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A thin-skinned thrust model for Variscan Pembrokeshire, Wales

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Abstract—The east and west coasts of Pembrokeshire (SW Wales) provide two sections through the Variscan fold and thrust belt. The evolution of these structures is interpreted in terms of a thin-skinned tectonic model. Balanced cross-sections are constructed for the high-level imbricate sequences, and these allow reasonably accurate estimates of shortening to be made. Basement control on structures developed in the Upper Carboniferous cover rocks is minimal, though some thrust ramp positions may be determined by the location of earlier normal faults.

The thrust belt may be divided into two parts, according to the depth to the décollement horizon. In the north, imbricate fans developed from a shallow-level detachment (<1 km) which dips gently south. In the southern part, a deeper level of décollement and thicker sedimentary pile gave rise to large-amplitude folds.

Shortening is heterogeneous, and both thrust periodicity and fold style are partly determined by rheology. Cumulative tectonic displacement increases to the west across Pembrokeshire, resulting in a net clockwise rotation of about 40°.

INTRODUCTION

RECENT interpretations of many linked-fault systems have been based on the construction of balanced cross-sections (see Hossack 1979 for review). This paper attempts to apply this method of structural analysis to two sections in the Variscan thrust belt in the Pembrokeshire Coalfield, SW Wales. The sections lie between Little Haven and Nolton in the west and Tenby–Amroth on the east coast (Fig. 1). Each section was constructed using area and line balancing methods, and these then provided accurate estimates of the amounts of finite shortening involved. The depth to décollement horizon can also be found from the sections, but the accuracy of this estimate diminishes to the south in each section. Finally, the overall sequence of structural development may be postulated.

Recent reviews of Pembrokeshire structural geology have been published by Hancock *et al.* (1981, 1983) and Dunne (1983). These structural interpretations are based on the erection of zones (Hancock 1973) which show the variation in structural style, but do not attempt to relate this to the depth to décollement. Also, they do not utilize balanced section techniques.

REGIONAL VIEW

The thrust systems in the sections deform Namurian and Westphalian fluvio-marine sequences. The only reliable marker horizons are marine bands, especially the *Gastrioceras subcrenatum* and Amman bands, which are both within Ammanian Coal Measures (Jenkins 1962). However, other markers such as thick sheet-flood sandstones and also non-marine shelly limestones may be used over limited distances (Kelling & George 1971).

The oldest rocks depicted in the balanced sections are Namurian (Figs. 2 and 3) but the majority of the deformed sequence is Westphalian. In south Pembrokeshire, Devonian and Dinantian rocks are deformed in large-wavelength periclinal folds (Hancock *et al.* 1983). Structural inliers of Precambrian–Silurian rocks are also present in both anticlinal fold hinge zones and the hangingwalls of two major thrusts (Fig. 1).

Both the Benton and Ritec Faults (Fig. 1) have histories of movement which predate Variscan deformation (Sanzen-Baker 1972, Hancock 1973). The Benton Fault was active in Siluro–Devonian times, downthrowing to the south and allowing the accumulation of a large thickness of Old Red Sandstone (Straham *et al.* 1914, Dunne 1983). The Ritec Fault shows evidence of sub- and intra-Viséan normal displacements (Sullivan 1965). The Carboniferous Limestone shows both facies and thickness changes away from this line. Both of these faults were reactivated as thrusts during Variscan deformation (Owen 1979).

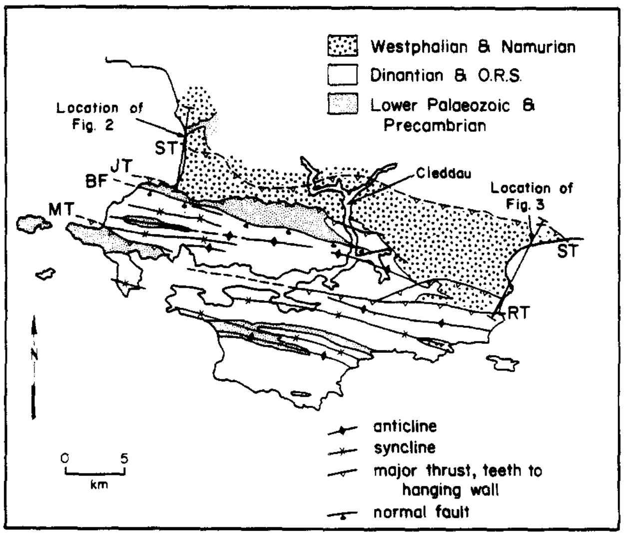

Fig. 1. Structural Map of Pembrokeshire (modified after Hancock *et al.* 1981). Cliff topography projected onto lines of sections shown in Figs. 2 and 3. ST, Sole Thrust; JT, Johnston Thrust; BF, Benton Fault; RT, Ritec Thrust; MT, Musslewick Thrust. See text for details.

