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The application of the illite "crystallinity" technique to geological interpretation: a case study from north Cornwall

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Illite "crystallinity" (IC) data, contoured at a statistically- valid interval, from the Camelford area indicate an anchizone to epizone transition (range 0.34-0.08Δ°2Θ) which cross-cuts the regional geological strike. The pattern of isocrysts (contour intervals 0.1Δ°2Θ) are related to an M2 metamorphism induced by regional D2 backthrusting of the Upper Carboniferous Culm rocks. Contact metamorphic effects on the IC parameter are distinguished. The interference of M1 and M2 metamorphic effects across the Camelford area gives rise to an apparent inverted metamorphism, with increasing grade occurring structurally upwards and into younger units within the Tintagel High Strain Zone. A diastathermal origin for M1 metamorphism is suggested.

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Introduction

Illite "crystallinity" (IC) is a parameter that quantifies the "sharpness" of the illite (001) X-ray diffraction peak. This 10Å peak progressively decreases in width (i.e. increases in sharpness) from upper diagenesis to lowest greenschist conditions, and reflects some change in the illite structure. Measurement of changes in IC therefore provides a useful indicator of variations in grade at low temperatures of metamorphism. This empirical method of relating the shape of the 10Å diffraction peak of illitic minerals to metamorphic grade was used first by Weaver (1960) and subsequently by Kubler (1967), who also introduced the IC concept. Since then it has been employed on a worldwide basis, mainly in the "non-metamorphic" external foreland regions of orogenic belts. A review of its usage from 1976-1983 is given by Kisch (1983) with more recent examples being Kisch (1984), Krumm (1984), Brime (1985), Roberts and Merriman (1985), Offler and Pendergast (1985), Primmer (1985a) and Kelm (1986). It has proved to be especially useful in terranes where argillaceous rocks predominate and where the more traditional petrographic techniques are of subsidiary use.

Most workers have accepted the IC technique as a "semi-quantitative" method which has a low precision of measurement when employed on a regional basis. Despite this some workers have chosen to closely contour IC data without consideration of the analytical errors involved. The "isocryst" approach in which some 15 contour intervals between 0.17-0.70Δ°2Θ were defined, was first introduced by Roberts and Merriman (1985) and subsequently several authors have also contoured IC data (Pharaoh *et al.* 1987; Smith 1988; Fortey 1990; Roberts *et al.* 1990). Such close contouring of IC values is not considered as a valid method when intra-laboratory error (1σ) of the technique is in the order of 10- 14% (Robinson *et al.* 1990).

The purpose of this paper is to present the results of an IC survey of the Camelford area (Fig. 1) and to assess the reliability of contouring IC data at different contour intervals based on the error estimations of Robinson *et al.* (1990). The geological interpretation of the IC results is presented in co-ordination with the recent re-mapping of the Camelford area by the University of Exeter mapping contract group (1986-1990). The results are also put into context with the regional patterns of metamorphism across SW England, and in addition the tectono-thermal history is discussed.

Methodology

A total of 150 samples were collected from the Camelford area during remapping of the BGS sheet 336, with an average spacing between samples of less than 1km. Sample quality varied from relatively fresh material from the coastal sections to weathered and solution-stained argillites of the inland regions. Numerous small disused quarries and road bank exposures formed the most frequent source for sampling across the relatively unexposed inland regions. Each sample was disaggregated in an ultrasonic tank, following which the <2μm fraction was separated by centrifugation and subsequent filtration. Three XRD mounts were then prepared for each sample by pipetting the remaining separated clay fraction onto three glass slides.

The slide mounts were irradiated using a Philips PW 1730/10, at the Department of Geology, University of Bristol. IC measurements were determined using Ni-filtered, Cu-Kα radiation at a tube rating of 40kV and 40mA. An automatic divergence slit, graphite monochromator, receiving slit of 0.1mm and a scanning speed of ½°2Θ/ min were used. Analogue and digital recordings of peak profiles were recorded, the latter using on-line computer control of the diffractometer. All the crystallinity data were recorded using digitized data, with computer manipulation of digitized profiles. No consistent difference has been found between the use of computerized measurements and manual measurements for any of the indices measured (Robinson and Bevins 1986). The IC parameter was measured in this study using the Kubler (half-peak width) index, which is suggested by Blenkinsop (1988) to be marginally advantageous at all grades compared with the other indices.

