A THERMAL ANOMALY ASSOCIATED WITH THE RUSEY FAULT AND ITS IMPLICATIONS FOR FLUID MOVEMENTS

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Andrews, J.R., Day, J and Marshall, J.E.A. 1996. A thermal anomaly associated with the Rusey Fault and its implications for fluid movements. *Proceedings of the Ussher Society,* **9,** 068-071.

Vitrinite reflectance measurements from the footwall of the Rusey Fault show a progressive increase in reflectance as the fault is approached, indicating a sharp perturbation of the regional geothermal gradient. Estimates suggest that there was a local temperature maximum some 80°C above the regional background metamorphic values. It is concluded that local heating accompanied fluid flow along the fault during inversion of the Culm basin during or just before peak Variscan metamorphism. The size of the thermal anomaly is compatible with large volumes of intermittent fluid flow over a period of several million years.

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INTRODUCTION

The Rusey Fault is one of the fundamental structures which control the present disposition of the strata of South-west England. It juxtaposes Namurian (H_1) turbidites of the Crackington Formation against the more distal turbiditic fades of the Boscastle Formation of probable Visean age. It has variously been interpreted (Freshney *et al.,* 1972; Andrews *et al.,* 1988) as a low-angle normal fault and/or lateral ramp associated with thrusting.

The fault is exposed on Rusey Beach as a 2 m-wide breccia zone bounded by polished slickensided surfaces (Figure 1 and 2a). The hanging wall rocks comprise the Upper Carboniferous Crackington Formation turbidites. Decametric recumbent south facing chevron folds with associated axial planar cleavage dominate the structure of these turbidites. Conjugate pre-folding quartz veins are developed in the massive sandy lithologies, together with syn-folding veins and late veins which cross-cut the folds and cleavage and are spatially associated with the Rusey fault. The footwall lithology (Lower Carboniferous Boscastle Formation) is dominated by cleaved mudrocks with occasional thin sandy beds and contrasts markedly with the Crackington Formation lithology. Near isoclinal recumbent folds are also southwards-facing and exhibit much higher strain states, with a well developed stretching lineation (parallel to slickenside striae on the fault). They display higher indices of illite crystallinity (Primmer, 1985) and have clearly been subjected to considerably higher temperatures and pressures. Syn- and post- and probably pre-tectonic quartz veins are developed in these rocks.

The fault breccia zone displays spectacular exposures of angular to rounded clasts surrounded by rinds of white quartz (Figure 2). Drusy infills between clasts are common, with the development of euhedral quartz prisms. Though the breccia is apparently matrix-supported, closer inspection (Figure 2c) suggests that progressive replacement of clasts by quartz has taken place, sometimes leaving only relic shapes of the original margins of the clasts. Large volumes of fluid must have passed through the breccia to achieve this. An extended history of fault movement and fluid flow is supported by numerous internal contacts, rebrecciation and several slickensided slip surfaces. Slickenside striae plunge gently north-north-westwards and lie in the regional transport direction for Variscan thrusting. 'Crag and tail' features on most recent slip surfaces indicate that the latest movements were top-to-the south-south-east giving an oblique reverse sense of thrust displacement. Much of this late movement may be associated with the latest stages of Variscan closure of the Culm Basin.

A sharp break in the metamorphic grade of the metasediments across the Rusey fault was first quantified by measurements of illite crystallinity (Primmer, 1985). New work reported here identifies a sharp local perturbation of the palaeotemperature profile in the footwall of the fault.

VITRINITE REFLECTANCE

Vitrinite is the remains of ligno-cellulosic plant tissues which have been degraded during diagenesis with the loss of their original structure. Its importance as an index of thermal maturation was

