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Low-grade metamorphism and accretion tectonics: Southern Uplands terrain, Scotland

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ABSTRACT. Previous studies of low-grade metamorphism in the Southern Uplands accretionary terrain indicated prehnite-pumpellyite facies/anchizone conditions developed throughout the area, except for local preservation of trench-slope sediments and an accreted seamount at zeolite facies/advanced diagenetic grade. New graptolite reflectance data are presented that show a general northward increase in temperature in the Southern Uplands. The results from two cross-strike traverses in the southern and central belts in contemporaneous sequences, using illite crystallinity, illite lateral spacing (b_0), and graptolite reflectance, indicate the development of systematic accretion-related low-grade metamorphism. Well-developed and constant anchizone conditions occur throughout the NE (Langholm) traverse, associated with common, F1 accretion-related folding and a regionally penetrative S1 cleavage. In the SW (Kirkcudbright) traverse, however, the youngest, last accreted packets are preserved at a transitional diagenetic stage and lack a penetrative S1 cleavage. Illite crystallinity, graptolite reflectance, and b_0 increase systematically northward through earlier accreted packets, reaching values of the NE traverse only at the northern end. The concomitant increase of b_0 with illite crystallinity suggests the relatively high P–low T trajectory characteristic of subduction zones. Integration of metamorphic and structural data relates increasing intensity of accretion-related F1 folding, development of S1 fabric, and onset of later fold phases to grade of metamorphism and structural level within the accretionary pile.

KEYWORDS: metamorphism, low-grade, illite, graptolite, Southern Uplands, Scotland.

IN this paper new regional graptolite reflectance results are presented for the Southern Uplands, together with a case study of the Southern belt (fig. 1), where new mapping and a detailed assessment of low- grade metamorphism allows the correlation of metamorphic grade to structural level and deformation intensity within the accretionary pile.

During the Ordovician and Silurian, the Southern Uplands–Longford Down terrain (fig. 1) appears to have occupied a fore-arc position at the northern margin of the Iapetus Ocean (Leggett *et al.*, 1979). The association of ocean-floor basalt, Fe-rich mudstones, cherts, and graptolitic shales, followed in sequence by trench sediments, has led to the hypothesis that the terrain evolved by progressive accretion during northward subduction of the Iapetus Ocean under Laurasia. Subduction–accretion commenced in the early Ordovician and persisted for some 40 Ma until the middle Silurian. Progressively younger packets of trench and oceanic sediments (between 0.5 and 5 km thick) were accreted such that, although the strata are usually young to the northwest, the packets or tracts become younger to the southeast. The youngest strata present are of Wenlock (C. lundgreni zone) age (see below). The boundaries between the tectonostratigraphic units are zones of intense imbrication of basalt, Fe-rich mudstone, chert, graptolitic shales, and trench greywackes in the northern belt, imbrications of chert and graptolitic shales in the central belt, whilst in the southern belt the imbrication occurs within the trench turbidites (see below). This accretionary prism is perhaps unique in that stratigraphical control, greywacke petrography, and sedimentary facies associations allow individual tracts, in many cases corresponding to accreted packets, to be traced for over 300 km along strike between Scotland and Ireland.

Regional prehnite–pumpellyite facies metamorphism in Ireland in metabasalts and metagreywackes in the Longford Down Massif was first described by Oliver (1978). Oliver and Leggett (1980) established the same grade of metamorphism in the Southern Uplands. Hepworth *et al.*

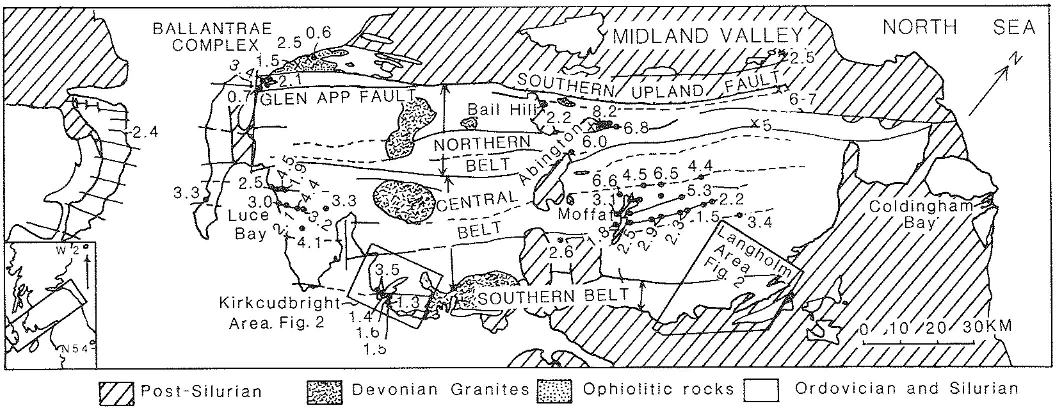


FIG. 1. Geological map of the Southern Uplands and part of Co. Down showing the various tracts of the accretionary prism (after Leggett *et al.*, 1979). + = conodont colouration indexes (Bergstrom, 1980); • = R_o = mean of maximum graptolite reflectance, including data from Watson (1976) and Hepworth (1981).

