Geometry of chevron folding shortening and estimates at Hartland Quay, North Cornwall, UK, and some regional implications for Culm Basin development

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The geometry of the spectacular chevron folding in the Hartland Quay area of Cornwall is examined using continuous photography of a 3.8 km long coastal cliff section from Hartland Point to 1 km south of the Hartland Quay Hotel. Mean fold wavelength was estimated at 146 m with range between 24 m and 530 m, and the average fold amplitude was 29 m, with a maximum of 100 m. Mean fold inter-limb angle is 67º. Once the folds have reached inter-limb angles of 45° or less, hinge zone thickening of the shales increases dramatically up to a maximum hinge:limb thickness ratio of 9:1. Bed length balancing indicates at least 45% shortening has occurred during folding, with approximately 3% due to ductile thickening in the hinge zones. Fluid inclusion analysis of quartz veins developed during folding indicates that they formed at temperatures close to 290°C, similar to temperature estimates determined from vitrinite reflectance data. The calculated 50% shortening of both the Hartland and Bude areas implies that the folds affected an Upper Carboniferous sequence which had an original stratigraphic thickness of approximately 4-5 km. The Culm Trough is interpreted as a syn-rift fill developed in an extensional basin with a crustal extension factor of approximately 2.

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Introduction

This study re-examines the geometry of folding at Hartland Quay, N. Cornwall (Figure 1). The locality is one of the best known for chevron folds in the World. The sea cliffs reach up to 120 m in height and extend along the coastal section for 3.8 km, from 950 m south of the Hartland Quay Hotel to the Hartland Point lighthouse (Figures 2 and 3). The fold geometries have been extensively studied (e.g. Zwart, 1964; Dearman, 1970; Ramsay, 1974; Sanderson, 1974, 1979; Ramsay and Huber, 1987; Lloyd and Whalley, 1986; Tanner 1989; Price and Cosgrove, 1990; Lloyd and Chinnery, 2002). In this study, several key features of the folds have been investigated in detail: (1) Most structural studies have been limited to observations of accessible parts of the cliffs near the Hartland Quay Hotel. In this study a new continuous panoramic photo-montage of a 3.8 km long section was analysed, in order to describe the large-scale geometry of the folds: amplitude, wavelength, interlimb-angle, and overall horizontal shortening. (2) Flexural–slip is the dominant deformation mechanism, but the fold hinges contain evidence of ductile deformation that has never been quantified, and the relative timing of the onset of hinge thickening and limb rotation is investigated. (3) The pressure-temperature conditions during fold formation have not been fully determined. Fluid inclusions are analysed from bedding-parallel veins, en–echelon veins in conjugate shear zones and saddle-reef quartz veins to obtain a syn-deformational temperature.

Lithology of the folded sequence

Hartland Quay sits in the centre of the Culm synclinorium, where the preserved Carboniferous sequence has a stratigraphic thickness of about 2.2 km (Figure 4). The Hartland cliffs consist of sandstones, siltstones and shales of the Crackington and Bude formations of Early Westphalian to Namurian age (Freshney and Taylor, 1972; Freshney *et al*., 1972, 1979; Melvin, 1986; Thomas, 1988). The sandstone bed thickness at Hartland reaches a maximum of about 1 m but is more commonly about 30-60 cm. The sandstones are interbedded with shales, which range up to 4 m in thickness (Hartland Quay and Long Peak shales, Edmonds *et al*., 1979), but average around 20-60 cm. Fine-grained sandstones grade upwards into very-fine grained laminated sandstones, then siltstones and finally shales. The sandstones are quartz-rich (97%) with a minor amount of white mica (<3%). Large flute and groove casts (up to 10 cm relief) are present at the base of the thicker sandstone units, which can be oriented in several directions, but are predominantly E-W trending parallel to the fold axes.

Fold geometry

Wavelength and amplitude

A tracing from a photo montage along the coastal cliffs, shot from a boat, shows 62 major folds with true fold profiles approximately perpendicular to the fold hinges (Figure 3). Beds were extrapolated above and below the cliff section to estimate fold geometries, and the bed in each fold with the largest amplitude was used to make amplitude and wavelength measurements. Where folds were asymmetric the amplitude was taken to be the maximum value of the two half halves of the fold.

The average wavelength is 146 m, with a range of 24 to 531 m (Figure 4). The fold amplitude average is 29 m, with a range of 4 to 101 m (Figure 4). The error on these measurements may range up to 10% where overlapping photographs were taken at slightly differing angles, but a constant viewing distance of 1 km

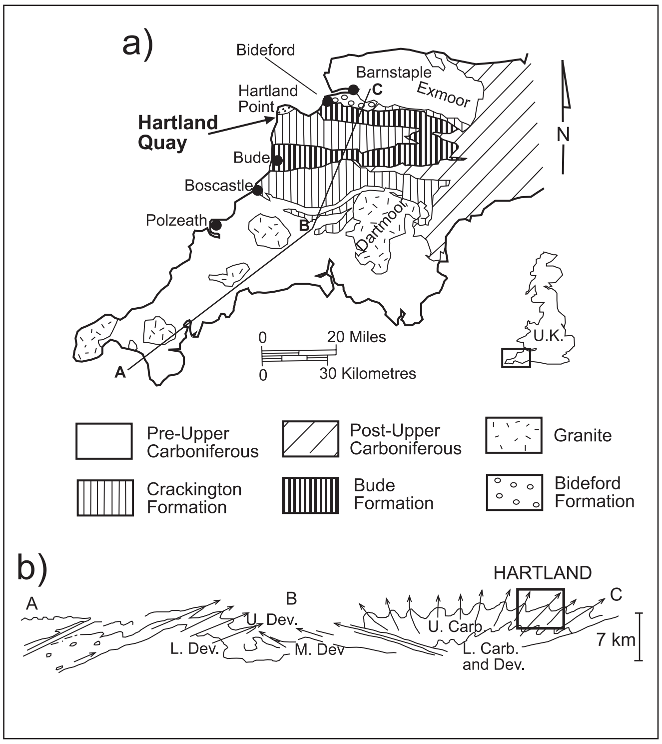


Figure 1. A. Map of the Culm trough in Cornwall and North Devon showing the location of Hartland Quay. B. Schematic cross section showing the overall structure of southwest England (after Melvin, 1986).