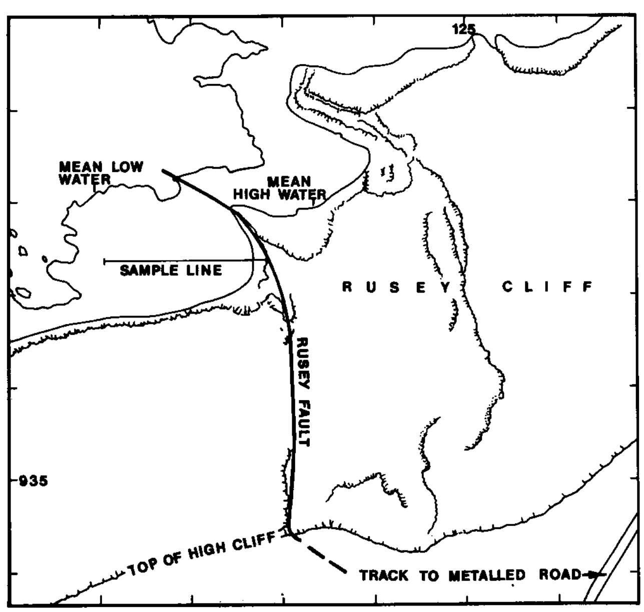

Figure 1. *Map of the foreshore below High Ciff showing the outcrop of the Rusey Fault and the sample line. Base map redrawn from Ordnance Survey 1:25,000 Sheet SX 19 with 100 m grid indicated.*

