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Orthogonal fracture systems at the limits of thrusting: an example from southwestern Wales

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Abstract—A well-developed orthogonal vein system is located in the autochthonous foreland just beyond the limits of Variscan thrusting in southwestern Wales. The two vein sets trend 200° and 290°, perpendicular and parallel, respectively, to Variscan structures. The veins contain stretched quartz fibers indicating horizontal extensions of between 0.3 and 2.5%. The 200° set has greater extension with a distinctive morphology, including shorter more curvilinear fractures that have components of normal offset. Vein intersections are simple, indicating episodic growth by alternating regional propagation of each set. During propagation, maximum compression was subvertical and the horizontal principal stresses switched direction with the alternation of set growth. The system formed during waning Variscan compression when the directions of horizontal principal stresses were still controlled by the tectonic compression. The differential stress may have been greater during propagation of the 200° set. This example indicates that orthogonal fracture systems in forelands beyond thrusting: (1) are initiated by fracturing parallel to tectonic compression; (2) form in a few stages that are controlled by changes in regional stress; and (3) form during waning tectonic compression that controls fracture orientations.

INTRODUCTION

ONE of the most common architectures for fracture systems is orthogonal pairs of joint or vein sets (Bock 1980, Hancock 1985). Such systems have been recognized in cratonic or basinal regions (Ver Steeg 1942, Babcock 1973, 1974, Bock 1980, Holst & Foote 1981, Hancock *et al.* 1984, Stauffer & Gendzwill 1987) and orogenic forelands (Hodgson 1961, Nickelsen & Hough 1967, Dunne 1986, Ramsay & Huber 1987, p. 660). In these settings, the systems are believed to form parallel and perpendicular to: (1) maximum horizontal compression during basin evolution (Price 1974, Bock 1980); (2) maximum horizontal compression as a function of forces at plate boundaries (Holst & Foote 1981, Hancock *et al.* 1984, Engelder 1985, Stauffer & Gendzwill 1987); and (3) orogenic compression before thrusting or beyond the limits of thrusting (Nickelsen and Hough 1967, Dunne 1986, Ramsay & Huber 1987, Stauffer & Gendzwill 1987). However, the evolution and causes of orthogonal fracture systems at the juncture between orogenic forelands and adjacent non-orogenic basins or cratons have not been specifically investigated.

In most cases, the two orthogonal sets have abundant fractographic surface features (Kulander *et al.* 1979) such as plumose markings or wall-perpendicular vein fibers. These structures demonstrate that both sets consist of extensional fractures with negligible shear. This geometry requires that least principal stress switches direction, perhaps due to elastic rebound, and produces two mutually perpendicular extensions (Price 1966, Bock 1980, Hancock *et al.* 1987, Ramsay & Huber 1987, Stauffer & Gendzwill 1987, North 1988). Yet, the literature contains little direct field evidence for whether the alternation of stress directions and fracture-set propagation actually occurs. Also, there is some question about whether the alternation is regionally uniform or a less systematic, local variation because of the small-scale material or stress heterogeneities.

The purposes of this paper are to: (1) present an example of orthogonal fracture evolution at the limits of thrusting from the Variscan thrust system; and (2) describe the alternation of fracture propagation in this orthogonal system.

REGIONAL GEOLOGY

The Variscan thrust system extends across Great Britain from the more intensely deformed hinterland of SW England northward through the progressively less deformed foreland of SW Wales (see papers in Hancock 1983, Coward & Smallwood 1984). The northern Welsh foreland is deformed by major faults, folds and cleavage that have a dominant WNW-ESE (about 290°) trend (Hancock *et al.* 1983). The major foreland structures are imbricate thrusts (Benton, Johnston, Musselwick and Ritec faults, Fig. 1) that include reactivated normal dip-slip faults (Dunne 1983, Powell 1987) with a detachment in the Lower Paleozoic rocks. These thrusts cut out of

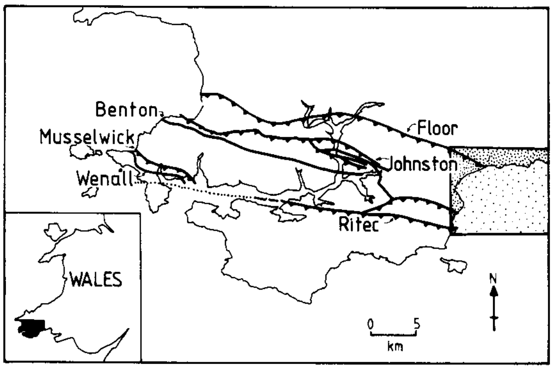

Fig. 1. Major Variscan thrust faults in SW Wales (stippled box is Fig. 2).

sequence through smaller imbricate fans, which are detached at a higher Carboniferous level (Smallwood 1985). These higher-level fans extend more distally into the foreland than the lower-level thrusts. The northernmost imbricate thrust of the fans and hence the known northern limit to Variscan thrusting is the Floor thrust (Smallwood 1985) immediately to the south of Amroth (Figs. 1 and 2a) (Tringham 1979, Smallwood 1985, Morley 1986). Displacement in the last fan containing the Floor thrust is between a few tens of meters and 200 m. Thus, this most distal fan did not significantly load the autochthonous foreland beyond the preserved limits of thrusting.