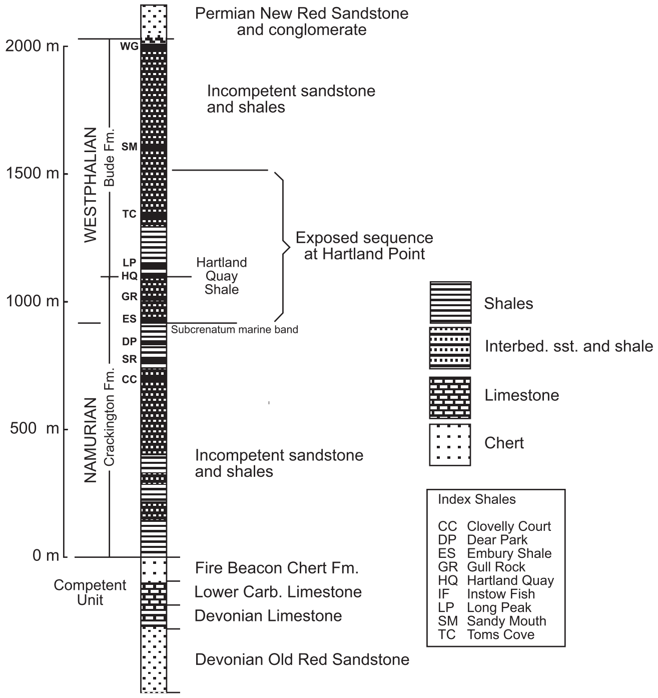


Figure 3. Stratigraphy of the Hartland Quay area and Culm Synclinorium (adapted from Thomas, 1988).

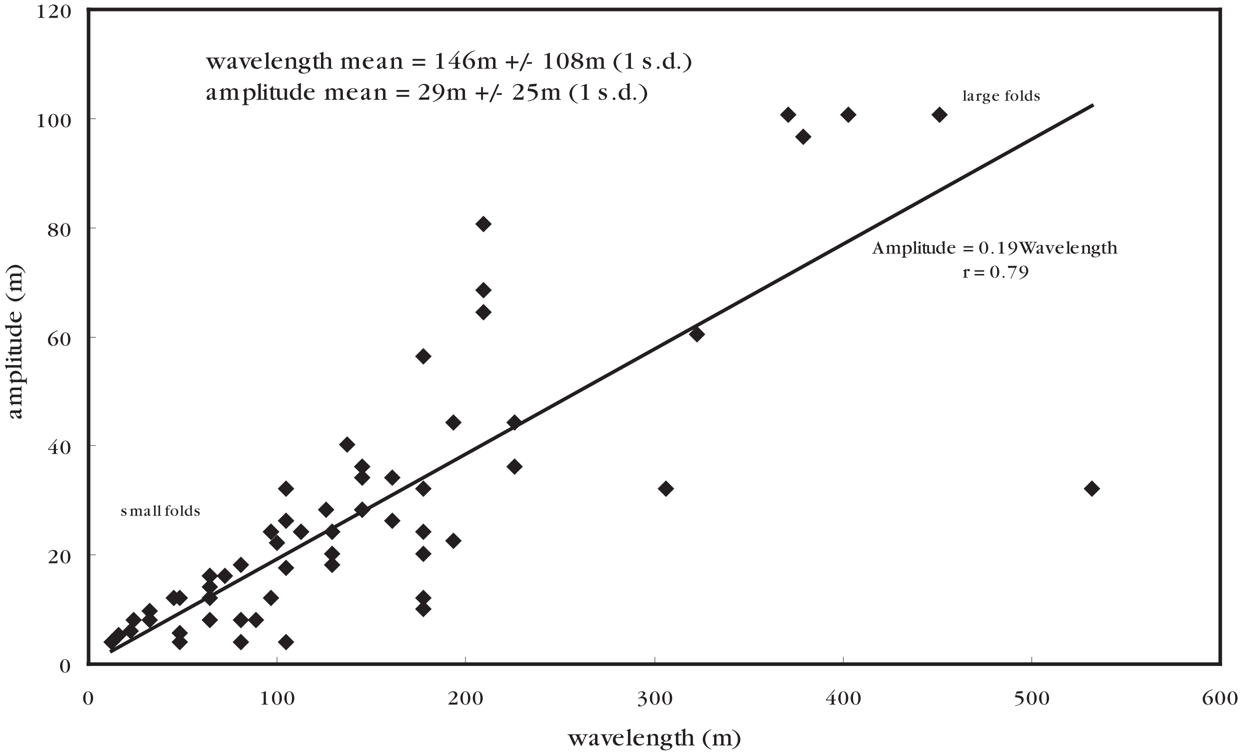


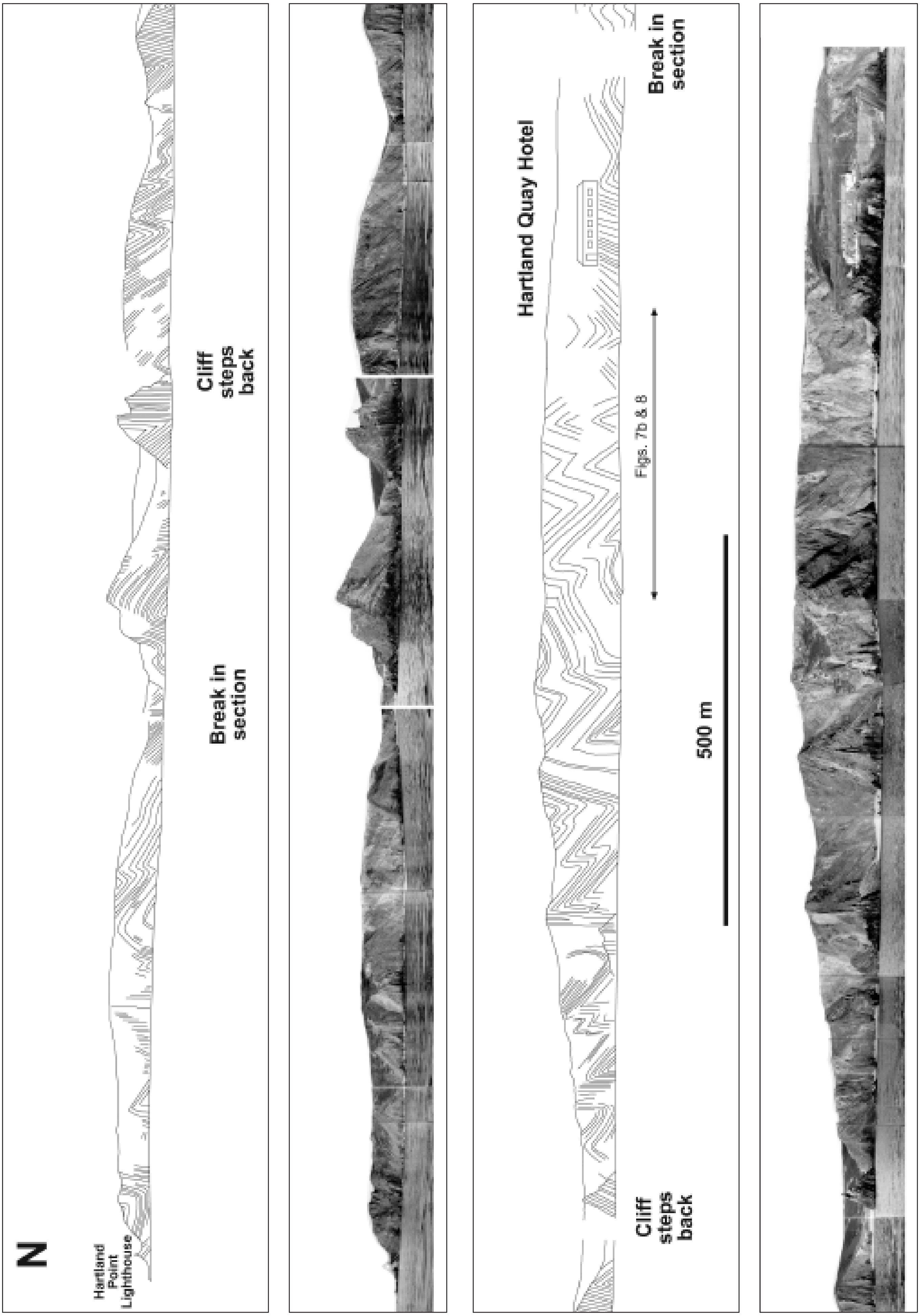
Figure 4. Plot of fold amplitude against fold wavelength for the folds shown in Figure 3 (n = 62).

