GEOMETRY OF CHEVRON FOLDING AND SHORTENING 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