Ramps first – interpreting thrust nucleation in multilayers

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Keywords: thrust faults, fault linkage, fault evolution

Abstract (193 words)

Models are key for geoscientists working in subsurface fold thrust belts, who want to interpret complex geometries. However, models based on a few landmark outcrop studies dominate interpretation. In these models thrust faults form first as flats along weaker beds and propagate upwards, producing a "hard linked", fully connected thrust fault structure. The Eisenstadt and De Paor (1987) model challenges the conventional thrust flat-first, reflecting field observations which show that fold thrust outcrops vary remarkably from each other, with a variety of geometric, linkage, and stratigraphic behaviours.

Here we investigate an outcrop of thrusted sediments at St Brides Haven, Pembrokeshire. Structural observations of the outcrop show an imbricated stack, where isolated thrusts have developed within and localised along sandstone layers. The outcrop provides an example of the alternative Eisenstadt and De Paor model of ramps first. But here deformation in the encasing 'soft' mudstone layers is accommodate by homogeneous shortening.

We suggest that the prevalence of "hard linked" thrust models is a bias towards conventional models and that promotion of a greater variety of fold thrust structures, geometries and evolution styles is needed to ensure a broader range of interpretations and evolutionary understanding that better reflects reality.

1. Introduction

Idealised models play an important role for geoscientists interpreting the geometry and kinematic evolution of the complex structural geometry of fold and thrust belts at outcrop and in the subsurface. Models inspire and inform the types of structures drawn in cross-sections. However, these models have only rarely been tested against outcrop examples. Here we document an exceptional, accessible outcrop that reveals strata imbricated by a series of discrete thrust faults. We find that the structures seen at outcrop do not conform to conventional kinematic explanations of imbricate thrust systems. These dominant models consider thrust systems to form systematically, with component thrusts branching from a basal floor thrust. In contrast, our example is consistent with the little-adopted alternative notion that thrusts nucleate in competent horizons – the “ramps-first“ model as formalised by Eisenstadt and De Paor (1987). Our aim is to document an outcrop where this “ramps-first” alternative model offers a viable explanation of thrust system evolution, and supports Eisenstadt and De Paor in their proposition that this model may be broadly applicable to thrust systems that deform well-layered stratigraphic successions.

In conventional fold-thrust models, (Figure 1a) so-called “footwall collapse” (Elliott and Johnson, 1980; Boyer and Elliott, 1982; Butler 1982), new faults in an evolving imbricate thrust system grow by splaying off the base of footwall ramps of existing fault surfaces and propagate upwards to carve staircases of flats and ramps. These thrusts can coalesce upwards to create a roof thrust and connect downwards onto a single continuous detachment surface, the floor thrust. For many interpreters of structural geometry, these conventional fold-thrust models are the starting point for understanding thrust systems – especially for large-scale considerations of regional cross-sections and in the subsurface. Other thrust models are dominated by folding e.g., trishear (Erslev, 1991) and fault-propagation folding (Suppe and

Medwedeff, 1990). In these models the thrust surface grows into a rock volume that is pre-conditioned by strain weakening as the instantaneous fault tip propagates. Again, the thrust surface is considered to propagate in a single, surface-seeking direction. Although conceptually relevant to our study, we do not consider these fold-focused thrust models further here as folding is a more minor component of the deformation for our chosen case study, although that is not to say that it doesn't play a role in deformation and thrust localisation in general.

Eisenstadt & De Paor (1987) challenged the conventional model. They proposed that faults in an imbricate thrust system nucleate as isolated segments in competent beams. The ramps form first (Figure 1b). Floor thrusts are only formed at a late stage in the kinematic evolution, when individual thrust segments have grown sufficiently to connect together at depth. Likewise, duplex roof thrusts only form when thrust segments, initiated at nucleation points in competent layers, have grown sufficiently upwards to connect into a single fault surface. For Eisenstadt and De Paor's (1987) model, it is the mechanical nature of sedimentary multilayers, especially the location of competent beds or formations, that exerts a first-order control on the geometry of thrust systems. In contrast, conventional models down-play the role of competent horizons, or indeed any other mechanical properties inherited from the original stratigraphic units, beyond weak horizons localising thrust flats (Elliott and Johnson 1980).

Eisenstadt and De Paor's (1987) model was developed after they reviewed published accounts of outcrops that appeared to be inconsistent with Boyer and Elliott's (1982) model for imbricate systems. While not illustrating these examples, they state that: *"actual field observations present puzzling examples of faults that deviate from the preferred path"*

(Eisenstadt and De Paor, 1987). Their examples included outcrop studies from across the USA: the Heart Mountain thrust in Wyoming (Pierce, 1957); Southern Nevada (Burchfiel et al., 1982); and from within the Knox Group dolomites of the southern Appalachians (Coleman and Lopez, 1986). They cite what Miller (1973) describe as “anomalous” faults from the Appalachians of Tennessee, Kentucky and Virginia. But beyond citing the literature, Eisenstadt and DePaor do not illustrate their account with images of these “anomalous” fault structures, a limitation that, many decades later, we aim to redress.