(1982) reported zeolite facies metamorphism in the Bail Hill Volcanic Group, which they interpreted as an accreted seamount. Diagenetic grade alteration was also documented in the Coldingham Beds on the Berwickshire coast and Casey (in Oliver *et al.*, in press) has interpreted these as remnants of inner trench-slope sediments down-faulted into accreted material. Oliver *et al.* (in press) have presented a synthesis of regional metamorphism in the Southern Uplands and adjacent areas, using data from Na-Ca-Al silicates, clay minerals, and conodont colouration. These studies have confirmed the regional extent of prehnite-pumpellyite facies metamorphism in the northern and central belts of the Southern Uplands. In the southern belt the lack of Ca-Al silicates has restricted the study of low-grade metamorphism to clay mineralogy and graptolite reflectance. Initial work indicated the local presence of diagenetic grade material in the southern belt and the detailed study reported here was instigated to establish the character of this occurrence and its relationship to the regional structure and tectonics.

First, new regional graptolite reflectance data are presented then an account is given of the detailed studies in the Kirkcudbright area.

Regional graptolite reflectance studies

Measurement of graptolite reflectance as a parameter of metamorphic grade was first used by Watson (1976). The methods used here are those recommended by the British Standards Institution (1981) for measuring vitrinite reflectivity. Between 10 and 50 measurements were taken in oil for each polished graptolite cut parallel to bedding. Errors in precision and accuracy are not large enough to affect the conclusions reached here, e.g. Watson (1976) measured the maximum reflectivity over a large graptolite fragment with the following results: number of measurements, 135; mean (R_o max.), 4.12%; mode, 4.17%; standard deviation, 0.19; variance, 0.04; minimum, 3.66%; maximum, 4.59%. The statistics for single measurements of fifty-three separate graptolite fragments in the same sample are: mean, 4.00%; mode, 4.18%; standard deviation, 0.39; variance, 0.15; minimum, 3.20%; maximum, 4.89%. Much of the variation is probably related to the quality of polish.

Watson (1976) demonstrated increasing reflectance of graptolite fragments towards dykes and plutons, suggesting that temperature is the primary control on reflectance. Like vitrinite, it must be assumed that the time and pressure are also important factors, the influence of the latter being unpredictable on the maximum reflectance and the degree of anisotropy (e.g. Chandra, 1965; Paproth and Wolf, 1973). However, preliminary results from Wales (Oliver, unpubl. data) show graptolite reflectivity values of 0.5–0.7% R_o max. for the Welsh Borderland (where conodont colour alteration index vary from 1 to 2.5, i.e. $< 140\,°C$) and reflectance values of up to 4.4% R_o max. in the Welsh Basin where conodont colour alteration indexes ranging up to 5 (i.e. 300 to 400 °C).

New reflectivity data for the Southern Uplands is plotted on fig. 1, together with the data of Watson (1976) and Hepworth (1981) and in Craig (fig. 6.14, 1983). There is a general increase in reflectivity values (and therefore temperature) from south to north (similar to meagre data from conodont colouration, Oliver *et al.*, in press).

Interestingly, the sample from the Bail Hill Volcanic Group has a much lower reflectivity (2.2% R_0 max.) than the Abington graptolites (8.1% R_0 max.). This is compatible with the zeolite facies mineralogy of the Bail Hill Volcanic Group (Hepworth *et al.*, 1982) and the prehnite-pumpellyite facies mineralogy of the Abington spilites (Oliver and Leggett, 1980). Results from these Ordovician graptolites suggest that the boundary between the zeolite and prehnite-pumpellyite facies is at about 2.5% R_0 max. reflectivity. Coincidentally, Kisch (1974) defines the boundary between the zeolite and prehnite-pumpellyite facies as vitrinite reflectance 3.0% R_0 max.

The results of graptolite reflectance data show that the regional metamorphic grade of the Southern Uplands appears to increase northwards. The significance of this is discussed in the conclusions below.

Southern belt

Tectonic stratigraphy. New detailed mapping in the southern belt of the Southern Uplands by one of us (A.E.S.K.) was centred on two cross-strike traverses through rocks of the same age, one in the Kirkcudbright area and the other some 90 km NE along strike in the Langholm area (figs. 1, 2). This has identified at least six distinct tectono-stratigraphic units corresponding to accreted packets, (figs. 3, 4).

The last three tectonostratigraphic units in the Kirkcudbright area (figs. 3, 4, 5) are internally coherent, with infrequent folding within units and major deformation generally confined to discrete zones of intense folding and boudinage between units. The older units, however, are cut by several major internal bedding sub-parallel faults and sheared and folded zones. Biostratigraphic control is not sufficiently refined in these older units to resolve accreted packets. Furthermore in the Upper Llandovery unit (Hawick Rocks, figs. 3, 4) biostratigraphic and sedimentological evidence indicate at least a tenfold tectonic thickening. Whilst the tectonic units are subvertical in the Kirkcudbright area they are overturned in the Langholm area (figs. 5, 6).