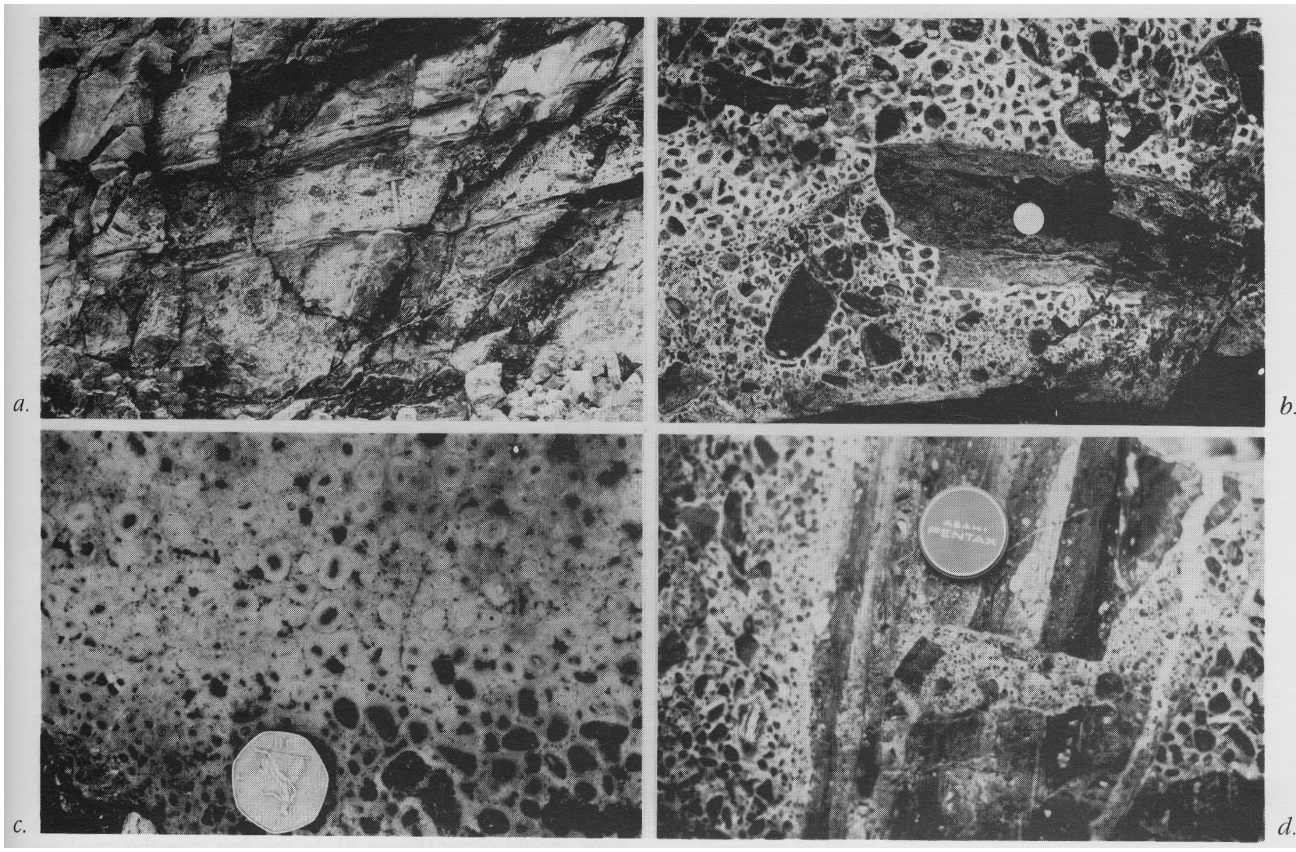

***Figure 2**. Photographs of the Rusey Fault zone and breccia at Rusey Beach.*
*a) Exposure of fault zone with 2 m-wide breccia transected by slickensided slip surfaces dipping moderately north-eastwards. **b)** Detail of the fault breccia. Note the darkened slate and sandstone clasts surrounded by rinds of white quartz, the radial arrangements of quartz crystal fibres and the apparent matrix-supported nature of the breccia. **c)** Further detail of the fault breccia. Here there is a progressive replacement of the dark clasts by quartz towards the top of the photograph. Relic shapes of the original margins of the clasts can be seen. **d)** Cross-cutting internal contacts within the breccia testify to a protracted history of fault movements and fluid flow.*

established on studies of Carboniferous rocks (eg. Stach *et al.*, 1982).

In an attempt to quantify the maximum temperatures reached in the footwall a series of fine-grained grey slate samples was collected along a traverse line perpendicular to the fault (Figure 1). Samples were collected at 17 m intervals from the fault to a distance of 170 m away on the wave-cut platform. The slates become noticeably darker in colour approaching the fault, particularly over the final 50 m.

Experimental methods

All vitrinite reflectance measurements were made on polished thin sections of kerogen isolates, prepared by the method described by Hillier and Marshall (1988). Mean random vitrinite reflectance in oil (R_o) was measured at 546 nm using a Zeiss UMSP 50 microscope fitted with a 40x oil immersion objective and with a measuring spot diameter of 2.5 µm. R_o was calculated from 50 individual reflectance measurements per sample. Experimental errors are thought to be negligible in comparison to the potential inaccuracies due to natural variability. A more detailed discussion of the methodology can be found in Hillier and Marshall (1992).

Results

Reflectance values are presented in Figure 3. Despite some degree of scatter, there is a clearly defined trend of rapidly increasing reflectance as the fault is approached. Reflectance values are interpreted as temperatures on the right hand side of the graph using the calibration curve of Barker and Goldstein (1990).

Discussion

The increase in temperature suggested by the thermal maturation of the vitrinite is of the order of 70° over a 170 m traverse, with a clear trend towards a background value just below 300°C. An average fault dip of 35° is obtained by tracing the fault from the top of the cliff down to the exposures on the wave-cut platform where it also dips at 35°. The true thickness of the marginal zone affected is about 100 m measured perpendicular to the fault.

There is ample evidence (eg the abundant hydrothermal quartz seen in Figure 2) that a large volume of fluid was flushed through the fault zone. Fluid inclusion studies show homogenization temperatures of 200° (Sargent, 1987) giving a minimum estimate of the fluid temperature. The trapping temperature obtained after a pressure correction would have been considerably higher. There is also a trend of progressively decreasing salinity with time (Davis, 1993). Decreasing salinity might reflect either meteoric recharge or more probably progressive metamorphism accompanying fault activity.