Underpinning Eisenstadt and De Paor’s (1987) proposition are the mechanical approaches of Gretener (1972) on the behaviour of failing competent layers. Stiff units in a stratigraphic multilayer of alternating competent and incompetent formations behave as beams which fail as thrust ramps under high stress. Layers fail as thrusts nucleated on inferred imperfections and then transfer stress to weaker soft layers. These thrusts cut across the competent beams, so represent isolated ramps, that then propagate both up and down stratigraphic section. For Eisenstadt and De Paor (1987), the soft layers localise thrust flats only when the ramps link to them (Figure 1b). As the succession continues to experience horizontal compression, continued fault growth may eventually result in a fully hard-linked thrust system with deformation localisation onto thrust planes even through soft layers, creating the stair-case ramp-flat geometry. The final geometry of faults may then mimic that formed in the conventional manner, as expounded by Boyer and Elliott (1982) but the structural histories are different. So too are the part-formed structures. This has implications for strain distribution within different units and how fluid pathways in the rock volume may develop and change through time.

There has been much research into the impact of multilayer systems on faulting across a range of tectonic settings. Normal faulting in multilayers has been studied extensively, with agreement that the faults initiate in stiff layers, link through weak layers and that it is possible to predict fault geometry from mechanical stratigraphy (e.g. Van der Zee and Urai, 2005; Schöpfer et al., 2006; Ferrill et al., 2017; Ferrill et al., 2011). Even in strike slip tectonics there is evidence that layer boundaries, grain size and fault core content exert strong controls on fault initiation, propagation, and refraction (e.g. Healy, 2008; Carlini et al., 2019). Multilayer influence on thrust fault geometries in contractional tectonics have been established for decades, with evidence for isolated faults forming in stiff layers, fault propagation up and down into weak layers, different mechanical packages in the multilayer deforming in different styles and strong controls on the style of associated folding. Examples include those described by Chester et al. (1991), Saha et al., (2016), Totake et al. (2018), Zuccari et al. (2022) and many others. Other studies show that original sedimentary architecture has strong controls on thrust deformation, with compositional changes within layers influencing the distribution and partitioning of strain (e.g. Cawood and Bond, 2018). It is not our intention here to develop a model for how faults form multilayers in detail, but instead to provide a case study in a relatively simple multi-layer stratigraphy of the Esienstadt and De Paor's alternative model.

Although long-published, the alternative "ramps-first" model (Eisenstadt and De Paor, 1987) has seen few applications in literature concerned with structural interpretation in thrust belts. Using metrics from Scopus (February 2024), we find that just 89 articles cite Eisenstadt and De Paor (1987) in the 37 years since publication. In contrast Boyer and Elliott (1982) has received 1301 citations. Even the basic "footwall collapse" description by Elliott and Johnson (1980) has received 269 citations. Consequently, while there are numerous studies that apply the footwall collapse concept in subsurface interpretations and outcrop analyses, "ramps-first" is only very occasionally investigated in outcrop. Rare examples include McConnell et al. (1997) who adopt this model to interpret fold-thrust structures in the Appalachians, similarly Ferril et al (2016) describe layer-confined isolated thrusts in outcrop from West Texas. In contrast, the “footwall collapse” model (Boyer and Elliott 1982) has been encoded into structural restoration software (Groshong et al., 2012) ensuring broader application and awareness of the model. We consider this contrast in adoption of thrusting models to be an example of cognitive bias that may therefore promote over-confidence in specific interpretations and models of thrust systems. The dominance of the “footwall collapse” model means that alternative concepts are often not considered or ignored in interpretation workflows. Research shows that individuals are biased by the models and concepts that are most familiar to them (Bond et al., 2007), so overuse; and perhaps misuse, of conventional models for thrust systems is not surprising. Therefore, our aim here is to redress the balance and document a field example of a contractional tectonic regime that conforms to Eisenstadt and De Paor’s (1987) “ramps first” alternative model. We enhance the value of the location as an analogue by providing access to a virtual outcrop, the acquisition of which is discussed below.