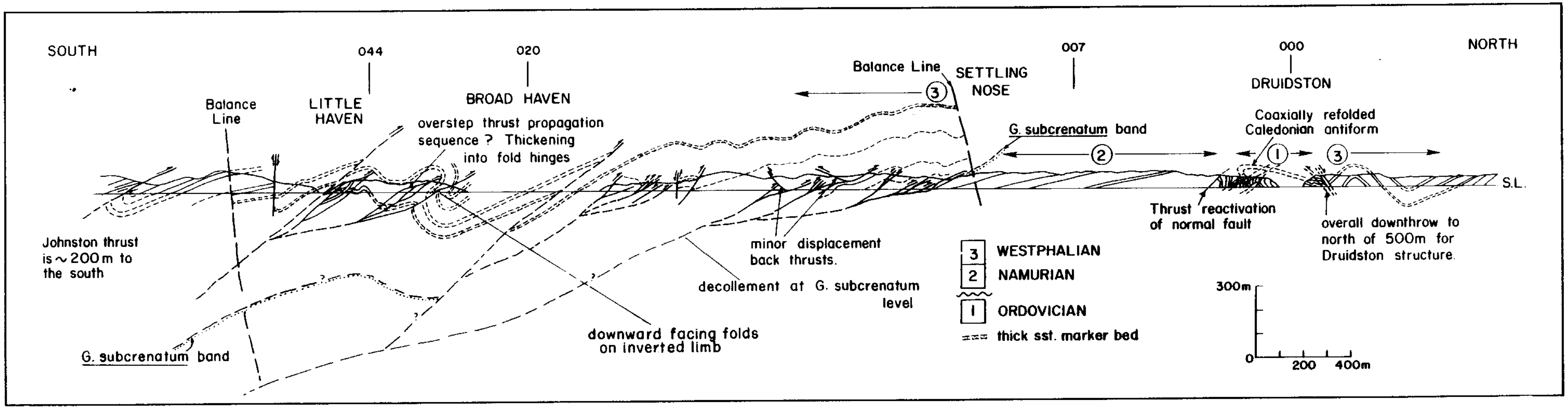

Fig. 2. N–S balanced cross-section along part of the west coast of Pembrokeshire. The *G. subcrenatum* band marks the base of the Westphalian.

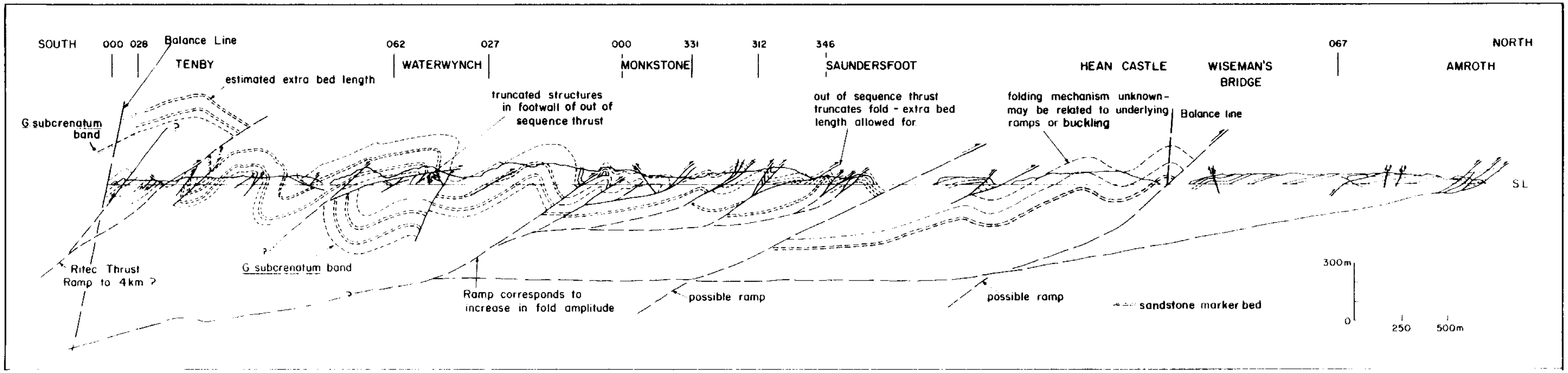

Fig. 3. N–S balanced cross-section along part of the east coast of Pembrokeshire. The *G. subcrenatum* band marks the base of the Westphalian.