from the boat was used. The positive linear correlation between fold amplitude (A) and fold wavelength (W) is:

$$A = 0.19W \qquad \text{(Figure 4)}$$

and the amplitude variance increases with wavelength.

The folds are developed in a well-bedded multilayer sequence, which are interpreted to overlie more competent Lower Carboniferous cherts and limestones and Devonian limestones and Old Red Sandstone. The maximum amplitude of the folds that could grow by internal buckling within this less competent Upper Carboniferous unit is governed by its thickness. The thickness of the less competent Carboniferous strata below the Hartland Shale is estimated to be in the order of 1 km (Thomas, 1988). The folds are probably detached from the underlying more competent layers of Lower Carboniferous/Devonian strata.


N
Hartland Point Lighthouse
Cliff steps back
Break in section
Hartland Quay Hotel
Figs. 7b & 8
500 m
Break in section
Cliff steps back

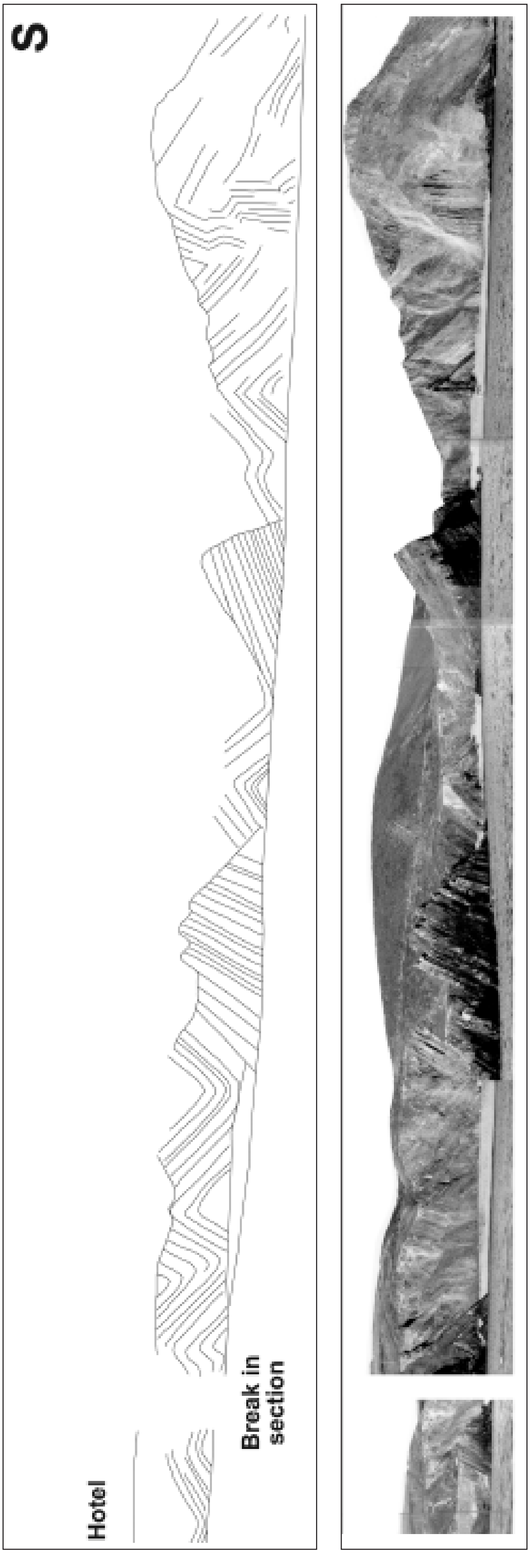


Figure 2. *A. Photo-montage from Hartland Point to 950 m south of the Hartland Quay Hotel. shot from a boat sailing at approximately 1 km from the coastline. B. Line drawing of fold geometry in A.*

Inter-limb angles

Fold interlimb angles range from 30° to 117° (Figure 5), and the mean is 67°, which is slightly larger than the predicted 60° angle for chevron fold lock-up (Ramsay, 1974). Approximately 55% of the folds have interlimb angles greater than 60°, and 33% of the folds have interlimb angles less than 60° (Figure 5).