2. St Brides Haven

Our case study is at St Brides Haven (SM 80243 11084), a small bay on the coast of SW Wales, rimmed by low cliffs up to 10m high. The location lies a few kilometres south of the local Variscan thrust front. This orogen, trends E-W across southern England and continues into central Europe, and formed during the collision of Euramerica and Gondwana to form Pangea in the Late Paleozoic (Figure 2a). The area is well-known for its deformed Devonian and Carboniferous strata (Hancock, 1982), that are well-exposed in sea-cliffs and platforms. Our study site is formed of continental red-beds (informally, part of the Old Red Sandstone) of the Moor Cliffs Formation, Milford Haven Group (Late Silurian to early Devonian; Williams et al., 1982; Allen and Williams, 1978). An undeformed section of these strata (Figure 2b) shows an interbedded sequence of grey sandstones and brick-red mudstones. The sandstones are rich in volcanic and sedimentary clasts, and the strata thins and interfingers to the west and north and is interpreted as an alluvial fan fed from the south or southeast (Allen and Williams, 1978).

The outcrop reported here consists mainly of a N-S oriented, 8m high cliff that provides a natural cross-section near-parallel to the regional direction of thrusting of the Variscan Front (e.g. Smallwood, 1985). This cliff section is enhanced by a large wave-cut platform at the base of the outcrop. This provides an optimum viewpoint, as well as a further dimension for structural data collection and analysis (Figure 2d). Although tidally affected, the St Bride's outcrops are accessible with care even at high-water, and its small size allows for a rapid and complete study. Collectively these attributes make it ideal as an outcrop analogue, accessible for further study and training in structural interpretation in thrust systems.

The cliff-section studied here reveals a series of open folds defined by the sandstone layers. The folds plunge gently to the East. The sandstone beds are offset by a series of thrust faults. It is these structures, together with their relationship to structures found in the encasing mudstone-siltstone successions that form the focus of our study.

3. Methodology

The structural geometry of the outcrop was observed, recorded, and interpreted directly in the field. Fieldwork took place over two field expeditions, a week in September 2021 and 3 days in April 2023. Data collection was focused on observations of fault linkage, fault and fold geometry, bedding orientation, fold orientation, cleavage measurements and lithological data. The dataset was primarily gathered in the field using traditional mapping techniques with additional photogrammetry work to produce a virtual outcrop. The field sketches and logs were digitised and collated together with digital images to form a detailed integrated outcrop dataset orientated parallel to the outcrop face using geographic bearings from magnetic North.

Key field data was gathered as:

1. Field sketches using pencils, graph paper and watercolour sketching.
2. Stratigraphic logs using pencils and graph paper.
3. Structural measurements using a compass-clinometer.
4. Terrestrial and aerial acquisition of digital images using a DSLR and UAV.

To create the virtual outcrop, we combined two distinct survey methods into one model, one using a UAV-mounted "structure from motion" survey, the other used terrestrial fixed photography. The photographs were taken across both field seasons, with the UAV images acquired in September 2021 using a DJI Phantom Pro and terrestrial images in 2021 and 2023 using a Nikon 5000 DSLR. We produced the virtual outcrop using the photogrammetry software Agisoft PhotoScan Professional, the workflow and processes of which are described in numerous papers, (e.g. Hodgetts, 2013; Tavani et al., 2014; Carrivick et al., 2016). The virtual outcrop was used to visually locate precisely the measurements and logs presented here. These data were collected on site. The virtual outcrop, non-georeferenced, is freely available, can be accessed online on eRock and provides the opportunity for further study.

4. Outcrop Observations

4.2 Stratigraphy

The outcrop is divided into a central sandstone-mudstone package, consisting of 4 sandstones between 15-60cm thick, encased within a package of fine-grained mudstone (Figure 3). The mudstones are lithologically uniform and are brick red in colour and fine-grained. The sandstones are all moderately sorted and coarse grained (Figure 3a). The sandstones are represented by four distinct beds of similar lithology, denoted A to D here (Figure 3a and b). Beds A and B are coarse grained sandstones with a maximum thickness of 20cm and contain very few pebbles (Figure 3a). Sandstones C and D are dominated by subangular quartz pebbles up to 5cm in size cemented together in a mudstone matrix, categorising them as breccias (Figure 3a and c). Sandstone C is the largest bed at up to 60cm thick, whilst D has a maximum thickness of 15cm (Figure 3a). Although clearly independent units, the sandstones have bases that are weakly erosional and across the study area the sandstone beds have irregular thicknesses, with amalgamated contacts locally present between the sandstone units and regular thin mudstone interlayers. Notably Sandstone D cuts into the lower Sandstone C to form a cohesive unit (Figure 3d). Sandstones B consists of two cross-sets evidencing two main depositional events, in places these two events are separated by a mudstone interlayer (Figure 3e). There are up to five homogenous mudstone packages in between and encasing the 4 alternating sandstone layers (Figure 3a)

4.3 Structure

The 8m high outcrop exposes a vertical cross section of three open folds with an imbricated thrust system localised within the sandstone-mudstone package (Figure 4). The gentle anticline-syncline-anticline fold-train is upward facing with interlimb angles of c. 160°. The folds have amplitudes of c. 50cm and a wavelength of 5m. Fold axial planes are orientated roughly E-W at 096° with hinge-lines plunging gently at of 03° towards the East (Hancock, 1982).