Locally to the north of the Floor thrust, Variscan folds, faults and cleavage exist, but they are rooted and not detached as they are in the south (Hancock *et al.* 1983). These structures provide a framework by which potentially non-Variscan fractures can be dated relative to the Variscan. For example, at station 8 (Fig. 2a) in the study area, the relative age of the orthogonal fracture sets to Variscan cleavage was determined by cross-cutting relationships.

For this study, structurally homogeneous stations (Hancock 1985) for examining the architecture of fracture systems were located across the Floor thrust between Pendine in the autochthonous foreland and Tenby in the allochthonous foreland (Fig. 2a). The foreland has a Carboniferous stratigraphic sequence (George 1982, George & Kelling 1982) that regionally dips gently to the southwest. It youngs southwards from Dinantian Main Limestone (station 1) to Namurian Millstone Grit (stations 2–7) to Westphalian Coal Measures (stations 8–13). The Namurian and Westphalian sequence include ripple-laminated, trough cross-bedded sandstones such as the Namurian Upper Sandstone Group that have strongly developed fracture systems, and which were preferentially sampled (nine stations) because they are well exposed.

FRACTURE SYSTEMS AND CLEAVAGE

Autochthonous foreland (*stations* 1–8)

Orthogonal vein sets trending 200° and 290° dominate the fracture architecture of the autochthonous foreland (Figs. 2a and 3a, Table 1). Other mesoscale structures exist, but are not as commonly developed as the orthogonal vein sets (Fig. 2b). Of particular note is a weakly developed Variscan (Tringham 1979, Morley 1986) stylolitic spaced disjunctive cleavage at stations 7 and 8. The cleavage does not offset or even cut the veins and their 'host' fractures, but is itself offset by the dilation of the veins, demonstrating that it is older than the orthogonal vein sets. Also, younger joint sets at stations 4 and 6, transect the orthogonal vein sets.

The dominant 290° and 200° veins are parallel and perpendicular, respectively, to the Variscan structures that are to the south of the Floor thrust (Fig. 1) (Hancock

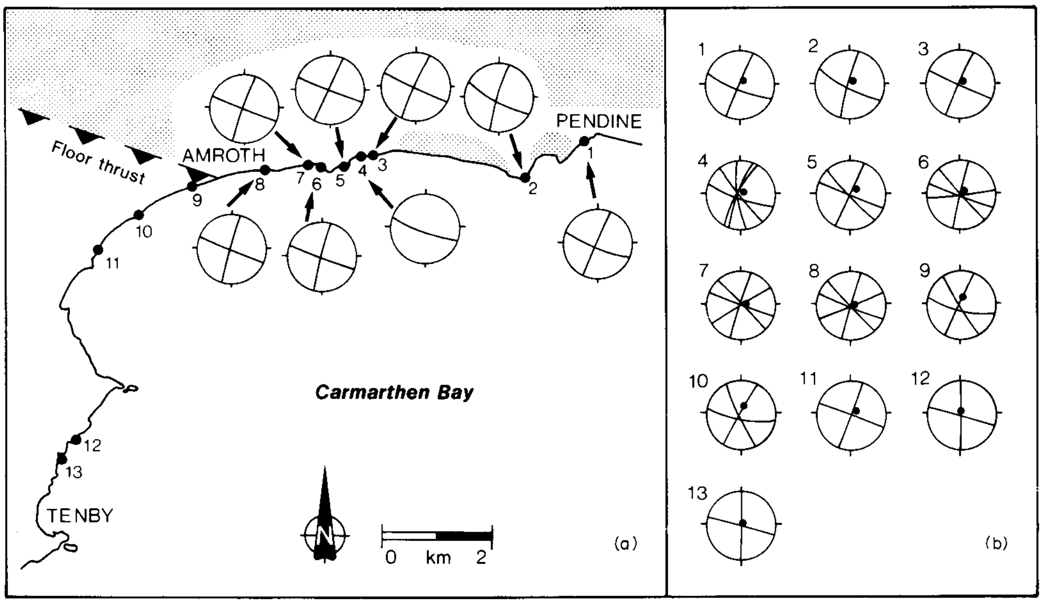

Fig. 2. (a) Location of all fracture-survey stations with lower-hemisphere equal-area stereonets of cyclographic traces for orthogonal fractures at stations 1–8 in autochthonous foreland (stippled area). (b) Stereonets of average cyclographic traces for all mesoscopic structures at all stations (dots are poles to bedding).

