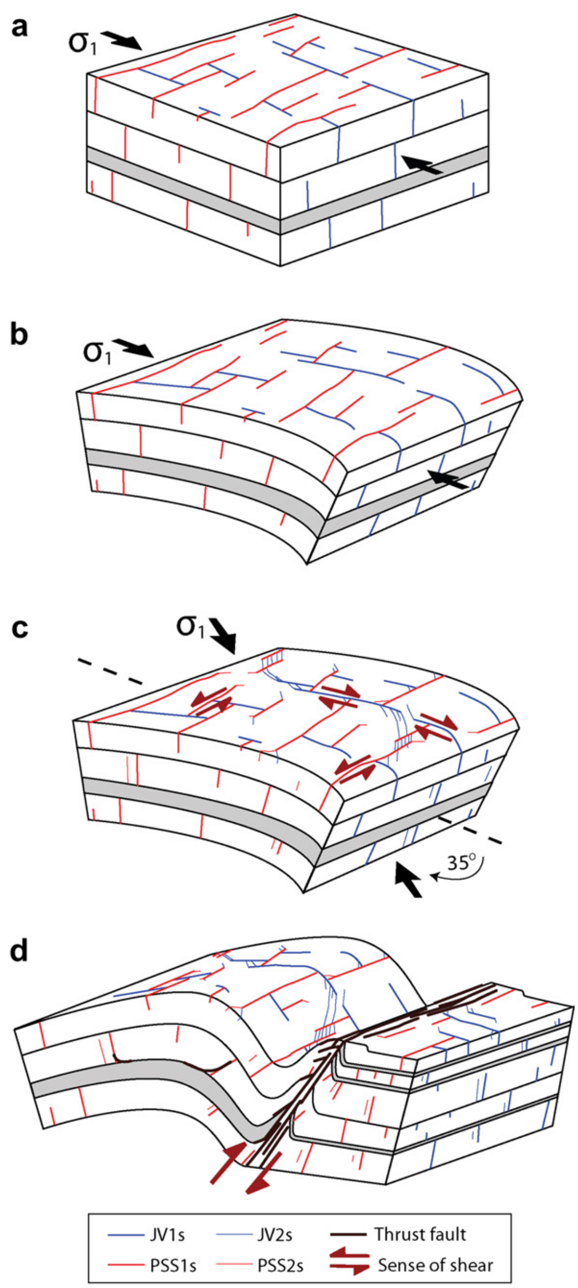

Fig. 17. Conceptual block model to show the initial PSS1 and JV1 assemblage (a); the onset of folding (b); the rotation of the remote greatest compressive stress that caused shearing of the initial assemblage to form PSS2s and JV2s with large strike-slip offsets along the sheared JV1s (c) and thrust faults that initiate from the shale horizons and propagate via PSSs in the sandstone beds, bedding planes or high-angle shale beds (d).

4.5. Relative timing of structural elements

PSSs generally remain at high-angle to bedding and strike-parallel on all parts of folds suggesting that they at least began to form before the initiation of folding. Folding is caused by a remote compression in a similar orientation to that which caused the formation of the PSSs (Fig. 17b). However, there are younger PSSs within steeply dipping limbs of large folds that are not bed-perpendicular. This indicates that PSS formation continued locally during the late stages of folding. The contemporaneous shearing of this initial assemblage is determined by the relationships between JV2s and PSS2s (Fig. 17c). The orientation relationship between JV1s, JV2s (splays) and bedding is maintained in some cases even when bedding has a high dip-angle (Fig. 16b). In Fig. 16b the bedding has an orientation of approximately 070/70/S and the JV2 has an approximate orientation of 005/55/W, whereas the JV2s (splays) have an orientation of approximately 25/85/W where the bedding is sub-horizontal. The orientations of the JV1s are relatively unchanged with respect to bedding attitude because they are sub-perpendicular to the fold hinge. This rotation of the JV2s would suggest that at least some strike-slip faulting occurred before the peak of folding. However, fold hinges with apparent offset by strike-slip faults as seen on the larger scale maps (Figs. 1 and 2) indicate that the activity across some large strike-slip faults has likely occurred either after or during the advanced stage of folding. The variation in trend of the fold axes (about 70°–90°) may reflect the change in greatest principle stress orientation responsible for the strike-slip faulting but the fold structures were not studied in detail. The presence of multiple slip surfaces with striations on the quartz vein infill shows that strike-slip motion continued after the deposition of the infill (Fig. 4a).