A total of five thrust faults are mapped that cut across the sandstone-mudstone package. Each thrust fault is between 5m-8m in length. The faults verge towards the north, with one back thrust verging towards the south, present at the northern end of the studied section (Figure 4). The thrust faults dip at 30° and show offsets of sandstones C and D of up to 1m (Figure 4). Lower in the section, the thrust faults diverge into multiple splays. More abundant faulting is seen at this stratigraphic level, with 8 minor faults localised in either Sandstone A or B with minor (up to 20cm) offset in these sandstones (A and B) (Figure 4). A later stage normal fault at the southern edge of the section offsets the sandstones by 60cm (Figure 4). Thrust faults are mapped as discrete planes linking across the mudstones between the sandstone layers (Figure 4b). Within the encasing mudstones, above and below the sandstones, fault planes are difficult to distinguish (Figure 4b). Above and below the sandstone-mudstone package, curved planes are observed in the mudstones that are apparent continuations of the fault planes extending 20cm – 2m from the sandstone-mudstone package (Figure 4c). These planes either tip out or bend into the pervasive cleavage that is present in the encasing mudstones (Figure 4c). A floor thrust below the structures is not observed (Figure 4).

The thrust faults are mineralised with a layer of quartz up to 1cm thick in which shear fibres can be observed (Figure 5). Although the quartz veins have been heavily eroded in many places, this mineralisation on fault planes is preserved across the outcrop along the top surface of Bed D, likely derived from quartz dissolution in the mudstones during cleavage development (Figure 5). The shear fibres show a clear down-stepping to the NNE pattern, consistent with top-to-the-North East shear sense indicating an overall thrusting direction to the NNE, as shown in the stereonet in Figure 5b.

Although the encasing mudstones do not display objects suitable for quantitative 3D strain analysis, spaced, slatey cleavage is well-developed as crenulations of the depositional lamination. We infer that this is a pressure solution cleavage developed in the mudstones at the same time as the thrusting in the sandstones, such that the cleavage represents the X-Y plane of the large-scale finite strain ellipsoid. Mapping of cleavage across the outcrop shows it to be extensively developed in the encasing mudstones, with a cleavage plane mean strike of 259° and a spacing of approximately 1cm (Figure 6a and b). Although having a consistent strike and parallel nature above the sandstones, below the sandstones the cleavage trajectory is modified at structural discontinuities as seen Figure 6.

The cleavage in the mudstones above and below the sandstone units has a strike of between 249° and 300°, but the dip direction shows variation (Figure 6a and c). These changes in cleavage plane dip are spatially associated with structural features. Above the sandstones the cleavage has on average a strike of 259° and a dip of 70° North (Figure 6a). In the mudstone below the sandstones the cleavage strike is also typically 259°, but the cleavage dip is more variable, dipping from 70° North to 70° South (Figure 6a). These changes in dip direction correspond to structural discontinuities where the cleavage bends into fault planes. When following thrust fault trajectories from the sandstone-mudstone package into the encasing mudstones, the cleavage dip changes over a few centimetres from a general dip of c. 70° to the North, to 30° to the South locally where it parallels the fault plane (Figure 6d). This change in cleavage trajectory into the fault planes creates an apparent continuity of the thrust faults into the mudstone. These changes in dip appear as kinks in the cleavage fabric and splay in a similar manner to thrust faults with distance from the base sandstone, creating a series of sub-parallel planes (Figure 6c and d).

Observations also show localised areas of cleavage fanning that is apparently associated with the folding and faulting. For example, in area B (Figure 6a) cleavage at the northern end of area B dips 70° to the South, but within a metre, the cleavage dip is 52° to the North (Figure 6a, stereonet B). Such variations in cleavage are not seen above the mudstone-sandstone package.

5. Fault Reconstruction and Displacement Distance Graphs

In the field the geometry of the stratigraphy and structures were qualitatively studied, creating a detailed sketch cross-section of the outcrop. This informed the digital interpretation of the structures observed in an orthorectified image produced from the virtual outcrop (Figure 4). The orientation of the orthorectified image is parallel to the trend of the main study section (30° to 210°) and creates a planar-cut through the outcrop. The four sandstone units were interpreted, and the upper sandstones C and D were used as the template beds for section restoration (Figure 7). Section restoration was completed manually on paper using the interpreted sandstones as the starting geometry (Figure 7a). In subsequent restoration steps the sandstone units are restored (Figure 7b and c).