The mean IC values from the three slide mounts prepared from each sample was taken as representative of a given locality. The meaned data were then contoured using a UNIRAS/UNIMAP facility on the PRIME mainframe computer at the University of Exeter. Four contour intervals were selected at 0.25Δ°2Θ, 0.05Δ°2Θ, 0.075Δ°2Θ and 0.1Δ°Θ which are shown in Fig. 2. The probabilities of samples falling within the contour intervals (1σ) for an IC value of 0.21Δ°2Θ were calculated using the error analysis of Robinson *et al.* (1990) and summarized as follows:

Contour interval	Probability at 14% error
0.025Δ°2Θ	0.3
0.05Δ°2Θ	0.6
0.075Δ°2Θ	0.8
0.1Δ°2Θ	0.9

From these calculations the 0.1Δ°2Θ and 0.075Δ°2Θ contour intervals are chosen as the most acceptable level for contouring, with over 8 out of 10 samples falling within the selected intervals at 1σ precision of measurement (Fig. 2d).

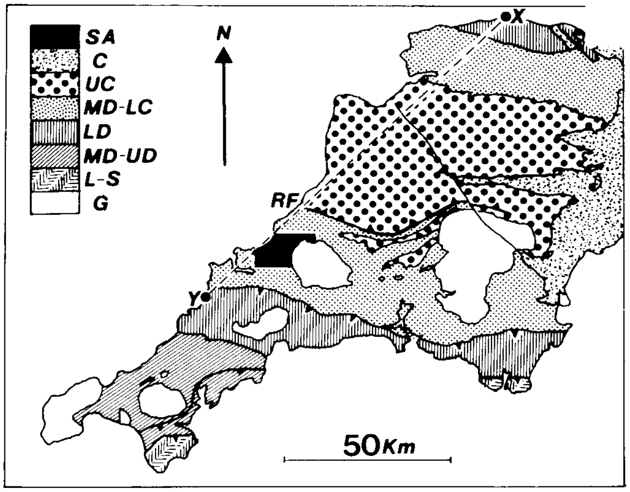

Figure 1. Simplified geological map showing the location of the IC survey of the Camelford area, north Cornwall. SA= Survey area, C= cover, UC= Upper Carboniferous, MD-LC = Middle Devonian to Lower Carboniferous, LD = Lower Devonian, MD-UD = Middle Devonian to Upper Devonian, L-S = Lizard and Start Complexes, G = Granite, X-Y = IC traverse shown in Fig. 4, RF = Rusey Fault.

Geology of the Camelford area

Recent, detailed descriptions of the geology of the Camelford area have been presented by Warr (1988, 1990a, b). A summary geological map is presented in Fig. 3 in which the IC contours at 0.1Δ°2Θ intervals, the outer margin of the granite aureole, and the anchizone/ epizone boundary are shown. Two main geological sub-areas can be identified (Warr 1990a), namely a southern area of Middle to Upper Devonian rocks, the Trevone Succession of Smith (1990(Abstract)), and a northern area of Upper Devonian to Lower Carboniferous rocks. Within this northern area two successions can be distinguished, the Bound's Cliff Succession (the Northern Succession of Selwood and Thomas (1986)) and the Tintagel Succession (Freshney *et al.* 1972). The boundary between these two areas was interpreted by Warr (1988) as a NN W-transporting late D2 thrust fault, showing a low-angle faulted relationship where it crops out at the coastline and a strong lateral ramp geometry as it strikes inland. This thrust emplaces the Middle Devonian basinal slates of the Trevone Formation upon the Upper Devonian outer shelf to shelf facies of the Jacket's Point and Tredorn Slate Formations, a boundary which regionally strikes from WSW to ENE. The northern part of the district shown in Fig. 3 (from Tregardock Beach, northwards) is part of a zone of intense ductile deformation extending to Boscastle, which is known as the "Tintagel High Strain Zone" (Sanderson 1979). Rocks in this zone have attained the highest grade of metamorphism in the region with a well-developed greenschist assemblage (Read and Robinson 1981). To the north of the Tintagel High Strain Zone is the WNW-ESE trending Rusey Fault, which juxtaposes this zone against rocks of the Upper Carboniferous Culm Basin.