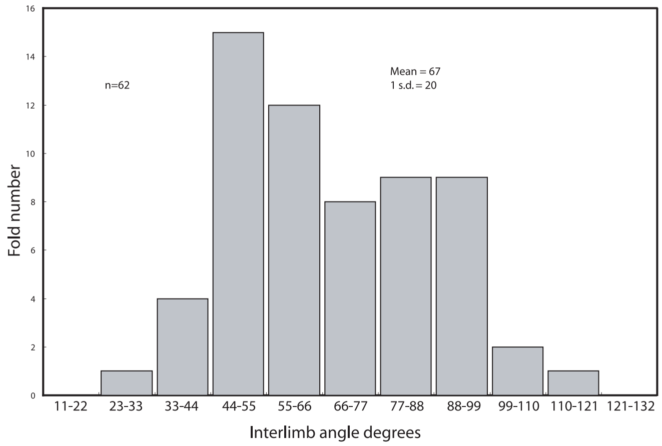


Figure 5. *Frequency plot of interlimb angles of the folds in Figure 3 (n = 63).*

Hinge thickening

Thickening of the sedimentary layers into the hinge zones is a common occurrence in chevron folds (Ramsay, 1974). To investigate the amount of hinge-zone thickening the maximum hinge/limb thickness ratios of accessible shale and sandstone beds in the folds on Hartland Quay Beach has been measured (Figure 6). Incompetent shale beds show thickening ratios up to 9:1, and sandstone bed thickening reaches a maximum of about 2:1 (Figure 6).

Hinge-zone thickening is usually limited to a zone approximately 4 m wide measured perpendicular to the axial trace. Using the average hinge/limb thickening ratio of both sandstone and shales of 2.5:1 (60% shortening) across an average 4 m wide zone of deformation along each fold hinge, an approximate amount of ductile shortening can be calculated. This is estimated to be ca. 150 m, over a measured transect length of 3800 m, equivalent to 3.6 % shortening.

The hinge: limb thickening ratio has been compared with the fold interlimb angle (Figure 6). There is a clear increase in thickening ratios of the shale layers for inter-limb angles less than 45° (Figure 6). This indicates that the main hinge thickening occurs once the folds have tightened to interlimb angles of 45°, although there is a limited amount of hinge thickening (< 2 : 1) in the shales before this value is reached.

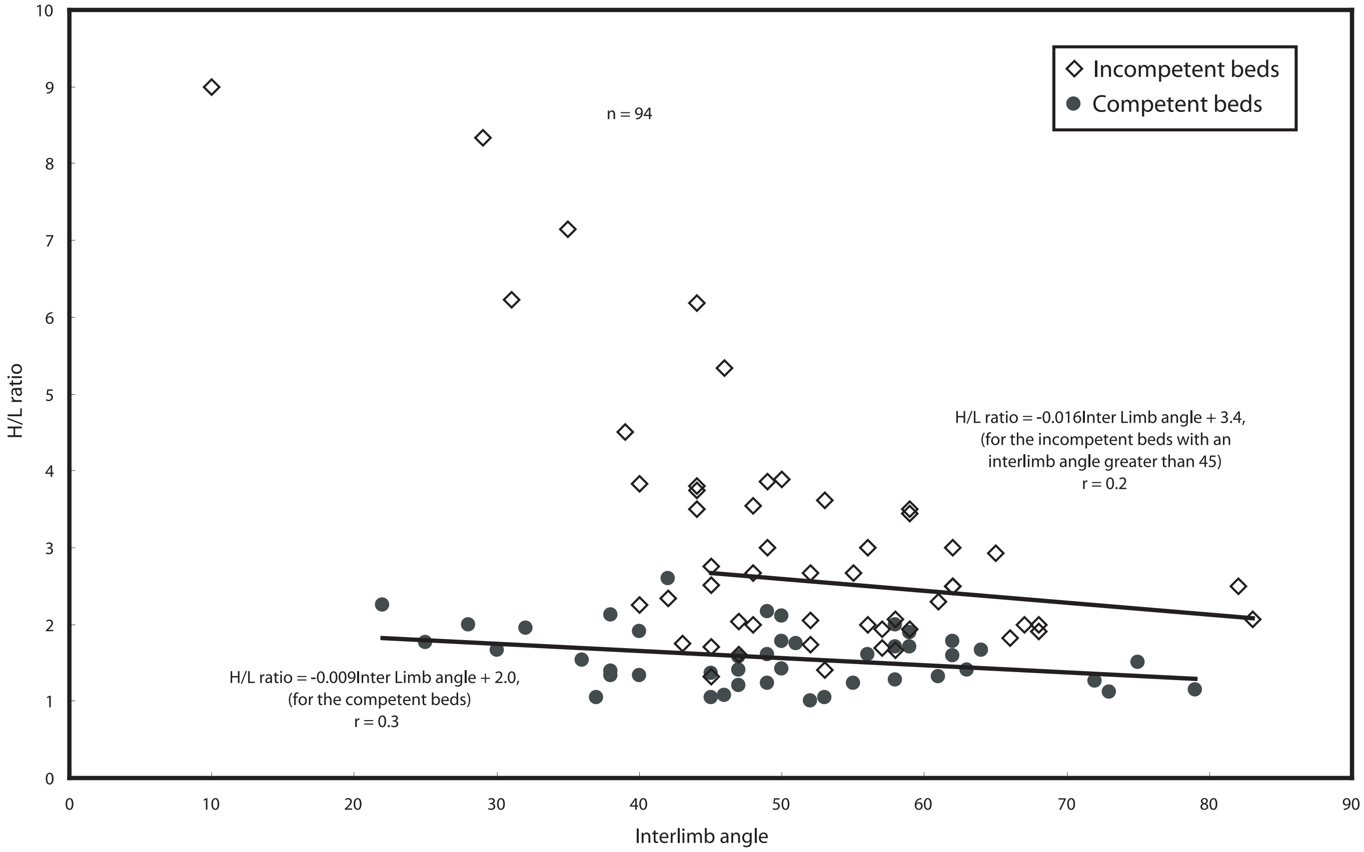


Figure 6. *Plot of hinge-zone thickening ratio versus interlimb angle for folds at Hartland Quay Bay. Inset shows the measurement method for hinge thickening ratio (n= 94). H = maximum stratigraphic thickness in hinge zone. L= thickness of same bed on fold limb.*

Bedding plane slip

The location of slip planes was studied to see whether there is a preferred location of slip planes at a particular type of lithological contact. The lithology above and below the slip zones was recorded for the accessible folds immediately north of the Hartland Quay Hotel (Figure 7a). Approximately half (84 of 161 planes) occur between sandstone and shale with the shale below the slip surface. This is the surface with the largest competence contrast in the sequence. Approximately 20% of the slip surfaces occur at the top of sandstones beds in contact with shales (Figure 7a). Only one slip surface was observed between two sandstone beds, and 11 (out of 161) slip surfaces occurred within shales. The relative proportions of slip zone locations will also clearly depend on the relative number of each pair of lithology contacts in the complete section, hence these values should be treated with caution. The base of thinner sandstones (<0.6 m) with more planar surfaces (i.e. with no scouring or groove marks) are the dominant slip planes. A similar conclusion was previously documented (Tanner, 1989), but with less data presented (45 slip surfaces).