The imbricate sequences on both coasts are bounded to the south by major faults. On the west coast (Fig. 1), the Johnston Thrust is a low-angle fault which has Precambrian rocks (Johnston Series) in the hangingwall (Cantrill *et al.* 1916, Baker *et al.* 1968). On the east coast, the southern margin of the imbricate fan is the Ritec Fault, which juxtaposes Dinantian rocks against Namurian rocks at Tenby (Dixon 1921). To the north of these two major faults, the thin-bedded Upper Carboniferous sequences are deformed by a series of imbricate thrusts with associated small-scale folds. The sole thrust to the imbricate fan crops out at Settling Nose (4 km north of Broad Haven) in the west, and at Amroth (8 km north of Tenby) in the east (Fig. 1). The imbricate thrusts generally propagated in the movement direction (i.e. 'piggy back'), but exceptions to this structural sequence are thrusts which climb ramps to become 'out-of-sequence', cutting through earlier, higher-level structures (Coward & Smallwood 1984). Thrust transport direction is dominantly north or north–northeast, and most folds are also north verging. Minor backthrusts transport material to the south within the imbricate stacks, and these produced S-verging folds.

To the south of the imbricate fan, large-wavelength periclinal folds are formed in Devonian and Dinantian rocks (Allen *et al.* 1978, Hancock *et al.* 1983). Fold axes trend WNW, though vergence is variable (see later). These large-scale fold axes are post-dated by a suite of NNW-trending dextral strike-slip faults, and these may also be later than movement on the Ritec Fault (Hancock 1973, Dunne 1983).

Variscan deformation extends further east–northeast as far as the Llandyfaelog Thrust, near Carmarthen, which is probably a reactivated basement fault that controlled Cambro–Ordovician sedimentation (Cope 1979). The Red Roses 'Disturbance' to the west may be another structure with a polyphase history (Evans 1902). These reactivated Caledonian basement lineaments reflect the shallow depth of burial of Precambrian rocks to the north of the Variscan thrust belt.

THE WEST COAST SECTION

The western section through the imbricate fan begins approximately 250 m north of the outcrop of the Johnston Thrust (Fig. 2), which is a low-angle structure dipping 10–15° south. In the south, Precambrian igneous rocks are thrust over folded Westphalian sediments, and there are also lenses of Carboniferous Limestone incorporated along the thrust plane (Tringham 1979, 1980). The fault truncates complex structures in the footwall, including northeast trending folds (Tringham 1979, Hancock *et al.* 1983) which are probably related to lateral and oblique ramps on earlier thrusts. These structures are therefore not directly related to movement on the Johnston Thrust.

Overall, 25% shortening is present in the 4 km long imbricate fan to the north of the Johnston Thrust. However, greater values of shortening may be found locally. The most intense deformation lies between Little Haven and Broad Haven, where there is 40% shortening in a 1.5 km section. Here, the main structure is a N-verging antiform with an inverted northern limb. Less competent siltstones and shales are thickened into the fold hinge by small displacements along thrusts which form a duplex in the fold core. The roof thrust to this duplex remains undeformed, implying an overstep thrust propagation pattern (Butler 1982). Downward-facing folds on the inverted limb were formed due to passive rotation during the propagation of lower thrusts. The floor thrust to this structure crops out on the south side of Broad Haven (Fig. 2). To the north of Broad Haven is a zone of box folds (Tringham 1980) in which folds are locally south verging due to small displacements along back thrusts.

The Sole Thrust outcrops at Settling Nose. The décollement surface is in shales associated with the *G. subcrenatum* band at the base of the Westphalian, and dips to the south, probably reaching a depth of 500–600 m below the outcrop of the Johnston Thrust. North of Settling Nose, the Namurian Succession is largely undeformed.

At Druidston Haven, Namurian sediments are faulted down against Ordovician shales (Tringham 1979, Hancock *et al.* 1981). The Lower Palaeozoic rocks are folded into a S-verging Caledonian antiform which has a refolded and thrust steep southern limb. To the north of Druidston, Westphalian rocks are faulted against the Lower Palaeozoic sedimentary rocks, and large-amplitude, open folds are present.