Metamorphism

Regional metamorphism

Within the Camelford region the IC results suggest that there are two zones, to the SW is an upper anchizone region with IC values between 034-0.21Δ°2Θ, and to the N and NE an epizone region with values between 0.21-0.08Δ°2Θ (Fig. 2d). The approximate anchizone/epizone boundary may be taken at 0.21Δ°2Θ (following Kisch 1980), a boundary which runs NW-SE from Jacket's Point (SX03328292) to Michaelstow (SX08007903). In parts of the epizone region there are areas in which IC values >0.21Δ°2Θ occur (Fig. 2). Detailed examination of these samples suggests that broadening of the 10Å peak has occurred as the result of mineralogical interferences on this peak.

When the contouring is undertaken at closely spaced intervals there are apparently localized areas in which the metamorphic grade supposedly shows rapid variations (Fig. 2a). Similar rapid variations in grade were also identified by Roberts and Merriman (1985) when IC data were closely contoured.

The general pattern of the IC results is supported by the mineralogical assemblages in the pelitic rocks. Within the anchizone the pelites consist predominantly of the 1M variety of illite, chlorite and minor quartz, while within the epizone the pelites consist largely of 2M illite, chlorite, minor feldspar and quartz, with occasional porhyroblasts of chloritoid and feldspar.

The transition from the anchizone to epizone conditions across the area is supported by the variation in metabasite assemblages. Characteristic biotite- and actinolite-bearing greenschist facies rocks of the Tintagel Volcanic Formation occur in the north, while occasional development of prehnite and pumpellyite in metabasites in the southern part of the region is suggestive of sub-greenschist facies conditions (Primmer 1985a,b).

Contact metamorphism

There is a detectable increase in IC towards the contact aureole of the granite in the south of the area where the anchizone/epizone boundary runs closely parallel to the granite margin (Figs 2 and 3). This effect is lost passing northwards into the epizone region which most probably reflects the decreasing sensitivity of the technique to increasing temperature within the epizone. The width of the contact aureole provides a good estimate of the general dip of the granite margin. In the granite aureole dark flinty hornfels (known as calc flintas (Reid *et al.* 1910)) reflect contact metamorphism of impure calcareous rocks. These are brittle, dense, frequently layered rocks, which are found extensively between Pencarrow (SX1082) and Helsbury (SX0980). The laminations are < 1 mm thick and in thin section are seen to comprise of interlayered diopside and albite-rich bands with minor quartz, iron oxides and white mica. The IC measured on these rocks suffer from peak broadening and may account for the positive IC anomalies around the northern margin of the granite (Fig. 2).

In the southern part of the Camelford area, south of Devil's Jump (SX0980), the granite margin is near vertical with a true width of the aureole estimated to be between 0.8 and 1km. The aureole widths appear less along the NW margin of the granite, e.g. St Clether (SX1983), but borehole information from Oldpark (SX16358277) shows the granite margin to be faulted and dipping 70-75 towards the north. Around the NW spur of the granite the aureole widens to 23km indicating a shallowing of the margin of the granite to 20-30° dip beneath the town of Camelford. A full description of the contact metamorphic rock types within the aureole is found in Warr (1990a).