The vitrinite profile is interpreted as signifying the maximum temperature reached by the footwall rocks due to the passage of hot fluids through the fault zone. The brecciated and mineralized nature of the fault zone indicates that a protracted series of rupturing events was accompanied by fluid outflow up-and along the fault to higher structural levels. To produce the observed perturbation would necessitate many fault ruptures. Large fluid movements are known to be associated with neotectonic fault activity for example the $M_{7.2}$ Kern County earthquake, California in 1952 when 10^7 m^3 water was discharged at the surface over two months during the aftershock phase (Sibson, 1981). Repeat times for such large events may be of the order

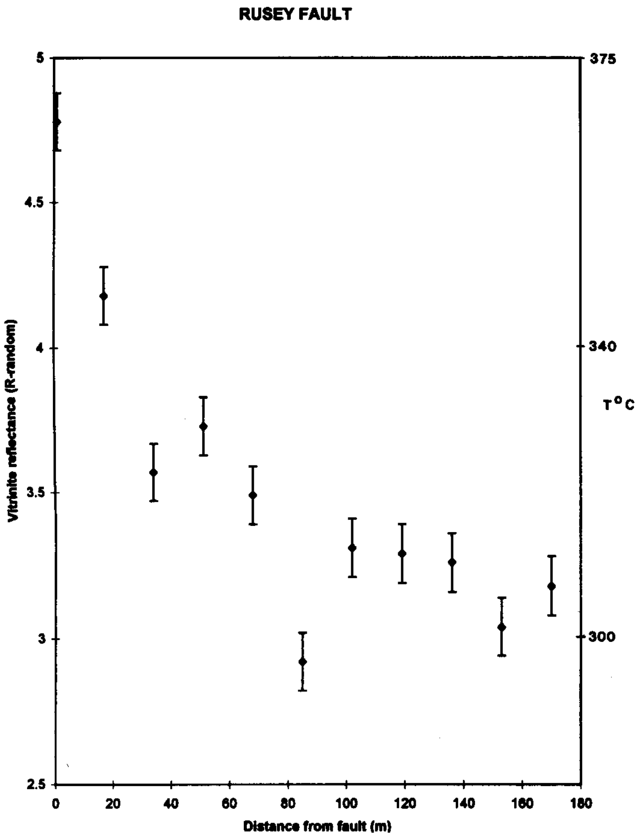

Figure 3. *vitrinite reflectance of grey slate samples at 17 m intervals along a traverse across the footwall of the Rusey Fault. For location of sample line see Figure 1. Error bars indicate one standard deviation from the mean in the experimental data.*

of 1000 years, so that intermittent upflow of hot fluids along the Rusey fault might have persisted over a long period of time, perhaps several million years.

As shape of the reflectance profile can be fitted to a negative exponential curve heat flow considerations suggest that the heating was effected primarily by conduction through the slates and thin sandstones which make up the footwall. The presence of several sets of quartz veins also necessitates consideration of the possibility that fractures conveyed some of the hot fluids away from the fault zone. Many quartz-filled fractures are believed to have been generated by brittle failure during shortening of the Culm basin (Jackson, 1991; Andrews, 1993) and could have been open pathways during basin inversion. However in this case there are two reasons for believing that convection has had minimal influence. Firstly it is likely that any fluid-pressure gradient would have tended to drive fluids upwards into the hanging wall. Evidence for this is seen in an extensive zone of blackening and sulphidation of the Crackington Formation turbidites immediately above the fault zone, but only a limited equivalent zone in the footwall. Secondly, flow of considerable volumes of hot fluid through quartz fractures should have resulted in a very uneven pattern of vitrinite values according to the distance of the samples from the nearest quartz veins. Further work is in progress to evaluate these considerations.

Unlike illite crystallinity, vitrinite reflectance is believed to respond to temperature increases over relatively small periods of geological time. The local perturbation of the vitrinite profile adjoining the Rusey fault is taken to indicate the maximum temperature reached by the metasediments. This might have occurred either before, during or after the regional Variscan metamorphism. It is not a simple matter to resolve this problem, as it is probable that the fault was initiated as an extensional fault during the formation of the Culm Basin and then inverted during basin closure. The shape of the vitrinite temperature profile away from the fault will depend on the time at which the local heating occurred and relative to the metamorphism. If it occurred either before or a significant time after metamorphism, then a break in slope should occur (Figure 4). In the first case the overlying sedimentary sequence would have been relatively thin and the ambient temperatures in the footwall relatively low. Assuming that heat loss from the fault zone is by conduction only, then the resulting profile (Figure 4a) would be expected to decay exponentially away to the ambient footwall temperature. It would be overprinted by the later metamorphic heating, producing the break in slope. The sharpness of the profile and consequently the amount of break of slope would also depend on the time over which hot fluids were flowing along the fault zone. The longer this was, the flatter the curve will be. If fluid flow occurred a significant time after metamorphism (Figure 4b) a proportionally flatter profile but still perturbed profile should result, as the ambient temperatures in the