The stratigraphic distance between slip planes (measured perpendicular to bedding) is typically 0.5 to 1 m, but some values are up to 8.5 m (Figure 7 b and c). The slip zones appear to have a log-normal frequency distribution (Figure 7c) but with a change in the cumulative number spacing relationship at approximately 1 m spacing. The explanation for this is not clear. Slip zones do not systematically increase or decrease in spacing toward fold hinge zones (Figure 7b). Also, the spacing of slip zones does not correlate to interlimb angles. Slip zones do not always correlate from one side of the fold to another (Figure 7b). This indicates that limbs are acting independently of each other. The slip amounts on bedding surfaces are difficult to determine due to a lack of displaced markers. However, continuous quartz fibres on the bedding surfaces reach up to 1.5 m in length, indicating the minimum amount of movement which has taken place.

Tectonic shortening estimate

The amount of horizontal shortening due to chevron folding has been estimated at -45% using bed length balance (comparing original bed length with horizontal length of section) on the Hartland Shale horizon, which has been extrapolated above and below the section in Figure 2. Shortening calculated by bed-length balance along a 5.4 km long section near Bude presented by Lloyd and Chinnery (2002) is approximately 58%. This is a minimum estimate of tectonic shortening, as major thrusting is also involved in the deformation (Lloyd and Chinnery, 2002). However, the amount of thrust shortening has not been quantified, and thrusting has not been recognised in the Hartland area so far.

PT CONDITIONS OF FOLDING USING FLUID INCLUSION DATA

Analysis

Quartz crystals fill saddle reefs in fold hinges, arrays of en-echelon veins and bedding-parallel shear veins, and are interpreted to have been produced during the main folding phase (sample locations in Figure 8). Quartz in saddle reefs and en-echelon veins is generally euhedral, up to 2 cm in size, whereas quartz occurring as bedding-parallel slickenfibres is anhedral and about 0.5 to 1 cm thick. Samples from all three types of vein were analysed for geo-thermometry of fluid inclusions (homogenisation and melting temperature, Table 1 and Figure 9a).

The two-phase aqueous fluid inclusions in the quartz samples vary in size from 5 to 25 μm, with a majority in the range of 7 to 15 μm. The inclusions are interpreted as primary fluid inclusions, because they occur preferentially along the

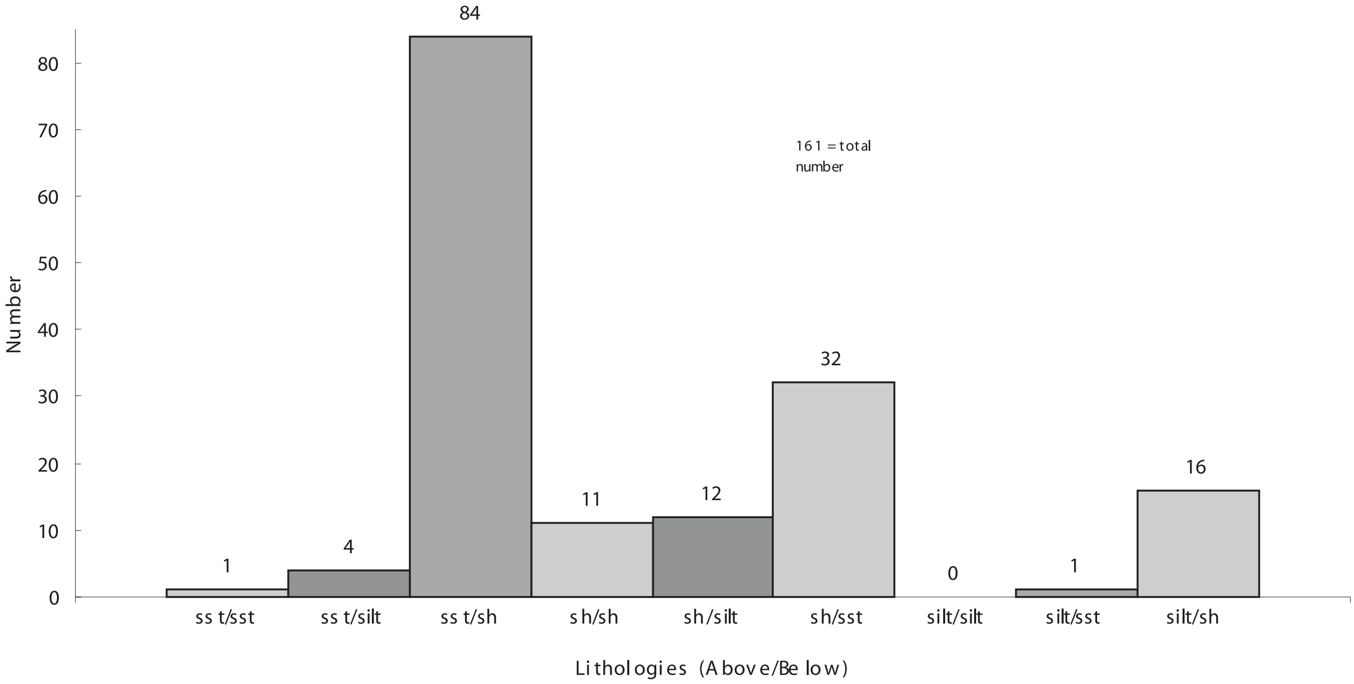


Figure 7a. *A. Graph showing number of slip zones against different pairs of boundary lithologies.*

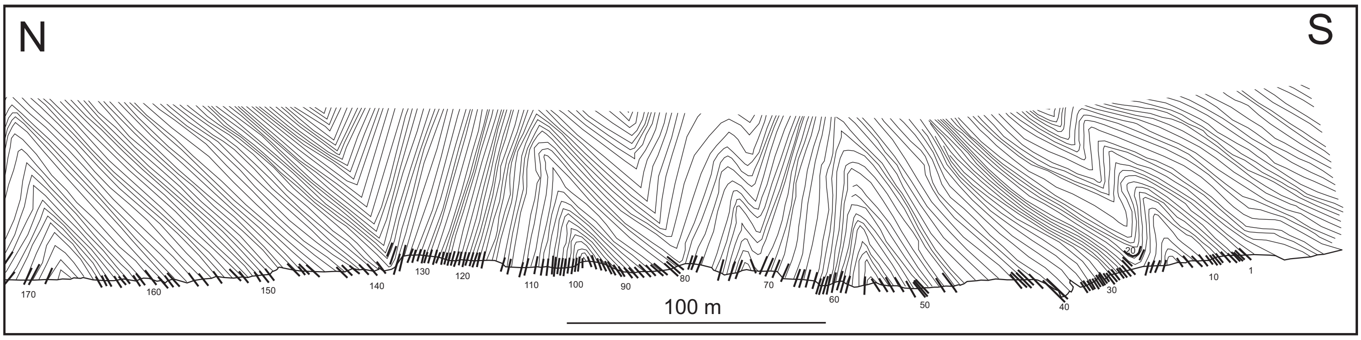


Figure 7b. *Drawing of the folds in Hartland Quay Bay with locations of slip surfaces marked with short thicker lines (mainly below the base of cliff line). Numbers on base are observation number.*