The reconstructions show that the upper sandstone beds have shortened through folding by 5% from an initial length of c. 25.4m to c. 24.3m and with the addition of thrusting there is a total shortening of 24% to a final length of c. 19.5 m (Figure 7). This shortening is accommodated in the sandstone-mudstone package by thrust faulting and folding whilst in the mudstones distributed deformation accommodates much of the strain. This distributed deformation takes the form of a dominant cleavage fabric in the encasing mudstones observed across the outcrop (Figure 6).

Fault reconstruction documents the overall shortening of the section but does not explain how the structure has evolved through time. In our restoration folding is the first increment of deformation but we acknowledge that the folding could, at least in part, have been synchronous with thrusting. We can however explore the localisation of thrust faulting and propagation through the workflows established by Williams and Chapman (1983). Following their workflow we have created displacement-distance profiles for four independent thrust faults (labelled 1-4 in Figure 8e) using hanging-wall cut-offs as displacement markers (Figure 8). Using this method, we can predict the location of fault nucleation. We assume that fault nucleation occurred where the profile shows maximum displacement, as the point of maximum displacement highlights where the greatest movement on the fault has accumulated and has hence seen slip over the longest time. As the fault tips propagate away from the nucleation point then the displacement decreases, reflected in a decreasing gradient in the displacement profile.

The four faults show maximum displacements, and therefore fault nucleation (according to the approach of Williams and Champman 1983), in the amalgamated, thicker, sandstones layers of C and D (Figure 8). Fault 3 (Figure 8b) shows maximum displacement in the thickest sandstone (C), this displacement of 1.5m is consistent across the sandstone unit. Maximum displacement for Faults 4 and 5 is at the boundary of the amalgamated contact between sandstone beds C and D (Figure 8c and d). Whereas Fault 2 shows maximum displacement at the top of sandstone D (Figure 8a). Based on the locations of the regions of maximum displacement, overall sandstones C and D, or their boundaries, appear to act as the layers in which the initiation of thrust faults occurs (Figure 8).

Fault displacement can be seen attenuating as it is plotted down-dip through sandstones B and A and the intervening mudstones (Figure 8). Faults 3, 4 and 5 all have maximum displacements at the amalgamated boundary of Sandstones C and D with attenuation in displacement away from this boundary (Figure 8b, c and d). Fault 3 has perhaps the most ‘classic’ fault displacement profile shape, with a bell-shaped displacement-distance profile (Figure 8b). For Fault 2, the pattern shows a more linear attenuation of displacement with distance through the sandstones, whereas in Fault 5 most of the displacement attenuates within Sandstones C and D (Figure 8a and d). We interpret the displacement-distance graphs as evidence that the faults have propagated down through the stratigraphy from the point of initiation in Sandstones C and D (Figure 8).

Fault 4 is the only thrust that shows an anomaly to this attenuation trend, for fault 4 the upper unit of sandstone B shows a second peak in displacement before attenuation continues down-dip (Figure 8c). This displacement is consistent across this upper bed, like that observed in Fault 3, sandstone C (Figure 8b). We interpret this as nucleation of a thrust fault within the upper bed of Sandstone B, potentially synchronously, or shortly after, that forming at the boundary of Sandstones C and D, with propagation of both thrusts up and down section (Figure 8c). This fault initiation is at a point where the two cross sets of Sandstone B briefly merge to form a 40cm thick unit and there is no mudstone interlayer (Figure 6). There are many minor faults which likely initiated within sandstones A and B but Fault 4 is distinct in that it links with the upper thrust initiation at the boundary of Sandstones C and D

Although Faults 3, 4 and 5 show the start of decreasing displacement from sandstone C-D, the full displacement profiles cannot be derived as the mudstones above Sandstone D do not contain any marker beds (Figure 8b, c and d).

6. Is this outcrop an analogue for the Eisenstadt and De Paor model?

Eisenstadt & De Paor (1987) proposed a thrust model in which the ramps form first. Thrust faults initiate as isolated segments in stiff layers, creating what at first appearance are thrust ramps. These thrust ramps grow linking upwards and downwards through the stratigraphy creating linked faults. The mechanical stratigraphy, particularly the stiff layers or beams control fault initiation, and dominate linkage patterns.

At St Brides Haven, the rocks are composed of a strongly defined mechanical stratigraphy of four sandstone units encased by softer interbedded mudstones. These rocks have been imbricated by five thrust faults which cut through all the sandstones and splay at the base (Figure 9), this is contrary to conventional thrust models in which thrust faults amalgamate into floor and roof thrusts. Here, no floor or roof thrusts can be observed. Thrust faults initiated in the mechanically stiff and thickest layers of Sandstone C and D, predominantly at their amalgamated boundary, and distinctly in Sandstone B for Fault 4 and other minor faults (Figure 8, Figure 9a). Initially these were isolated faults that then propagated up and down section (Figure 8, Figure 9b and c). For thrust fault localisation in stiff layers the studied outcrop at St Brides Haven, meets the criteria as an analogue for the Eisenstadt and De Paor (1987) model. However, the mudstones tell a different story.