et al. 1983). They are well exposed in plan and profile views of the bedding surfaces, which dip at about 318/10SW. The 200° set trends across bedding at about 20° to the dip direction, so the set is both subvertical and subperpendicular to bedding with dips mostly exceeding 85°. The 290° set trends across bedding at about 20° to strike, and is either subvertical (stations 3–8) or subperpendicular to bedding (stations 1 and 2).

Although the fractures are more abundant in the ripple-laminated, trough cross-bedded sandstones, they do not terminate abruptly at bedding surfaces. Instead, the fractures taper to terminations within 30 cm of a bedding surface between the sandstones and adjacent ripple-laminated, mud-draped siltstones. A few veins have symmetric branching terminations that extend about 20 cm into the siltstones, with fan angles of less than 10°.

Both vein sets are filled by antitaxial quartz fibers (Fig. 3b). The only exception is station 1 where massive calcite fills the veins that are contained in bioclastic calcarenitic limestones.

The 290°-striking set has the simpler morphology of the orthogonal vein sets. Unlike the 200°-striking set, it consists of longer, more planar veins (Fig. 4) that extend the length of the stations. The 290° set has regular spacing of 1–2 m, are narrower (0.5–2 cm wide), and contain wall-perpendicular fibers only, indicating simple wall-perpendicular extension. The bulk extension achieved by this set varies between stations from 0.3 to 1.2%. In contrast, the extensions achieved by the 200° set are greater at 1.2–2.5%.

The greater extension across the 200° set is generally accompanied by a fundamental difference in morphology from the 290° set at stations 4–8. The difference is swarms of 3–10 fractures with spacings of only 2–20 cm and widths of 1–6 cm (Figs. 3c and 4). The swarms consist of curvilinear fractures, including many too small (Fig. 3c) to be represented in Fig. 4. The constituent veins may be inclined up to 10° from the bedding perpendicular and in places they form conjugate arrays of en échelon veins that are symmetric about the vertical. The fractures have normal offsets of 1–6 cm that are mostly down-to-the-west (Fig. 4), and contain fibers that are oblique to the vein walls, even in vertical fractures (Fig. 3d). Hence, some vertical and all steeply inclined fractures are normally offset and contain oblique vein fibers. These geometries demonstrate that fracture opening for the 200° set was accompanied by a component of shear. However, vein fibers do not always accommodate the entire offset: where the displacement exceeds 3 cm, the fibers have a shallower wall-oblique growth angle than the angle of drop for the top of the footwall from the top of the hangingwall. This geometry indicates that the fracture walls formed and had some normal offset (up to 3 cm) before the commencement of fiber growth.

The difference in extension between the vein sets is more simply accommodated at stations 1–3. The 200° set does not form swarms, but instead is present as more abundant wider veins than in the 290° set. Furthermore, vein fibers in the 200° set have only the simple wall-perpendicular geometry, demonstrating that the 200° vein set at these stations did not accommodate shear during extension, unlike those at stations 4–8.

Allochthonous foreland (*stations* 9–13)

The stations in the allochthonous foreland were similarly positioned to stations in the autochthonous foreland. The same rock-type (ripple-laminated, trough cross-bedded sandstone) was used at localities with similar dips (<20° SW), but away from major fold hinges and faults (Tringham 1979). These similarities were employed to minimize the effects of structural geometry and lithology, to allow comparison with fracture development across the Floor thrust.

The orthogonal vein system does not exist in the allochthonous foreland. The only vein set to the south of the Floor thrust with a similar morphology to the 200°-striking set of the autochthonous foreland, occurs alone