growth zones of the crystal and have a consistent water/vapour ratio based on visual observation. Ten to seventeen sets of homogenisation temperatures and final melting temperatures were measured from each sample (Figure 9a). The average homogenisation temperature of 4 quartz samples ranges from 187°C to 202°C (Table 1). The final melting temperature varies from -3.15°C to -3.91°C, corresponding to a salinity of 5.3 wt. % NaCl to 6.3 wt.% NaCl (Table 1). The quartz inclusions from all four samples have a similar range of homogenisation temperature and final melting temperature (Table 1, Figure 9a), which we interpret as indicating that all of these crystals were precipitated from similar fluids.

Fluid inclusion interpretation

The measured homogenisation temperature represents a minimum temperature for quartz precipitation during the main folding event, the true trapping temperature of quartz precipitation can be calculated after a pressure correction. Two vitrinite reflectance measurements of organic matter from the Hartland section yielded values of Ro = 4.4, suggesting palaeo-burial depths of approximately 7 km (Cornford *et al.*, 1987).

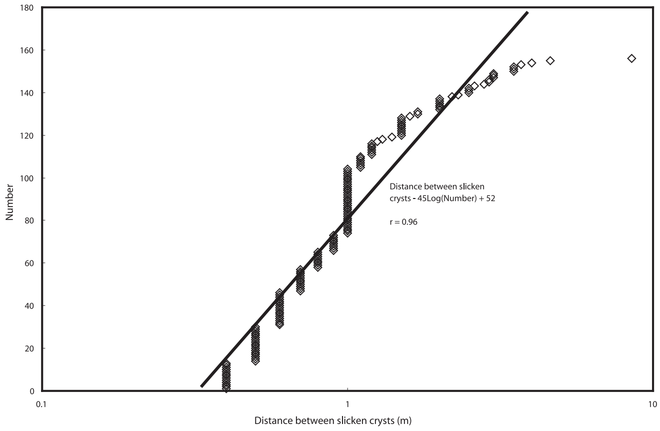


Figure 7c. *Plot of the logarithm of stratigraphic spacing between adjacent slip zones against the cumulative number of slip zones. A log normal distribution is apparent with a change in spacing relationship above 1 m spacing. The reason for this is not known.*

Assuming 7 km burial depth and hydrostatic pressure, the trapping temperatures for inclusions during quartz precipitation was approximately 250°C (Figure 9b), using the method and equation of Brown and Lamb (1989). The temperature of quartz precipitation, however, probably approaches 290°C, if the lithostatic pressure is assumed for the pressure correction (Figure 9b). Some tensional veins are parallel to the bedding and formed early in the deformation history, when the beds were sub-normal to the gravitational load. However, we have not sampled any of the bedding-parallel tensional veins. Hence, fluid pressure was probably close to lithostatic pressure during vein formation. The temperature of quartz formation is, therefore, interpreted to be nearer 290°C (Figure 9b). This temperature is very close to the previously published maximum temperature of 260-270°C (Cornford *et al.*, 1987), based on thermal modelling of vitrinite reflectance. Assuming a surface temperature of 20°C during the late Carboniferous, a maximum burial depth of 7 km, and a quartz precipitation temperature of 290°C (our estimate), the palaeo-geothermal gradient was approximately 38.5°C/km during the late Carboniferous. This value is higher than the average continental geothermal gradient (25°C/km), suggesting a higher heat flow regime in the Hartland region which may have been enhanced by deformation and fluid convection.

Sample no.	Location	Th (average)	Tm	wt. % NaCl equ.
7-1	slickencrysts	199.3 (10)	-3.62 (10)	5.9
7-2	sheared veins	193 (11)	-3.91 (11)	6.3
7-3	syncline hinge	187.3 (10)	-3.59 (10)	5.9
7-4	anticline hinge	201.6 (17)	-3.15 (17)	5.3

Table 1. *The average homogenisation (Th) and average final melting temperatures (Tm) for fluid inclusions. Note: the number in the bracket represent the number of individual inclusions that were measured in each sample.*

IMPLICATIONS FOR REGIONAL TECTONICS

The exposed stratigraphic thickness of Upper Carboniferous rocks above the Hartland Quay sequence is approximately 1 km, with a similar thickness of Carboniferous rocks below making a total thickness of approximately 2 km (Thomas, 1988, Figure 4). The Upper Carboniferous strata lie conformably on the Lower Carboniferous Teign Chert with the underlying Devonian Old Red Sandstones exposed in the Quantock Hills of Somerset, and to the south in Devon (Figure 4).

The maximum burial of the Hartland Quay section is estimated to have reached up to 7 km. Assuming the calculated minimum shortening of 50% and plane strain, with no E-W horizontal extension, then the original stratigraphic thickness of the Carboniferous strata above the Hartland section may have reached 3.6 km. The total Upper Carboniferous stratigraphic thickness may therefore have reached 4.7 km, with 1.1 km of Carboniferous sequence below the Hartland Quay Shale (Thomas, 1988). Deposition of this thickness of strata indicates that a sedimentary basin developed rapidly in Late Carboniferous times.

The high geothermal gradient during folding developed very shortly after the basin was developed suggesting an extensional rift setting, rather than a foreland basin (see also Warr *et al.*, 1991). Assuming an extensional basin setting with a typical syn-rift fill of at least 4 km, suggests that the sedimentary basin has extended by at least a ß factor of 2.2 (Mckenzie 1978, using reasonable crustal and sediment parameters, and the simplified equation in Barr, 1987). The McKenzie (1978) model would predict a geothermal gradient of approximately 40°C/km in late Carboniferous times with this amount of stretching, which is similar to the gradient calculated here. The present-day N-S width of the Culm Trough is approximately 50 km. The minimum shortening of the basin was calculated to be ca. 50%. Hence, the original width of the basin must have been at least 100 km before folding.