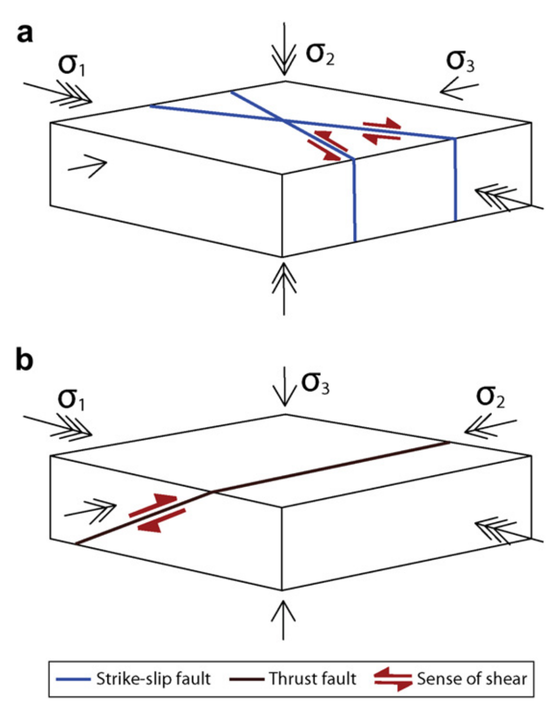

Fig. 18. Conceptual model to show how the switching of the least and intermediate compressive remote stress can form strike-slip (a) and thrust faults (b) according to the Andersonian model based on Coulomb failure criteria for a homogenous medium.

Sheared JV1s and their splays are observed to join the veins along thrust fault planes suggesting that strike-slip and thrust faulting occurred more or less contemporaneously (Figs. 16a and 17d). The presence of strike-slip faults in a fold and thrust belt environment has been generally rationalised in terms of a major reorientation of the principle stresses in such a way that the minimum and intermediate principle stresses switch either in space locally or in time (Fig. 18) according to the Andersonian model of three major faults and the corresponding stress states based on the Coulomb failure criterion for a homogenous medium (Anderson, 1951; Guiton et al., 2003). The data presented in this study supports the contemporaneous evolution of strike-slip and thrust faults from initial arrays of JV and PSSs as well as weak shaley stratigraphic horizons in the Irish Variscan orogenic belt (Fig. 17). Although a stress rotation has been inferred based on the shearing of the JV1s and PSS1s, this stress reorientation is more relevant to resolving shear stresses on the previous principal planes, which were then merely weak zones prone to slip in a strike-slip sense. Note that according to the Andersonian model, the two conjugate strike-slip fault orientations make an angle bisected by the direction of the greatest compression (Fig. 18a). However, in this study area the two sets of strike-slip faults are nearly orthogonal (Fig. 17c). The discrepancy between the field observations and the Andersonian model appears to be because of the presence of the initial assemblage of fundamental structures weakening the rock in certain orientations.

It is interesting to note that from a regional perspective, aside from the fold and thrust belts, right-lateral strike-slip faults are the most prominent structures (Figs. 1 and 2). This is because of the clockwise rotation of the greatest compressive stress component by an acute angle to the fold-normal orientation. This resolves a greater Coulomb stress (σ_c) along the JV1s as calculated using the equation (Pollard and Fletcher, 2005):

$$\sigma_c = 1/2(\sigma_1 - \sigma_3)(\pm\sin2\gamma + \mu_i\cos2\gamma) + 1/2(\sigma_1 + \sigma_3)\mu_i, \quad \sigma_1 > \sigma_3$$

where σ_1 is the maximum principal stress (−50 MPa; tensile stresses being positive) at an angle, γ, to the normal, *n*, of the potential shear fracture (Fig. 19). μ_i is the coefficient of internal friction (taken to be 0.5 for sandstone) and σ_3 (−100 MPa) is the minimum principal stress; in this case it is the most compressive stress. The orientation representing the initial JV1s was subjected to a greater degree of Coulomb stress ($\sigma_c = -9.7$ MPa) following the 35° clockwise rotation of the principal stresses. The JV1 orientation has a greater potential for slip than that of the PSS1 orientation which has a more negative Coulomb stress, $\sigma_c = -18.3$ MPa (see plot in Fig. 19). This analysis supports the field observations.