Above and below the mudstone-sandstone package, the thick encasing mudstones are intensely cleaved, contractional strain has been accommodated by pressure solution resulting in cleavage formation. The limited continuation of the thrust faults cutting the sandstones are observed as cleavage planes and as kinks in cleavage planes where they intersect the dominant cleavage fabric (Figure 9d). Local areas of cleavage fabric variation and intensity attest to zones of concentrated pressure-solution and contraction that accommodate incompatibilities between the sandstones, thrusts and folds, and the encasing mudstones. This is an important deduction because it directly negates, for our example, the conventional model of simple upward propagation of thrust surfaces through stratigraphic multilayers. That thrusts form as isolated segments in competent layers, encased in incompetent units that deform by distributed strain, is consistent with the Alternative Model for thrust localisation proposed by Eisenstadt and De Paor (1987). However, their model has been enhanced by our study to show how localised faulting and distributed strain have worked together to accommodate bulk layer-parallel shortening across the multilayer package. (Figure 9).

7. Implications for thrust localisation in multilayers

The case study of the structural geology at St Bride's Haven highlights that components within multilayers can deform by distinctly different mechanisms. While competent sandstones beds accommodate layer-parallel contractional shortening through localised thrust faulting, the encasing mudstones principally show distributed deformation recorded by the spaced cleavage. Therefore thrusts have formed as an array of ramps before forming flats – indeed at St Brides, these layer-parallel fault segments have yet to form. Perhaps, if deformation had continued, thrust flats may have developed to form a fully hard-linked system, as envisaged by Pfiffner (1985) and applied by Totake et al. (2018).

The sandstone-mudstone package that is encased in the mudstones, acts as a distinct mechanical unit, within which the thrust faults form and propagate. The mudstone layers between the sandstones have not been shortened by cleavage and are instead faulted and folded like the sandstones. In essence these interlayered mudstones are "strengthened" by the stiff sandstones. This notion is consistent with the general findings of Li et al. (2022), who noted that the presence of a few weak layers in a majority stiff interbedded rock mass did not decrease its overall strength. Additionally, in our example, there is a higher proportion of stiff sandstones compared to thin mudstones within this part of the multilayer, which is inferred to have further enhanced the strengthen the package as a whole (e.g. as proposed elsewhere by Xie et al., 2023). The presence of slickenfibres along the top surface of Sandstone D with top to the NE kinematic indicators, along with cleavage in the mudstones above the sandstones dipping to the NE is evidence that the upper surface of this package is shearing towards the NE and deformation is non-coaxial (e.g. as proposed and discussed for other examples by Twiss and Gefell., 1990; Bell et al., 1992; Viola and Mancktelow, 2005; Yonkee and Weil, 2010; Ferrill et al., 2021). Meanwhile, there are no slickenfibres along the base of the sandstone-mudstone package and the cleavage below the sandstones is much more upright, despite some refraction around fold axial planes, so we infer that the deformation here is more coaxial (e.g. as proposed elsewhere by Bell et al., 1992; Viola and Mancktelow, 2005; Yonkee and Weil., 2010; Ferril et al., 2021). Nevertheless, strain incompatibilities must exist at the boundaries of the mechanical packages.

Additionally, the sandstone-mudstone package shows distinct stratigraphic and mechanical heterogeneities within it. Mechanical heterogeneity within the sandstone-mudstone package changes the strain localisation behaviour as evidenced by thrust ramp formation within Sandstone B, Fault 4 and further minor faults throughout sandstones A and B. Such bed-scale mechanical heterogeneities in thrust systems are seen elsewhere (e.g Woodward and Rutherford, 1989; Lloyd and Chinnery, 2002; Meng et al., 2006; Cawood and Bond, 2018). The lower sandstones A and B are significantly more folded than the thicker upper sandstones C and D in the package, indicating that thin-bedded units may increase the chance of folding, as seen elsewhere by Butler and McCaffrey (2004), Hayes and Hanks (2008).

8. Interpretation bias

It is our view that there is a long-standing tendency to use outcrops to inform subsurface interpretations (Ramsay and Huber, 1987). St Brides Haven has been included in many geological fieldtrips since at least the 1980s, so why has it not been published on until now? Perhaps researchers tend to focus on outcrop examples which fit our expectations and dismiss complex outcrops which support alternative models as localised phenomena. The lack of citation of Eisenstadt and de Paor (1987) compared to conventional models, must be either due to a lack of applicability, or perceived applicability, to natural systems, or because of a bias in community access to literature. As we have shown evidence that the St Brides Haven outcrop is applicable to the Eisenstadt and de Paor alternative model, we believe that the issue is either the lack of perceived applicability, or bias in access to, and use of, literature and concepts.