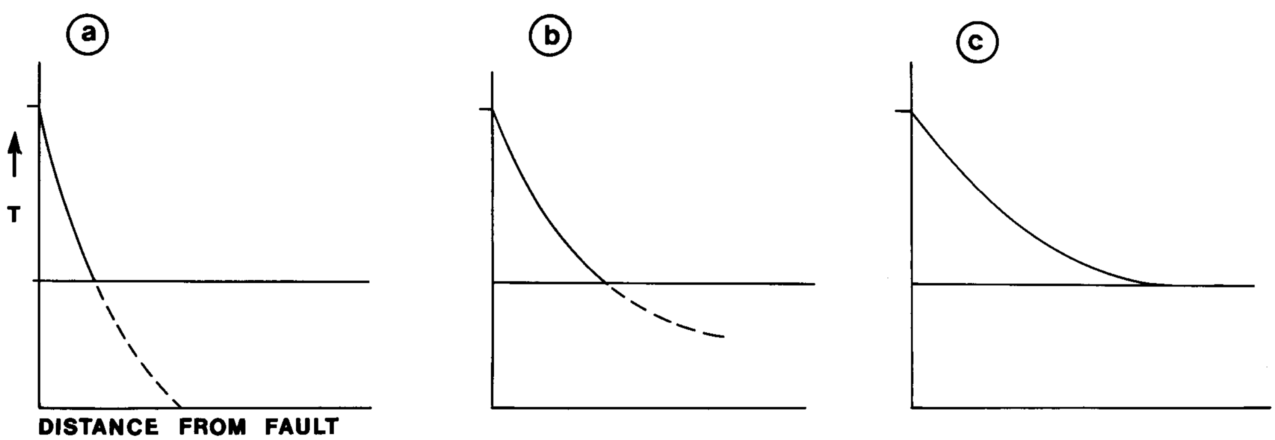

***Figure 4**. Schematic vitrinite profiles across the footwall of the Rusey fault. a) Profile if the local anomaly is created during dewatering of the Culm basin during crustal extension. The local anomaly will become asymptotic to the regional ambient temperature. This will be relatively loci if the overlying sedimentary veneer is only thin. The subsequent regional metamorphic overprint (horizontal line) will create a sharp inflection in the observed profile. b) Profile if the local anomaly is created during an episode of later fault reactivation (eg. during the Tertiary) when the regional ambient temperature has relaxed from the peak metamorphic temperature but is maintained at higher value due to thicker residual crustal overburden. The inflection of the profile will be less pronounced. c) Negative exponential profile predicted if the local anomaly is created during Variscan convergence and fault inversion. The background ambient temperature would be close to the maximum reached during peak metamorphism.*

footwall could reasonably be expected to be elevated due to a thicker overlying crustal pile. The actual thickness would also depend on the degree of post Variscan uplift and erosion which had taken place before fluid flow commenced. If hot fluid dewatering was synchronous with Variscan metamorphism and accompanied inversion of the Rusey fault during crustal shortening and thickening, then a profile asymptotic to the regional metamorphic vitrinite profile should result (Figure 4c). There is no clearly identified break of slope in the observed profile (Figure 3) which is becoming asymptotic to a suggested temperature of just below 300°C. More data would be helpful, but it is concluded that local heating was synchronous with peak metamorphism. Mite crystallinity values (Primmer, 1985; Wan *el al.,* 1991) show that the footwall just reached the base of the epizone (-300° C). Hot fluids would be readily available at relatively shallow depths with high fluid pressures promoted by dehydration reactions. This model is consistent with the trend to progressively less saline low-salinity fluids (Davis, 1993) observed in the fault zone.

ACKNOWLEDGEMENTS

Discussions with Dave Sanderson, Duncan Hodson and Chris Cornford have helped develop the ideas in this paper.

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