Discussion

Regional metamorphic effects

The isocryst pattern with contours closely spaced at 0.025Δ°2Θ suggests a complicated pattern of rapid variation in metamorphic grade across the region (Fig. 2a). It is difficult to link any of these supposed variations in metamorphic grade with known features of the geology. This complicated pattern contrasts with the simplified gradation from upper anchizone into epizone metamorphic conditions from south to north across the area, seen where a wider contour interval is chosen (Fig. 2d). As shown earlier, the probabilities calculated for differing contour intervals, based on the statistical analysis of the IC technique of Robinson *et al.* (1990), show that the narrow contour intervals have low values (0.6 or lower), such that a majority of samples would not be expected to fall within the contouring intervals. The wider intervals of 0.075 and 0.1Δ°2Θ have high probabilities (0.8 or greater) such that the data meet a satisfactory level of confidence. On this basis it must be concluded that the patterns of rapid varying grade as depicted in Figs 2a and 2b do not represent actual changes in metamorphic conditions, but represent the problems that will arise when contouring intervals are chosen without reference to the precision of the data involved. It is evident from the IC results that there is a marked cross-cutting relationship between the isocrysts and the regional strike. This is clearly seen by tracing the epizone/anchizone boundary, which cuts obliquely across the regional D2 thrust boundary previously described (Fig. 3). As the