Table 1. Mesostructural data for stations 1–8

Station	National grid location	Lithology	Bedding orientation	200° set average orientation	200° set % extension	290° set average orientation	290° set % extension	Other mesostructures
1	SN23190777	limestone	306/14SW	203/89W(5)	N/A	292/80N(5)	N/A	
2	SN22140715	quartzarenite	312/10SW	196/85E(6)	1.7%(12)	297/76N(5)	0.5%(8)	
3	SN19240751	ripple-lam. sandstone	310/08SW	203/88E(5)	1.2%(26)	294/89N(5)	0.3%(5)	
4	SN19150749	siltstone	316/10SW	N/A	N/A	290/83N(6)	0.9%(13)	joints—199/83E(5) joints—318/87W(5) joints—028/83E(5)
5	SN18890732	ripple-lam. sandstone	316/10SW	206/90(6)	1.4%(17)	292/90(5)	0.4%(9)	veins—318/85NE(5)
6	SN18340730	ripple-lam. sandstone	318/12SW	198/89E(8)	1.4%(18)	290/87N(6)	0.3%(8)	joints—318/90(3) joints—267/87N(3)
7	SN18260731	ripple-lam. sandstone	332/09W	199/88E(5)	1.2%(8)	291/89N(5)	0.3%(9)	joints—319/90(5)
8	SN17560722	ripple-lam. sandstone	334/08W	196/89E(5)	2.5%(10)	290/89N(5)	1.1%(10)	cleavage—245/89N(6) joints—316/88NE(6)

N/A—not available; lam.—laminated; number in parentheses—number of measurements; vein fill at all stations is fibrous quartz except at station 1 where it is massive calcite.

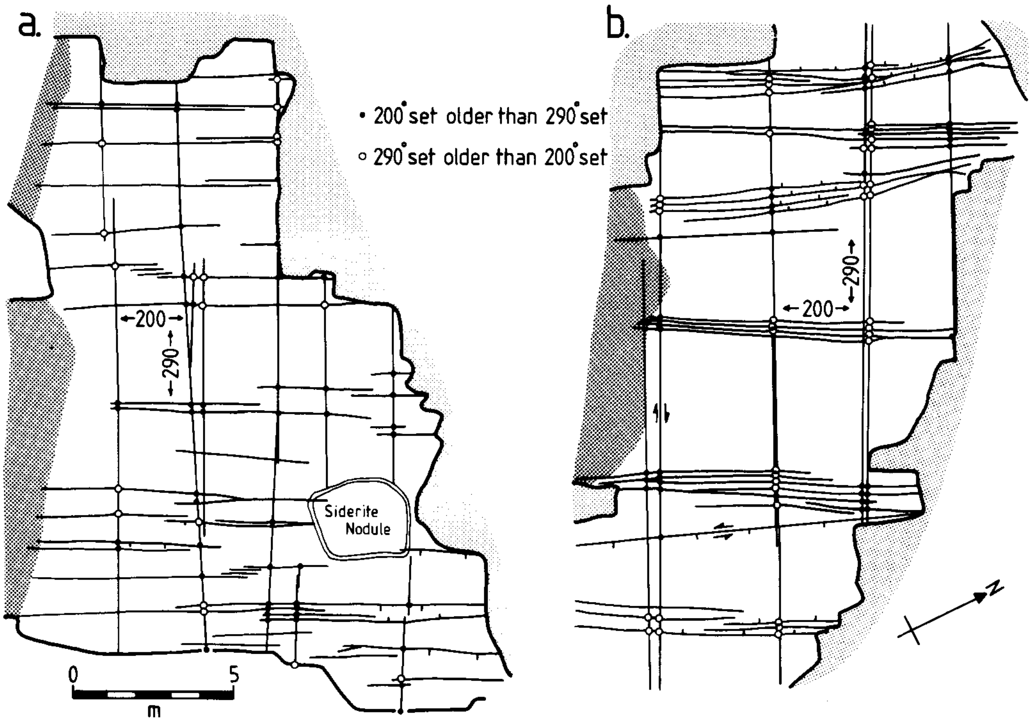

Fig. 4. Maps of orthogonal fracture system at (a) station 8 and (b) station 6. Vertical displacements across a vein indicated by tick on downthrown side. Age relationships denoted by solid or open circles (see key) at vein intersections. The lack of a circle at an intersection means that vein fill is eroded and the age relationship is indeterminate.

at station 10. It is a subvertical vein set with a 205° trend that has an oblique fibrous fill with normal offsets, some swarming and about 3% extension.

Several sets of mesoscale structures are locally parallel to the 290° trend of Variscan thrusts and fold-axial traces, including cleavage (stations 12 and 13), radial veins in small fold hinges (station 11) and barren joints (stations 9 and 11) (Fig. 2b). However, these structures are not geographically widespread, are bedding-normal rather than subvertical in attitude, and have not overprinted or preceded a vein set like those in the autochthonous foreland to the north.

Structures that are parallel to a 200° trend are rarer in the allochthonous foreland. A barren joint set exists at station 11 and a weakly developed vein set is at station 9. Again, these structures are normal to bedding rather than subvertical.