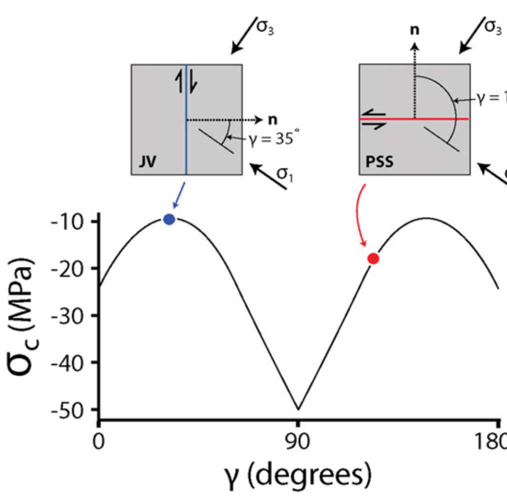

Fig. 19. Plot to show the Coulomb stress on a potential shear fracture with a normal, n, at an angle, γ, to the greatest principal stress, σ_1 (tension is positive). The associated configuration diagrams (insert) show that the JVs have a greater potential for slip than the orthogonal PSSs following the 35° stress rotation.

5. Conclusions

Two orthogonal pervasive sets of fundamental background structures within the Ross Sandstone were subject to approximately north-south compressive deformation at the end of the Carboniferous: arrays of 170° oriented set 1 joints and veins (JVs) and approximately 75° oriented set 1 pressure solution seams (PSSs) sub-parallel to fold axes and thrust fault traces. The mutually abutting relationship between these sets of structures suggests contemporaneous formation under the same stress condition.

Subsequently, set 1 JVs and PSSs have undergone right-lateral and left-lateral shear respectively evidenced by measurable offsets, pull-aparts and splay JVs and PSSs. The orientations of the splays (set 2) structures suggest a relative clockwise remote greatest compressive stress rotation in the order of 35° during the Variscan orogeny that is responsible for the contemporaneous shearing of both set 1 arrays. As a higher Coulomb stress is resolved on the set 1 JV system than that of the set 1 PSS system, the more prominent strike-slip faults are sub-parallel to or slightly inclined to the pre-existing JV set and have a right-lateral sense of slip. Concentrated sheared set 1 and set 2 JVs and PSSs provide weak zones of fragmented rock along which larger faults develop. Evidently, there is not any significant fault rock development along these faults compared to faults with comparable offsets formed in sandstones reported in the literature. Zones of linked en-echelon strike-slip faults are responsible for apparent strike-slip offsets up to hundreds of meters as seen at the geological map scale.

Thrust faults initiate within shale horizons and follow either the PSSs in the sandstone units or in some other cases, high dip-angle shale units within the steeper limbs of the folds that are entrained into fault zones. Offsets of these thrust faults range from the sub-centimetre scale to over 30 m of apparent vertical offset. Within the large thrust fault zones, blocks of rock bodies with varying dip domains are bounded by strands or segments of thrust faults with various dip angles thereby compartmentalising the deformed rock, the smallest size of these compartments are sandstone layers between sheared high dip-angle shale units.

Strike-slip and thrust faulting are inferred to be contemporaneous and this coexistence may be due to the initial weaknesses in the form of JVs and PSSs, rather than by changing relative stress magnitudes and orientations in conjunction with the Andersonian relationships between the major fault types and principal stress orientations. The result from the stress transformation exercise is consistent with the observation that greater amount of shear is resolved on the JV1s in cross-fold orientation than the PSS1s due to the clockwise rotation of the principal stresses, which supports the prominence of roughly north-south right-lateral strike-slip-faults at a regional level.

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