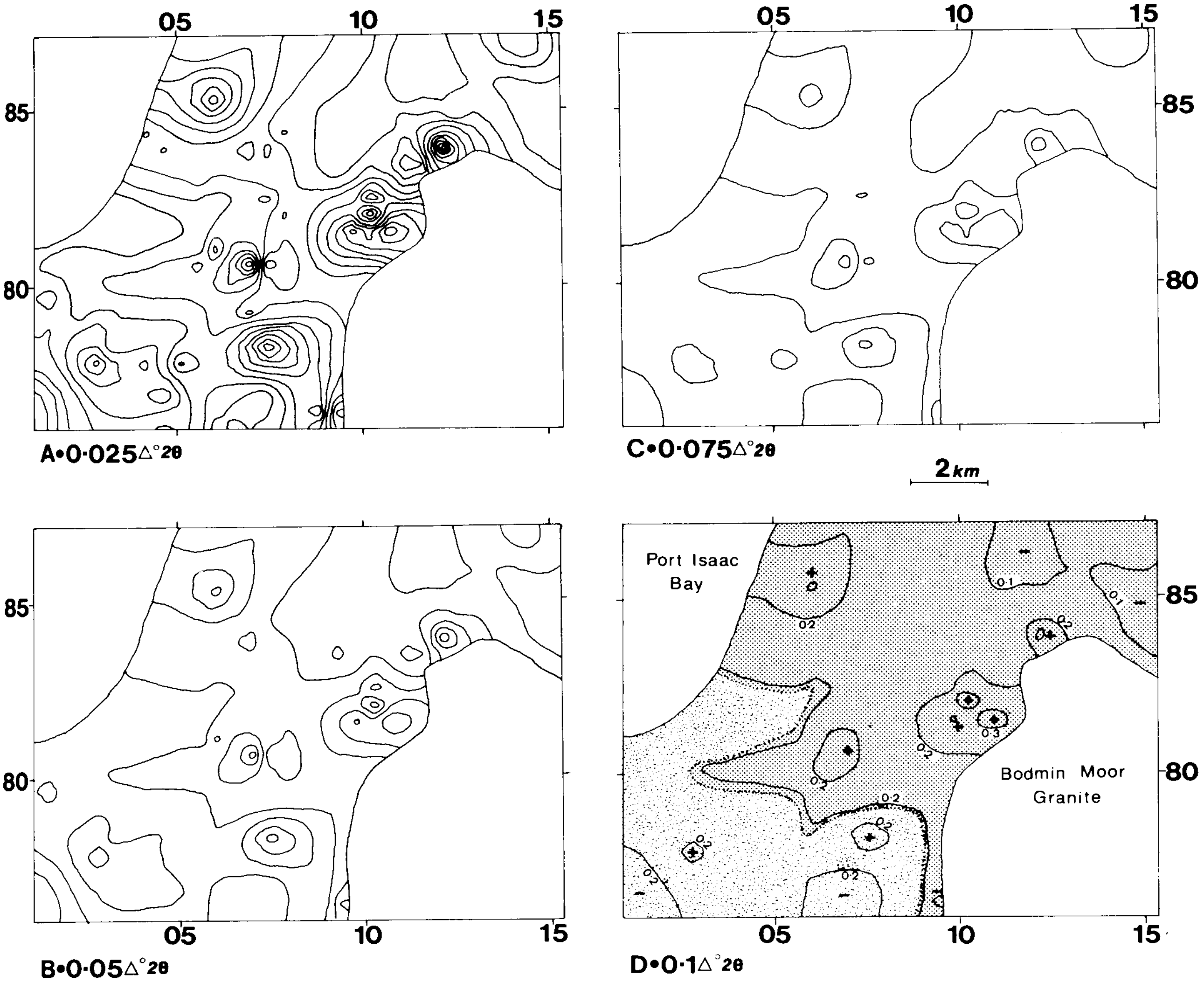

Figure 2. Contoured IC data (isocryst maps) of the Camelford area compiled using UNIRAS (UNIMAP) computer facility. (a) contour interval 0°025Δ°2Θ, (b) contour interval 0.05Δ°2Θ, (c) contour interval 0.075Δ°2Θ, (d) contour intervals 0.1Δ°2Θ. + = positive IC anomalies, - = negative IC anomalies.

IC pattern does not appear to be influenced by this structure the IC would seem to have been produced after any significant displacement along the thrust. Alternatively the displacement along this line may have been of insufficient magnitude to result in a detectable change in the metamorphic grade across the boundary. Further constraints can be placed on the timing of metamorphism within this area, which help to evaluate between these two alternatives. Petrological studies of the Tintagel Volcanic Formation indicate that peak greenschist facies metamorphism occurred synchronously with D1 and early D2 strains (Andrews *et al.* 1988; Pamplin 1988). From the trend of IC contours in relation to the thrusting it is suggested that the development of the IC occurred after D2 thrusting and could reflect a longer time period required to attain equilibrium.

There is no relationship between the pattern of regional metamorphism and the distribution of the Devonian intrusions and lavas, suggesting there is no association between the regional metamorphism and igneous development.

Regional perspective

Regional metamorphic grade in the Camelford area spans the anchizone/epizone transition, passing northwards into the Tintagel High Strain Zone. This increase in grade occurs structurally upwards into younger rocks, giving rise to an inverted metamorphic pattern. The IC results show the boundary between the anchizone and epizone to pass obliquely across the strike of the area (Fig. 3). This trend, however, runs parallel with the southern margin of the Culm Basin, marked by the Rusey Fault Zone. It is therefore suggested that the distribution of metamorphic grade was controlled by the backthrusting of Upper Carboniferous Culm rocks and not by the sequence of thrusting which the isocrysts overprint. This suggestion is consistent with the deformational history of the area (Warr 1989, in press), which involved D2 underthrusting of the southern margin of the Culm Basin some time during late Westphalian to earliest Stephanian times (Warr 1989). This event was accompanied by protracted heating within the underthrusting wedge giving rise to a localized M2 event. Resetting of the K-Ar dates (Dodson and Rex 1971) within this zone therefore reflect M2 cooling ages (refer to Warr in press, Fig. 8) and affect a 10-15km wide belt which runs parallel to the southern margin of the Upper Carboniferous Basin. The *P-T* history within the Tintagel High Strain Zone is well constrained (Primmer 1985a,b,c) with a synchronous M1/D1 event approaching greenschist facies temperatures, followed by an M2 event at higher temperatures (c. 500°C), but lower pressures. Finally there was a phase of retrograde metamorphism at temperatures of 200-300°C. This clockwise *P-T-t* path history is characteristic of thrust-related metamorphism, with rapid tectonic burial followed by thermal re-equilibration and subsequent exhumation.