Other structures found in the allochthonous foreland include a strongly developed vein set with a 340° trend at station 10, and barren joints with a variety of trends at stations 9, 11 and 13. In all cases, the joints are bedding-normal and mutually cross-cutting, which indicates indeterminate relative age. Therefore, none of the cleavage, veins or joints have the regional distribution, attitude to bedding or morphology to be equivalent to, or reactivated versions of, the orthogonal fracture system to the north.

Sequence of development for orthogonal veins

An important feature of the orthogonal vein sets in the autochthonous foreland is that on single bedding surfaces at stations 6 and 8, the vein fills have preserved the relative ages of most fractures. All intersections consist of the younger vein fill simply cross-cutting the older vein fill without complex intergrowths (Fig. 3b) (fig. 13.31, Ramsay & Huber 1983). This geometry demonstrates that veins of each set actively opened only once, during single events at each intersection, so younger veins simply cut and offset older veins. Using this geometry at the intersections, the relative ages of the vein sets were mapped at stations 6 and 8 (Fig. 4). The recorded pattern of relative ages from the intersections constrains the interpretation of the sequence for fracture propagation at the two stations. By selecting older fractures at given intersections and proceeding through all intersections, the population of oldest fractures can be determined (Fig. 5a). Then, by determining progressively younger coeval populations of fractures from the intersections, maps for the sequential growth of the fracture systems can be constructed (Figs. 5b–d).

Perhaps surprisingly, the growth sequence for the orthogonal vein sets can be reduced to four stages, each consisting of fracture growth in one set at a time across an entire station (Fig. 5). The growth sequence from first

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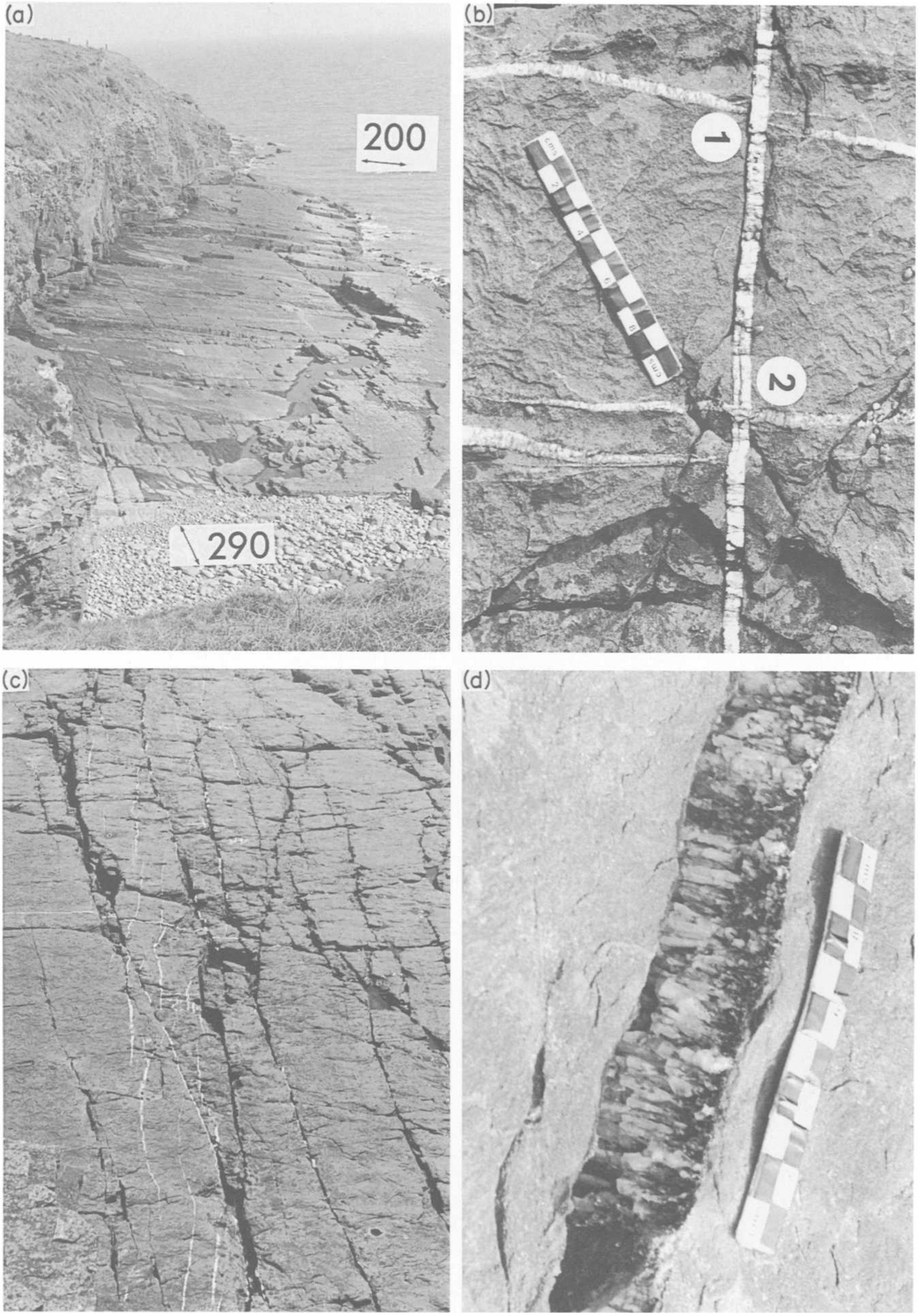
Fig. 3. (a) Cliff and foreshore at station 6 with strongly developed orthogonal 200° and 290° vein sets (width of platform about 45 m with view to east). (b) Simple single intersections between orthogonal vein sets. 1: 290° older than 200° vein, 2: 200° older than 290° vein (10 cm scale). (c) Swarm of 200° veins with close spacings, curvilinear traces, short lengths and normal offsets (down to the right and west). Width of view about 3 m. (d) Oblique stretched quartz fibers in a 200° vein indicating downthrow to the west (front). 10 cm scale.