THE EAST COAST SECTION

The eastern section through the imbricate fan is shown in Fig. 3. The Ritec Fault cuts the section at Tenby, where it is represented by several steeply dipping faults (Kelling & George 1971, Hancock 1973), which have a net displacement of over 500 m (Hancock *et al.* 1983). This increases to at least 1 km at Pembroke Dock, but the fault may not be definitely traced as a thrust further into Milford Haven. To the north of Tenby, inliers of Namurian rocks occur in anticlinal hinge zones. A major low-angle thrust occurs 500 m north of Waterwynch Bay. This fault has Namurian and Lower Westphalian rocks in the hangingwall, and clearly truncates earlier thrusts and backthrusts in the footwall. It has thus climbed out of sequence to cut through higher level structures. The fault may have formed due to footwall collapse of the Ritec Fault, as the two thrusts link by an oblique ramp along strike to the west (Fig. 1).

Two other major thrusts occur in the section, at Saundersfoot and at Wiseman's Bridge, and these separate areas of contrasted deformational style (Fig. 3). Deformation to the south of Saundersfoot is dominated by small-scale folds above minor imbricate thrusts. However, at Hean Castle to the north, large open folds dominate the structure. North of Wiseman's Bridge the Westphalian rocks are essentially undeformed, except

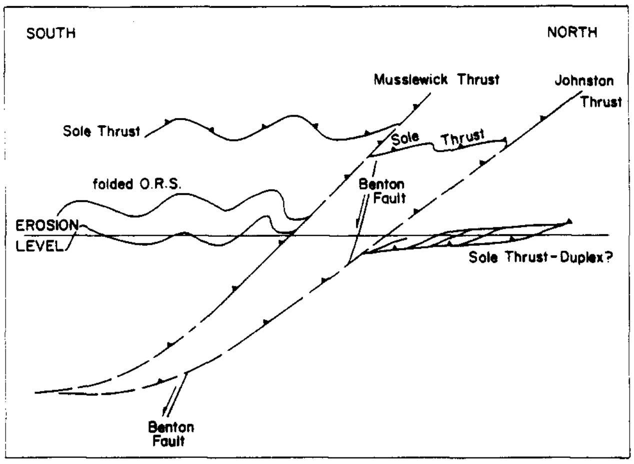

Fig. 4. Schematic section showing the structure of the Variscan Thrust Belt in southwest Pembrokeshire.

for the section at Amroth, where one Sole Thrust crops out. Shortening for the entire section is about 30%, but most of the deformation occurs between Tenby and Saundersfoot.

The décollement horizon of the Sole Thrust is within Namurian rocks in the southern end of the section but control on the exact stratigraphic level is poor. However, to the north, the Sole Thrust must climb up section before outcropping in shales in Ammanian coal measures at Amroth. This is a higher stratigraphic level than the décollement horizon on the west coast, suggesting that the Sole Thrust must also climb up stratigraphy to the east.

DISCUSSION

The two sections demonstrate that the imbricate fans on both coasts developed from gently S-dipping sole thrusts. It is not possible to correlate the imbricate sequences between the east and west coasts because of the lack of inland outcrop and also the possible effects of lateral ramps and/or differential displacements. Also, given the generally small displacements within the imbricate fans, individual faults are likely to terminate within 2–3 km along strike (Elliott 1976).

The Johnston and Ritec Thrusts both developed out of sequence, cutting through the higher-level imbricate stacks which were then uplifted, folded and eroded to the south (Fig. 4) (Coward & Smallwood 1984). The location of the folded Sole Thrust is not clear: it probably lies to the south of the Musslewick Fault. The Musslewick Fault may be another steep ramp structure developed out of sequence (Fig. 4). This is supported by the anomalous bedding/cleavage relationships at Marloes Sands (Graham *et al.* 1977). Initial folding of the Lower Palaeozoic rocks during the early stages of thrust propagation was followed by cleavage formation associated with displacement on the Musslewick Thrust. This alternative explanation has the implication that the Musslewick Thrust propagated obliquely across the folded Old Red Sandstone (Dunne 1983).

Recent seismic work (Brooks *et al.* 1983) has shown that the Johnston Thrust has a displacement of 3–4 km, and that the hangingwall is composed of allochthonous basement. The seismic data suggest that the Johnston Thrust has a 25–30° ramp for a distance of at least 5–10 km down the fault plane from the position of outcrop. It is therefore likely to cut through any low angle earlier thrusts. Since shortening in the high-level imbricates is unrelated to displacement on the Johnston Thrust, there is no need to take the shortening into account when calculating displacement (Fig. 4) (Coward & Smallwood 1984, Williams & Dunne 1984). The inclusions of Carboniferous Limestone along the Johnston Thrust are horses (Boyer & Elliott 1982), which were incorporated during a late stage of fault movement. They indicate a minimum displacement of about 1 km.