Outcrop studies, where the uncertainties in structural interpretations are minimised due to ease of access and observations, such as presented here (see also Ferril et al, 2016) are critically important for testing conceptual and theoretical models in structural geology. The lack of field examples studied results in an over-reliance on a few models because of a few highly cited papers. Citation practices reinforce this – bias - an example of herding (e.g. Baddeley, 2010), where the research community focusses on a single explanation or approach to interpretation to the exclusion of others.

Our case study joins a very limited set of published field examples that conform to Eisenstadt and De Paor's (1987) "ramps first" model, in which thrust fault evolution is controlled by mechanical stratigraphy (Eisenstadt and De Paor, 1987; McConnell et al., 1997; Onderdonk et al., 2005; Newsom, 2015; Ferrill et al., 2016; Alsop et al., 2021; Cawood and Bond, 2020; Wiggington et al., 2022). Some of these have re-evaluated existing models which were originally based on conventional fold-thrust models.

In their examples, both McConnell et al. (1997) and Ferrill et al. (2016) note the relationship between displacement gradients on thrust faults and the presence of folding in their wall-rocks. Ferril et al. (2016) further suggest that these folds may be diagnostic of "ramps-first" thrust evolution. The explanation echoes proposals by Williams and Chapman (1983, see also Pfiffner, 1985) that folds in thrust belts can be related to thrust propagation and the former location of fault tips. However, for our study, the distributed deformation related to displacement gradients on thrusts is not represented by folding but by cleavage formation in the encasing mudstones. The distinction is important. Cleavage and other distributed deformation fabrics are only rarely considered in interpretations of thrust belts and are unlikely to be imaged seismically in the subsurface. Interpretations of structural geometry may therefore fail to consider the possibility of displacement gradients and the option of applying the "ramp first" model in their explanations.

Similarly, the strong, genetic correlation of the term "ramp", which was used as a verb by Dahlstrom (1970, p. 345, Hossack personal communication) to describe the upward propagation of thrust flats through the stratigraphy, creates a problematic descriptive term that implies a process rather than a geometric relationship. This contrasts with an earlier term for ramps - "steeps" (Douglas, 1950), a term which solely built on geometry and is a direct comparator to flats.

The lack of descriptions of alternative ways of understanding thrust systems contrasts against well-supported and oft-cited conventional models, further emphasising this bias by narrowing the availability of alternative structural geometries. We hope that the example given here can contribute towards correcting this bias, creating a more diverse appreciation for thrust system evolution.

9.Conclusions

In this paper we have provided a detailed examination of an outcrop at St Brides Haven in SW Wales that displays an array of imbricate thrusts.

- The thrust faults nucleate in sandstone beds that we interpret as mechanically competent units.
- The sandstone beds are separated by thin mudstone layers to create a mechanically distinct sandstone-mudstone package, which is encased in a thick succession of cleaved mudstones.
- The imbricate thrusts pass into the encasing cleaved mudstone rocks, tipping out as they do so.
- Within the encasing mudstone, the cleavage has a simple, broadly consistent orientation indicative of N-S compression. However, the cleavage deflects close to the tips of the isolated thrust faults.
- The cleavage pattern is qualitatively consistent with distributed shearing passing from the discrete faults to maintain strain compatibility.
- Overall, the outcrop structure does not conform to the conventional model popularised by Boyer and Elliott (1982) – there are no roof or floor thrusts from which the imbricate thrusts have branched, and no evidence for thrust flats between ramps.
- The structure does conform to the alternative model of Eisenstadt and De Paor (1987) in which the ramps have formed first, but without the presence of thrust flats in incompetent layers. In our case study the encasing thick mudstones accommodate the contractional strain through pressure solution cleavage.

It has been 35 years since Eisenstadt and De Paor published their alternative “ramps-first” model, yet very few publications have considered their explanation for thrust growth and linkage. Outcrop-based tests, of theoretical models, are rarely documented. In contrast, the conventional model of thrust evolution has been widely applied, along with descriptions of outcrops that conform to it. In our view, the lack of field tests, along with other factors, has biased structural interpretation approaches in thrust systems towards a narrow range of models such as “footwall collapse. In proposing the “ramps first” model, Eisenstadt and De Paor (1987) stressed that they did not believe that this was the only mode for thrust formation, rather one of many. Indeed, in our view, the nature of deformation is clearly strongly regulated by the nature of the multilayer and further examples of this model in a variety of different multilayer sequences should be sought. This highlights the need for diversity and variety in theoretical or conceptual models along with a greater drive to publish tests of these models against structural geometries found at outcrop.