(a)
200
290
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1
2
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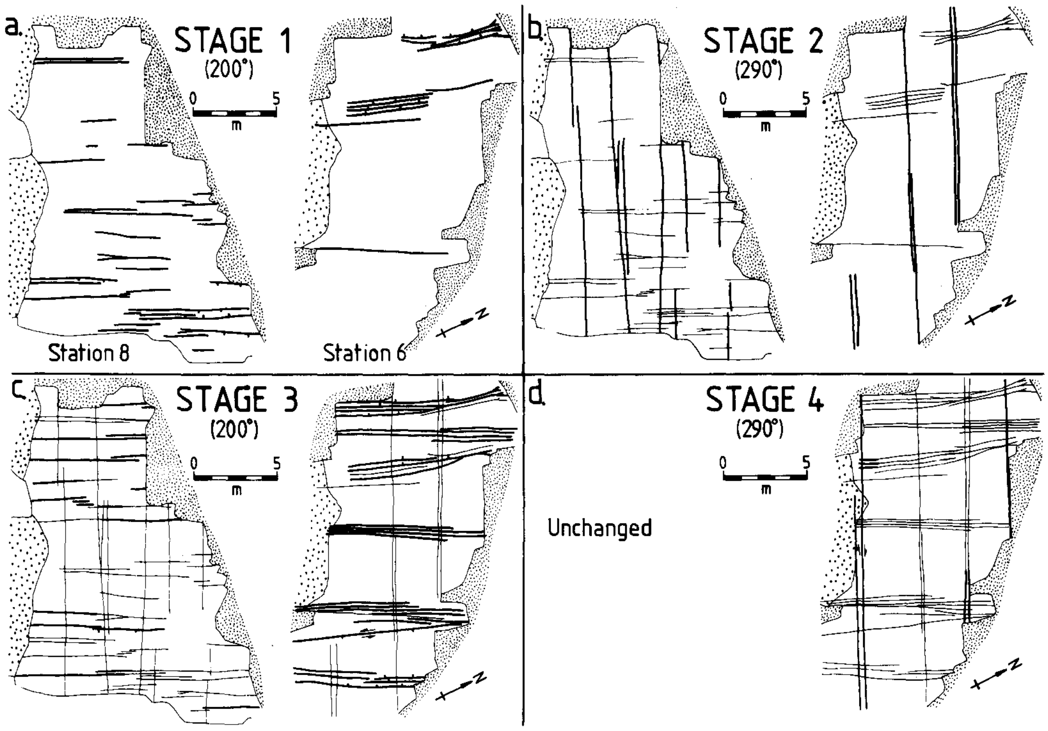

Fig. 5. (a)–(d) Sequential maps from oldest stage (1) to youngest stage (4) of fracture propagation at stations 6 and 8. Bold lines are fractures that form in given stage and thin lines are older fractures or fracture segments (coarse stipple—barnacles, fine stipple—overlying bed).

to last is parallel to 200, 290, 200 and then 290°. If stress magnitudes and directions fluctuated with material properties on the scale of 1 to a few meters during system growth, the stages would probably still consist of fractures from only one set. However, each set would cover areas smaller than entire stations and the development sequence would consist of more than four stages. Instead, not only do the stages cover entire stations with just a few events, but *the sequence of stages matches between stations* 6 *and* 8, which are 750 m apart. Thus, the most important factor during the evolution of the orthogonal vein sets must have been the regional stress at the scale of about 1 km rather than local material and stress heterogeneities.