It appears that approximately 5-6 km of Carboniferous sedimentary sequence were eroded from the Variscan Fold Belt in SW England. The disposal of most of this material probably took place to the south in the Plymouth Bay Basin and in the Pennant Basin of south Wales where reworked Late Carboniferous coal measures are present. There is a large jump in vitrinite reflectance values from the folded Carboniferous to the unconformbale Permian beds above (Cornford *et al.*, 1987). This indicates that the folding and denudation took place from the Westphalian C to end Stephanian (ca. 15 M yr.).

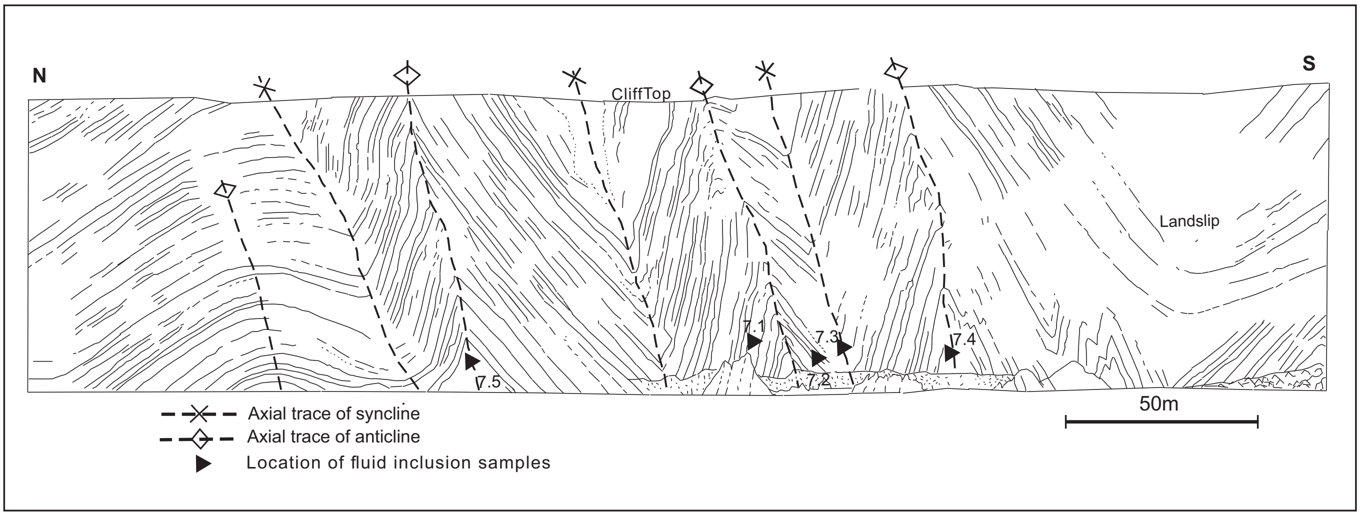


Figure 8. *Location of fluid inclusion samples at Hartland Quay.*

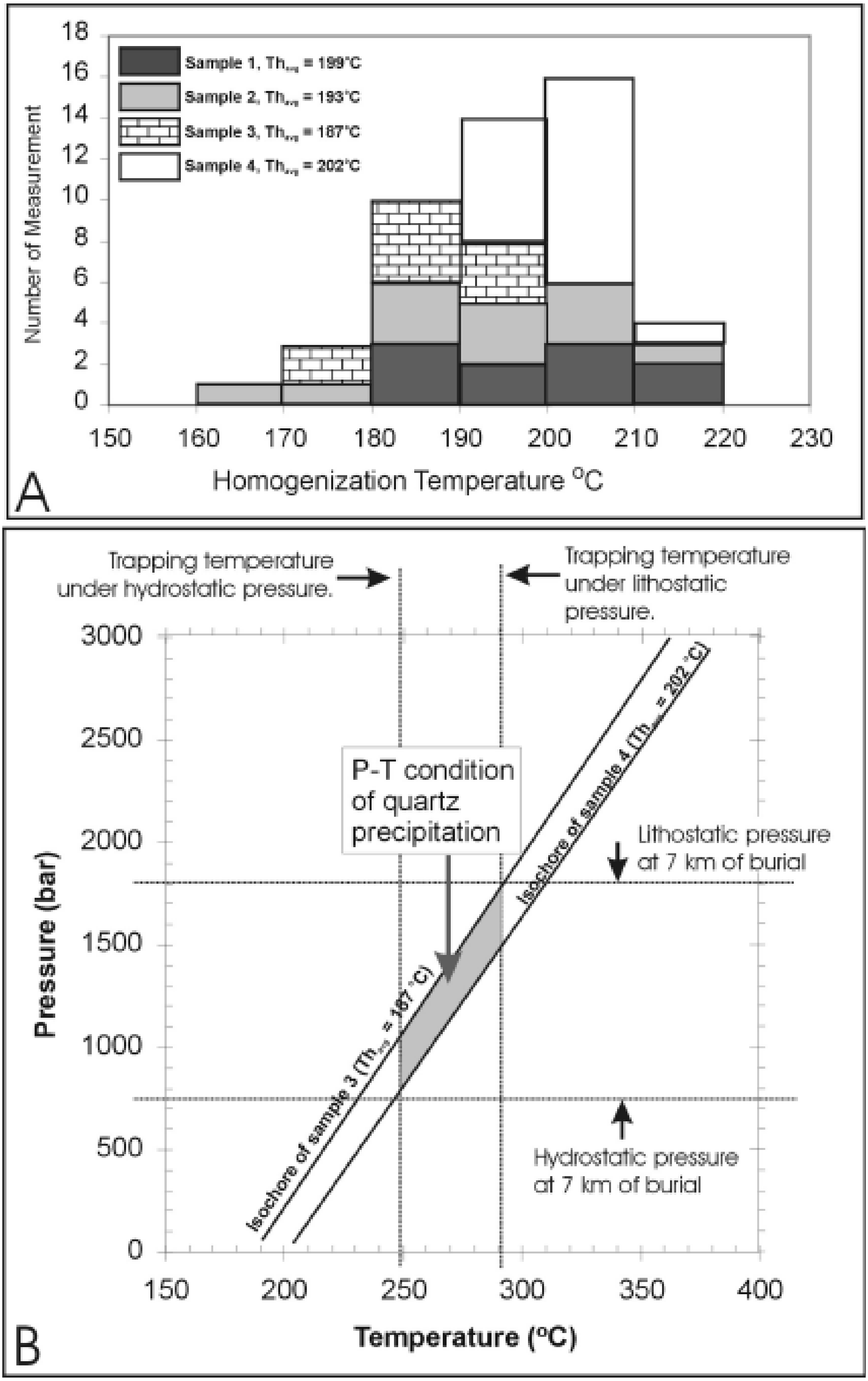


Figure 9. *A. Histogram of homogenisation temperature (T_h) of individual inclusion of each quartz sample. The average T_h for each sample is also given. B. Two isochores of fluid inclusions are constructed using equation of Brown and Lamb (1989) and computing program of Brown (1989). Isochore of sample 3 represents the minimum average T_h (187°C) while the isochore of sample 4 is the maximum average T_h (202°C) measured in this study.*

CONCLUSIONS

1. Bed length balancing indicates that horizontal shortening of 50% at Hartland and north of Bude took place in late Carboniferous times. The original late Carboniferous basin may have contained an original thickness of 4.7 km of sediment. Approximately 6 km of folded strata were removed from the Variscan mountain chain before and during deposition of Permian red beds.