In north Devon and to the south of the Tintagel High Strain Zone the variation in metamorphic grade through anchizone to epizone conditions appears to be broadly related to stratigraphical age. In a traverse

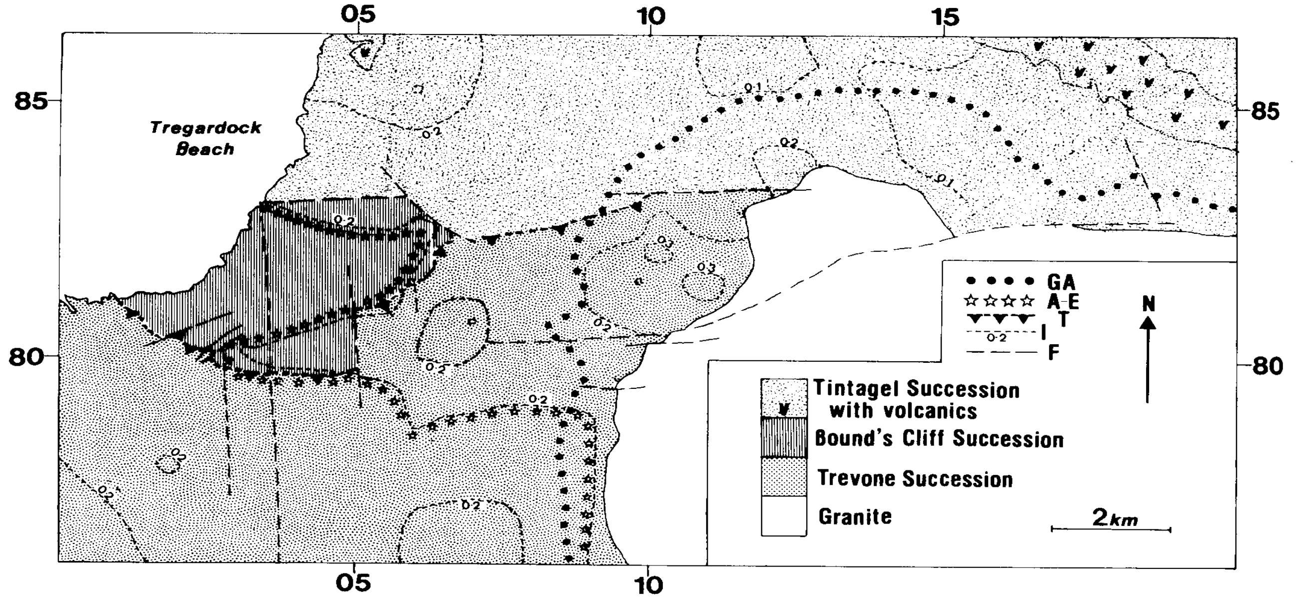

Figure 3. Summary geological map of the Camelford area (mapping by L. Warr, O. Smith and R. Clayton) in relation to the main isocryst values. GA =outer margin of the granite aureole, A-E = regional anchizone/epizone boundary, T = D_2 thrust fault, I= IC contours at 0.1 ° intervals, F = Fault.