The position of the Ritec Thrust is probably determined by a basement fault which was active in Dinantian times (Sullivan 1965, 1966). Thrust reactivation along the Ritec Fault terminates to the west of Pembroke Dock (Dunne 1983) resulting in only a normal displacement further to the west.

The high-level linked fault systems on both coasts show no evidence of basement control, and developed by 'piggy back' thrust propagation. Both ramp location and thrust periodicity have lithological controls, that is facies changes on a larger scale. The thin-bedded Westphalian sequences favour the production of chevron folds and abundant small-scale structures. Thrust ramps frequently occur in thicker sandstones, and flats occur in incompetent silts and shales, which provide easy glide horizons.

Fold wavelength and amplitude increase to the south of the Benton Fault (Hancock *et al.* 1983, Coward & Smallwood 1984) and this corresponds to an increase in the depth to the décollement surface. The increase in fold size may also be due to the markedly non layer-cake stratigraphy. There is also a reversal in fold vergence direction. Near St. Anne's Head, folds are S-verging. However, to the north, they become upright, and then near to the Johnston Thrust they are N-verging. Some thrusts are present (e.g. at St. Anne's Head), but these are related to local areas of high strain and have very small displacements (Coward & Smallwood 1984). Fold formation is thus unlikely to be related to thrust ramp positions. A more likely process was by layer-parallel shortening due to sole thrust slip rate having been fast relative to thrust propagation rate. After this initial buckling, the folds would have been carried passively with little additional deformation as thrust propagation continued.

The clockwise rotation of about 40° suffered by Pembrokeshire structures may be due to the Sole Thrust 'sticking' more towards the east (McClelland-Brown 1983), or, alternatively, an eastward decrease in driving force. Both would result in the observed increases in both cumulative displacement and flattening strain towards the west (Dunne 1983). The latest phase of deformation was dextral strike-slip faulting, which may be related to the late movement of the Johnston Thrust.

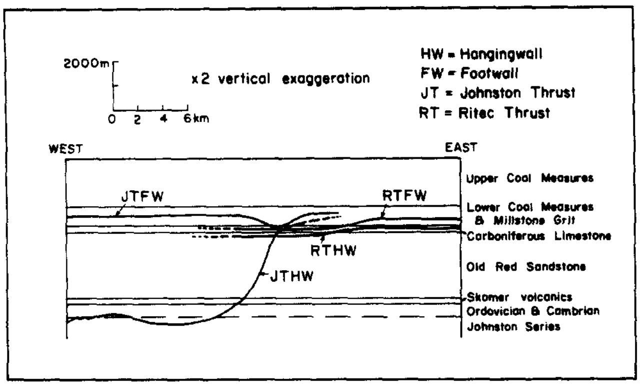

Fig. 5. Composite stratigraphic separation diagram for the Ritec and Johnston Thrusts. Both stratigraphic displacement and separation diminish towards the centre of the Pembrokeshire peninsula, indicating a possible strain transfer zone by bed-parallel slip.

Displacement on the Johnston Thrust decreases to the east until the fault terminates just east of the Cleddau (Hancock *et al.* 1981). Thrust displacement on the Ritec Fault decreases to the west of Pembroke Dock. The fault probably becomes extensional somewhere to the west of Stack Rock (Dunne *et al.* 1980, Hancock *et al.* 1983). In hangingwall section (Fig. 5), the Johnston Thrust cuts up section to the east until the tip lies in Devonian rocks west of the Cleddau. The Ritec Thrust also has Devonian rocks in the hangingwall 6 km to the south. Strain was transferred between the propagating en échelon thrusts by bed-parallel slip within the Old Red Sandstone?

CONCLUSIONS

The Variscan thrust belt in Pembrokeshire may be separated into two parts according to the depth to the décollement horizon: (1) a northern imbricate fan, developed from a shallow-level sole thrust which dips gently towards the south at less than 1 km; (2) a southern zone of large-amplitude, periclinal folds associated with a décollement horizon at 3-5 km depth. Separating these two zones are major thrust ramps which cut through and deform higher level imbricates, thus climbing out of sequence. The high-level imbricate fans developed with a piggy-back thrust propagation pattern, independently of any direct basement control. However, the location of the Johnston and Ritec Thrusts both show evidence of basement control, and may also be influenced by related sedimentary facies and thickness variations.

It should be emphasized that these sections are not unique solutions to the structure of the imbricate fans. In the same way, the model is not a unique answer to the structure of the Variscan thrust belt in Pembrokeshire.

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