9. Acknowledgements

The work contained in this paper was conducted during a PhD study undertaken as part of the Centre for Doctoral Training (CDT) in Geoscience and the Low Carbon Energy Transition (NERC Grant Code RG15727-10). It is sponsored by Aberdeen University, via their GeoNetZero CDT Studentship, whose support is gratefully acknowledged.

Many thanks to Magda Chmielewska for assistance with the virtual outcrop model processing and to Elizabeth Unsworth and Jack Connors for assistance with drone piloting in the field. The virtual outcrop is available at: https://sketchfab.com/3d-models/st-brides-haven-pembrokeshire-d9808f4cd1ca46e8aef549f2300913b4

We thank Bob Holdsworth and an anonymous reviewer for their critical reviews of an earlier draft of this paper, though the views and any remaining errors remain the responsibility of the authors.

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Figure Captions

Figure 1 – Schematic illustrations of models of thrust system development a) Conventional Models (based on Boyer and Elliot (1982)). b) The Alternative model of Eisenstadt and De Paor (1987) The purple and green layers represent stiff beams in the stratigraphy embedded in softer rocks. The red lines are thrust faults.

Figure 2 – Outcrop location and key features a) Summary map of Variscan sedimentology and structure of Pembrokeshire from Cawood and Bond (2020). b) Relatively undeformed section of the key red mudstone and grey sandstone units. c) Orthographic image of the key

outcrop, looking directly East from the wave cut platform, created from a virtual outcrop model showing the open fold pair and imbricates in the grey sandstone. d) View of the outcrop towards the North showing the wave cut platform and the 8m outcrop.

Figure 3 – Outcrop stratigraphy and key features a) Stratigraphic log with sandstone beds alphabetically labelled b) Digitised field photograph of sedimentary sequence at study site, colours corresponding to those prescribed in 4a) c) Field photograph of sandstone beds C and D showing the amalgamated contact between the two units, a thin sliver of mudstone can be seen d) Field photograph of breccia clasts in sandstone bed D, and contact with overlying mudstone e) Field photograph of sandstone B showing the mudstone interlayer.

Figure 4 – Outcrop interpretation a) Study section with full structural interpretation, key, stereonet for folds and stereonet for thrust fault poles b) Field photograph of minor faults crosscutting the lower sandstones A&B. Digitised interpretations on left and non-digitised on right. c) Field photograph of the largest thrust fault splays into curved cleavage planes.

Figure 5 – Fault kinematics a) Field photograph of quartz mineralisation preserving striations along the thrust plane b) Associated stereonet plotting striation lineations relative to thrust planes as lines and points of best fit.

Figure 6 – Cleavage mapping across the outcrop a) Study section with full cleavage interpretation and associated stereonets of cleavage fabric in the mudstones above and below the sandstone beds. The mudstone below the sandstone is divided into areas A, B, C & D, the ends of the black bars in the figure define the vertical limits of the four areas. Cleavage

measurements in the mudstones have been taken from the wave cut platform from within two metres of the main outcrop face. b) Field photograph of parallel cleavage in mudstones c) Field photograph of changes in cleavage dip above and below the sandstones with beds C&D highlighted. Digitised interpretations on left and non-digitised on right. d) Field photograph showing the bending of cleavage into the fault planes. Digitised interpretations on left and non-digitised on right.

Figure 7 – Structural reconstruction produced using interpreted template from orthorectified image Showing a) Present day structure b) Unfaulted c) Unfaulted and Unfolded – and the shortening associated.

Figure 8 – Displacement Distance Graphs of faults which crosscut all the sandstones layers that are over 1m in length. a) Displacement distance graph for Fault 2 b) Displacement distance graph for Fault 3 c) Displacement distance graph for Fault 4 d) Displacement distance graph for Fault 5 e) Cross section of outcrop with the key faults numbered.

Figure 9 – Model of thrust development at St Brides Haven. a) Sandstone D fails due to imperfections at the interface with Sandstone C, forming an isolated fault. b) The fault propagates down into Sandstone C and stress is transferred to the weaker soft layers. Ramp initiation may occur in Sandstone B. c) Fault capture links ramps through the soft layers. D) Fault terminates in the encasing soft rocks and shortening is accommodated by cleavage. Key - The coloured layers represent Sandstone Beds A-D as stiff beams in the stratigraphy embedded in softer rocks (white). Red lines are thrust fault planes – soft linked (dashed) and hard linked (solid). Black circles are strain ellipsoids.

Folding not represented in figure, folding contorts the cleavage below the stiff beds.