2. Most flexural-slip planes created during folding occur at the base of sandstone beds with relatively planar bases. The average spacing between the slip zones is approximately 0.75 m. There is no apparent relationship between slip zone spacing and position in the fold. Some slip zones do not correlate from one side of a fold to the other.

3. Fold hinge zone thickening accounts for approximately 3-4% of the overall shortening. The ratio between the thickness of shale in the hinge zone to thickness on the limbs reaches a maximum of 9:1. Most of this ductile shortening takes place once the folds have tightened to interlimb angles less than 45°.

4. Fluid inclusions analysed from saddle reefs, en-echelon veins and bedding-plane slip zones at Hartland Quay formed with ambient fluid temperatures of approximately 290°C at depths of 7 km (estimated from vitrinite reflectance data from Cornford *et al*., 1987) giving a geothermal gradient of approximately 38°C /km. This suggest an extensional rift basin developed in Namurian to Westphalian B times rather than a foreland basin.

5. Assuming a McKenzie (1978) crustal stretching model, the crust is calculated to have extended by a factor of approximately 2 during late Carboniferous rifting in the Culm Trough.

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REFERENCES

BARR, D. 1987. Lithospheric stretching, detached normal faulting and footwall uplift. In: COWARD, M.P., DEWEY, J.F. and HANCOCK, P. (eds), *Continental extension tectonics*. Geological Society, London, Special Publications, **28**, 75-94.

BROWN, P.E. 1989. FLINCOR: a microcomputer program for the reduction and investigation of fluid inclusion data. *American Mineralogist*, **74**, 1390-1393.

BROWN P.E. and LAMB W.M. 1989. P-V-T properties of fluids in the system H_2O-CO_2-NaCl: New graphical presentations and implications for fluid inclusion studies. *Geochimica et Cosmochimica Acta*, **53**, 1209-1221.

CORNFORD, C., YARNELL, L. and MURCHISON, D.G. 1987. Initial vitrinite reflectance results from the Carboniferous of North Devon and Cornwall. *Proceedings of the Ussher Society*, **7**, 232-236.

DEARMAN, W. 1970. Some aspects of the tectonic evolution of south-west England. *Proceedings of the Geologists' Association*, **81**, 483-491.

EDMONDS, E.A., WILLIAMS, B.J. and TAYLOR, R.T. 1979. Geology of Bideford and Lundy Island: Memoir sheets. *Memoirs of the Geological Survey of Great Britain*. HMSO, London.

FRESHNEY, E.C. and TAYLOR, R.T. 1972. The Upper Carboniferous stratigraphy of north Cornwall and west Devon. *Proceedings of the Ussher Society*, **2**, 464-471.

FRESHNEY, E.C., MCKEOWN, E.A. and WILLIAMS, M. 1972. Geology of the coast between Tintagel and Bude. *Memoirs of the Geological Survey of Great Britain*. HMSO, London.

FRESHNEY, E.C., EDMONDS, E.A., TAYLOR, R.T. and WILLIAMS, B.J. 1979. *Geology of the Country around Bude and Bradworthy*. Memoirs of the Geological Survey of Great Britian, SHeets 307 and 308.

LLOYD, G.E. and CHINNERY, N. 2002. The Bude Formation, SW England: a three dimensional intra-formational Variscan imbricate stack. *Journal of Structural Geology*, **24**, 1259-1280.

LLOYD, G.E. and WHALLEY, J.S. 1986. The modification of chevron folds by simple shear: examples from north Cornwall and Devon. *Journal of Geological Society, London*, **143**, 89-94.

LLOYD, G.E. and WHALLEY, J.S. 1997. Simple shear modification of chevron folds: implications for facing interpretations, strain analysis and deformation history. In: SENGUPTA, S. (Ed.), *Evolution of geologic structures from micro to macro scales*. Chapman and Hall, 373-396.

McKENZIE, D. 1978. Some remarks on the development of sedimentary basins. *Earth and Planetary Science Letters*, **40**, 25-32.

MELVIN, J. 1986. Upper Carboniferous fine-grained turbiditic sandstones from southwest England: a model for growth in an ancient delta-fed sub-sea fan. *Journal of Sedimentary Petrology*, **56**, 19-34.

PRICE, N.J. and COSGROVE, J.W. 1990. *Analysis of Geological Structures*. Cambridge University Press, Cambridge, UK.

RAMSAY, J.G. 1974. The development of chevron folds. *Bulletin Geological Society of America*, **85**, 1741-1754.

RAMSAY, J.G. and HUBER, M. 1987. *The techniques of modern structural geology, vol. 2 folds and fracturing*. Academic Press, London.

SANDERSON, D.J. 1974. Chevron folding in the Upper Carboniferous rocks of North Cornwall. *Proceedings of the Ussher Society*, **1**, 96-103.

SANDERSON, D.J. 1979. The transition from upright to recumbent folding in the Variscan fold belt of southwest England: a model based on the kinematics of simple shear. *Journal of Structural Geology*, **1**, 171-180.

TANNER, P.W.G. 1989. The flexural slip mechanism. *Journal of Structural Geology*, **11**, 635-655.

THOMAS, J.M. 1988. Basin history of the Culm Trough of Southwest England. In: BESLY, B.M. and KELLING, G. (eds), *Sedimentation in a synorogenic basin complex; the Upper Carboniferous of Northwest Europe*. Blackie and Son, 24-37.

WARR, L.N., PRIMMER, T.J. and ROBINSON, D. 1991. Variscan very low-grade metamorphism in southwest England: a diasthermal and thrust-related origin. *Journal of Metamorphic Geology*, **9**, 751-764.

ZWART, H.J. 1964. The development of successive structures in the Devonian and Carboniferous of Devon and Cornwall. *Geologie en Mijnbouw*, **43**, 516-526.