The map of relative fracture ages (Fig.4) and the derived sequence of fracture development (Fig. 5) show that during a stage of fracture propagation, the formation of new fractures dominated growth (Fig. 5), though some fractures did lengthen their traces along bedding. As reworked vein intersections were not observed, it is concluded that the lengthening of these fractures did not cause significant dilation of older segments.

STRESS AND TIMING RELATIONSHIPS

Stress geometry and sequence

Since extension fractures are initiated at right-angles to the minimum principal stress, the vertical fractures of both sets require a horizontal minimum stress. Vein fibers are horizontal or locally, indicate normal dip-slip, which supports a subhorizontal attitude for minimum stress during vein growth (Fig. 6). Therefore, as fracture propagation alternated from the 200–290° set and back, the horizontal minimum principal stress switched from 290° to 200° trend and back.

In general, the minimum principal stress may switch with either of the other principal stresses. However, elastic modelling for vertical systems of orthogonal fractures (Price 1966, Stauffer & Gendzwill 1987) indicates that the vertical stress will be the maximum principal

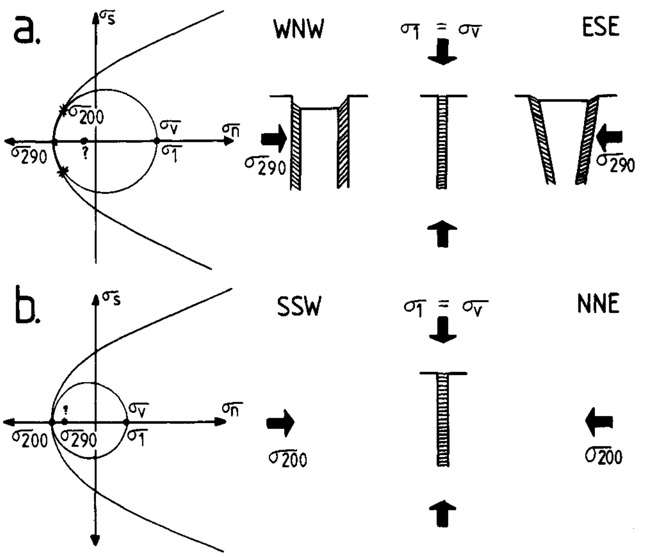

Fig. 6. Fracture morphology, fibre angles and schematic stress conditions for: (a) 200° and (b) 290° sets. σ_V—vertical principal stress, σ_{290}—horizontal principal stress trending 290°, σ_{200}—horizontal principal stress trending 200°. Thin lines are vein fibers in fractures.

compression. Thus, the minimum principal stress would only switch with the intermediate principal stress in the horizontal plane.

The interpretation of a consistent vertical maximum compression with switching horizontal principal stresses is supported by the morphology in the 200° set (Fig. 6a). Some vertical and all steeply inclined fractures are normally offset and contain oblique vein fibers. Further, this morphology is in strike-parallel fractures with conjugate offsets (Figs. 4 and 6a). This geometry indicates biaxial rather than triaxial strain for the incremental strain from the 200° set (Reches 1978, Hancock 1985). The biaxial geometry means that maximum compression bisected the acute angles between fractures, and hence, maximum compression was vertical during formation of the 200° set.

Switching principal stresses during the formation of orthogonal fracture systems is most easily achieved when the intermediate and minimum principal stresses are nearly equal (Hancock *et al.* 1987). If the stresses are nearly the same, the differential stresses will be the same, producing two fracture sets with the same morphology. However, in this study, morphological differences between the two sets indicate unequal differential stress (Fig. 6). The 200° set has conjugate fractures, normal offsets and oblique fibers unlike the 290° set, implying lesser differential stress during the formation of the 290° set (Fig. 6). The lesser differential stress for the 290° set would be in the plane (parallel to 200°) that coincided with Variscan orogenic compression, which could have increased horizontal stress and hence reduced the differential stress.

Age of orthogonal system

Three pieces of evidence indicate that the orthogonal vein-system post-dates the peak of Variscan orogenic compression. First, the system is absent south of the Variscan Floor thrust. Second, at station 8 the orthogonal vein system offsets, and hence post-dates, Variscan (Tringham 1979, Morley 1986) stylolitic cleavage. Third, the 290° set would have formed perpendicular to maximum Variscan compression, which is inconsistent with the stress geometry for extension fractures. Additionally, as already discussed, the orthogonal vein system formed during vertical maximum compression, and therefore, could not develop during a period of maximum horizontal compression such as peak Variscan orogenic stress.