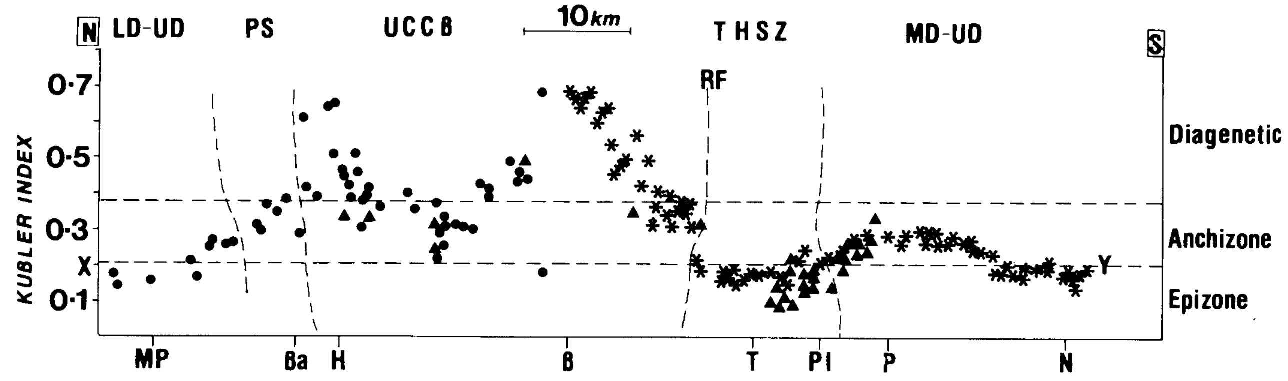

Figure 4. Summary of IC data across north Devon and north Cornwall amalgamating data from this work (triangles), Primmer (1985b; represented as stars) and Kelm (19K8; represented as (lots). LD-UD = Lower Devonian to Upper Devonian, PS = Pilton Shale, UCCB = Upper Carboniferous Culm Basin, THSZ = Tintagel High Strain Zone, MD-UD = Middle Devonian to Upper Devonian, MP = Morte Point, Ba = Barnstaple, H = Hartland Point, B = Bude, T = Tintagel. PI = Port Isaac, P = Padstow, N = Newquay. For position of X-Y traverse refer to Fig. 1.

from north to south across north Devon, there is an increase in metamorphic grade from Lower Devonian to Upper Carboniferous strata (Kelm 1986, 1988; Kelm and Robinson 1989) (Fig. 4). A correlation between grade and stratigraphy also appears in the Padstow area where IC decreases towards the core of the St Minver Syncline (Primmer 1985a, Fig. 1; Pamplin 1988, Fig. 3.12). This structure is considered to represent a south-facing F1 syncline (Durning 1989: Warr and Durning 1990) involving rocks of Middle Devonian (Givetian) to Upper Devonian (Famennian) age. Both these areas are characterized by Namurian cooling ages (Dodson and Rex ! 971) and are suggested by Warr (in press) to represent the age of the regional D1 basin inversion. A diastathermal (extensional) model (Robinson 1987: Robinson and Bevins 1989) may well be applicable to the M1 metamorphism of the Rhenohercynian of SW England (Warr in press) in which a high thermal flux developed during crustal thinning and was maintained during regional (D1) basin inversion. This hypothesis however remains to be tested.

Conclusions

Close contouring (0.025Δ°2Θ) of IC data results in isocryst patterns which are indicative of apparently rapidly varying grade. Such patterns are lost when the data are contoured at an interval (0.1Δ°2Θ) that allows for a high degree of confidence in the results being representative of the actual contoured value.

The IC survey of the Camelford area shows the boundary between the anchizone and epizone to pass obliquely across the regional strike with no perceivable relationship to the D2 thrusting which affected the area. This variation in metamorphic grade is attributed to backthrusting of the Culm rocks which would have overlain the area during the regional D2 thrusting phase. This thrust load has given rise to an inverted metamorphic pattern with increasing grade towards the NE in passing structurally upwards into younger rocks. Interestingly there is a continuous increase of metamorphic grade through the Upper Carboniferous rocks south of Bude, into the Lower Carboniferous/Upper Devonian successions of the Tintagel High Strain Zone (Fig. 4).

The high temperatures attained around the margin of the Bodmin Moor granite have increased IC values within areas of anchizone grade (Fig. 4). It is therefore deduced that the time and temperature was sufficient to cause restructuring of the illite within the contact aureole of the granite.

The increase of metamorphic grade towards the north of the area resulted from an M2 metamorphic event which was associated with underthrusting of the Culm Basin. The metamorphic history of the Tintagel High Strain Zone is one of a clockwise *P-T-t* path (Primmer 1985b) which is characteristic of thrust-related metamorphism. The

M1 metamorphism (as defined by Warr in press) seen in north Devon and to the south of the Tintagel High Strain Zone appears to be broadly related to stratigraphy. A diastathermal (extensional) model (Robinson 1987; Robinson and Bevins 1989) for the heat source may well be applicable.

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