The youngest possible age for the orthogonal vein system can be deduced from considering regional stress conditions after the Variscan orogeny. The formation of late-Permian to mid-Cretaceous basins in southern Britain was controlled by NW–SE-trending minimum principal stress (Chadwick 1985, Lake & Karner 1987, Chadwick & Smith 1988, North 1988). From the late Mesozoic and through most of the Tertiary, the principal horizontal stresses in Britain have been oriented at about 225° and 315° (Batchelor & Pine 1986, Bevan & Hancock 1986). Neither post-Variscan stress-regime matches the stress distribution that has been deduced to cause the orthogonal fracture system.

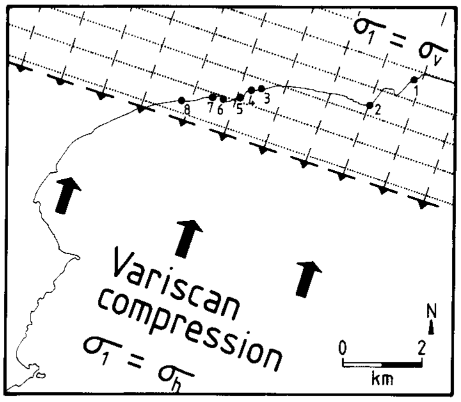

Fig. 7. Regional stress conditions during the formation of the orthogonal vein sets around stations 1–8. Dashed line with teeth is approximate limit of Variscan thrusting and is southern limit for formation of orthogonal vein sets. Dotted and dashed lines are trajectories of horizontal principal stresses during formation of orthogonal fracture system.

Therefore, the orthogonal vein-system is proposed to have formed during the late Variscan, when orogenic compression had waned enough in the outer foreland for the vertical stress to be the maximum compression (Fig. 7). Sufficient orogenic compression existed to orient the initial intermediate principal stress to 200° (the trend of Variscan compression) and the minimum principal stress to 290°. Stauffer & Gendzwill (1987) have also proposed that orogenic compression similarly controls the direction of horizontal principal stresses in the stress field of the foreland beyond thrusting. Also, they proposed that the first propagation stage of an orthogonal system would consequently be parallel to the direction of the weak orogenic compression, but they were unable to demonstrate this timing from field data. The data from stations 6 and 8 (Fig. 5) support this proposal because the first set to to form was the 200° set, which is parallel to former Variscan orogenic compression.

DISCUSSION

A remaining problem in the interpretation of the orthogonal fracture system is the cause of the regional alternations in fracture propagation. Previously suggested causes include fluctuating tectonic compression during the waning stages of orogeny, an erosional unloading history with fluctuating rates, and elastic rebound. The morphology and geometry for the orthogonal system in the study area provides insufficient constraints to select between these and other possible mechanisms.

Despite this problem, the interpretation for the orthogonal vein system in the autochthonous Variscan foreland can be used to predict the spatial development of orthogonal fracture systems in foreland thrust systems. If thrusting is essentially continuous, the orthogonal system only forms once at the limits of the thrust system as orogenic compression wanes. However, if thrusting is episodic with intervening periods of waning orogenic compression, the distribution changes for the orthogonal system. Instead, during waning compression, the orthogonal system forms where the horizontal stress decreases sufficiently for maximum compression to become vertical and intermediate stress to be parallel to orogenic compression. Then, as orogenic stress increases, those orthogonal fractures are incorporated into the thrust system. Thus, orthogonal fractures would be distributed in uneven belts through the thrust system, marking locations where orogenic compression waned sufficiently to allow vertical extension fracturing. Unfortunately, the present study area does not contain such a belt in the allochthonous Variscan foreland, perhaps because the area does not transect a sufficient portion of the foreland.

CONCLUSIONS

(1) Two subvertical orthogonal vein sets formed in the Variscan foreland just beyond the limits of thrusting. They trend 200° and 290°, perpendicular and parallel, respectively, to Variscan folds and thrusts to the south. The sets are absent south of the limits of thrusting and probably formed during waning orogenic compression.

(2) The orthogonal vein system grew in four alternating stages, which were parallel to 200, 290, 200 and then 290°. Each stage was dominated by the formation of new fractures and their propagation sequence was not locally controlled.

(3) Maximum principal compression remained vertical during formation. Intermediate and minimum principal stresses switched between being parallel and perpendicular to orogenic compression with alternating set-propagation.

(4) This example indicates that orthogonal fracture systems in forelands beyond thrusting have orientations controlled by orogenic compression direction, form in a few regional stages of fracturing, and are initiated by a fracturing stage parallel to the orogenic compression.

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