Structure. The first and only regionally pervasive

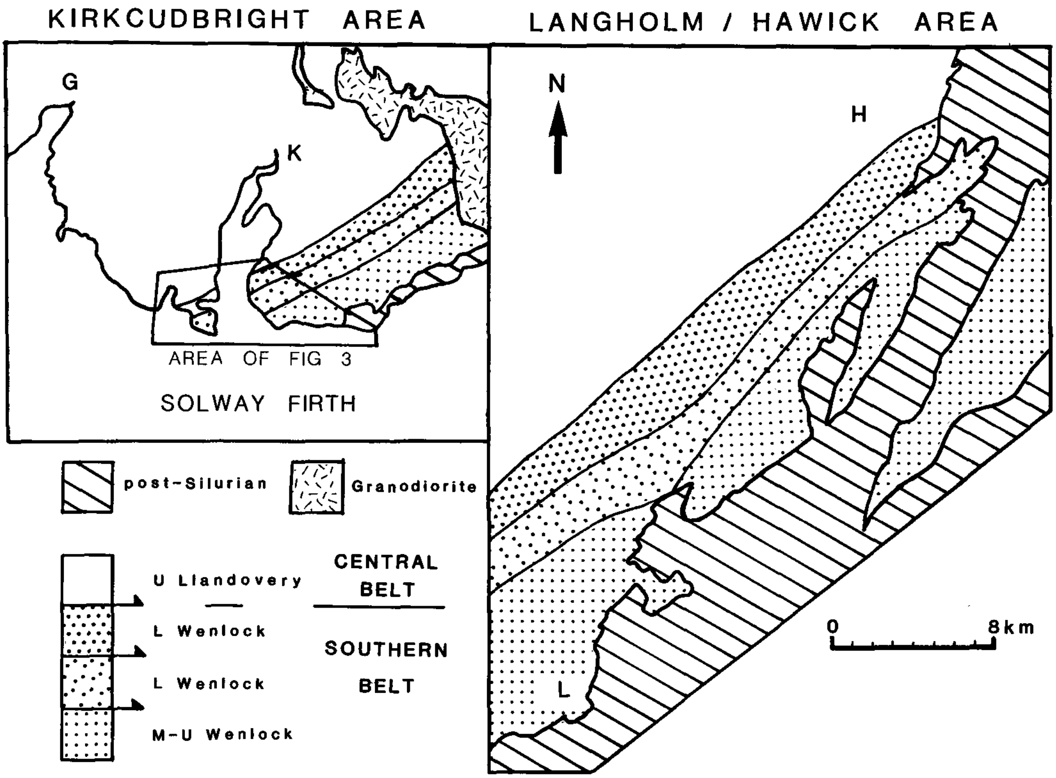


FIG. 2. Synoptic maps showing the two traverse areas: G, Gatehouse of Fleet; K, Kirkcudbright; H, Hawick; L, Langholm.

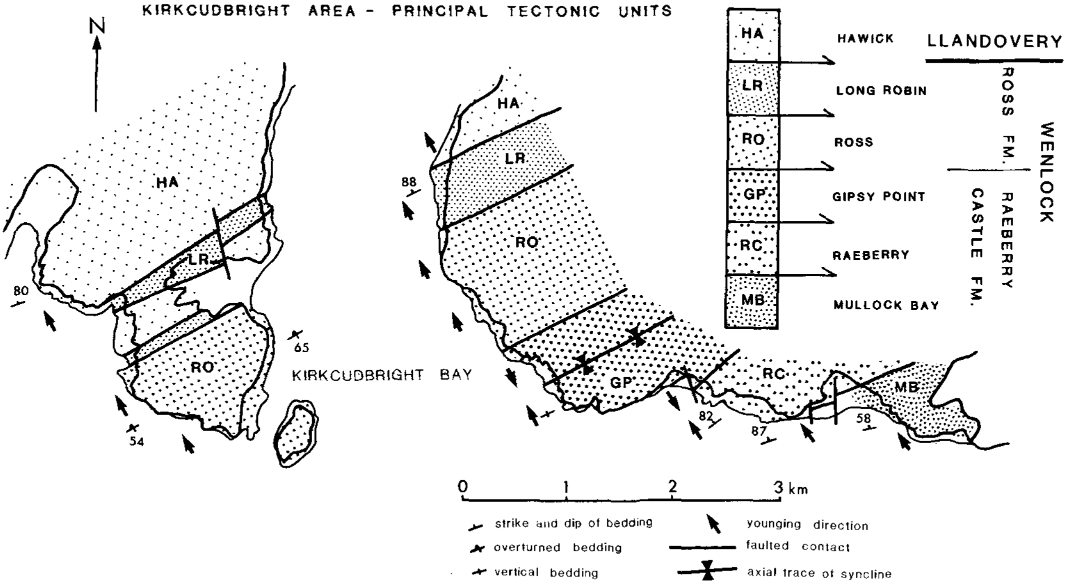


FIG. 3. Detailed map of southern section of Kirkcudbright area showing disposition of tectonic units.

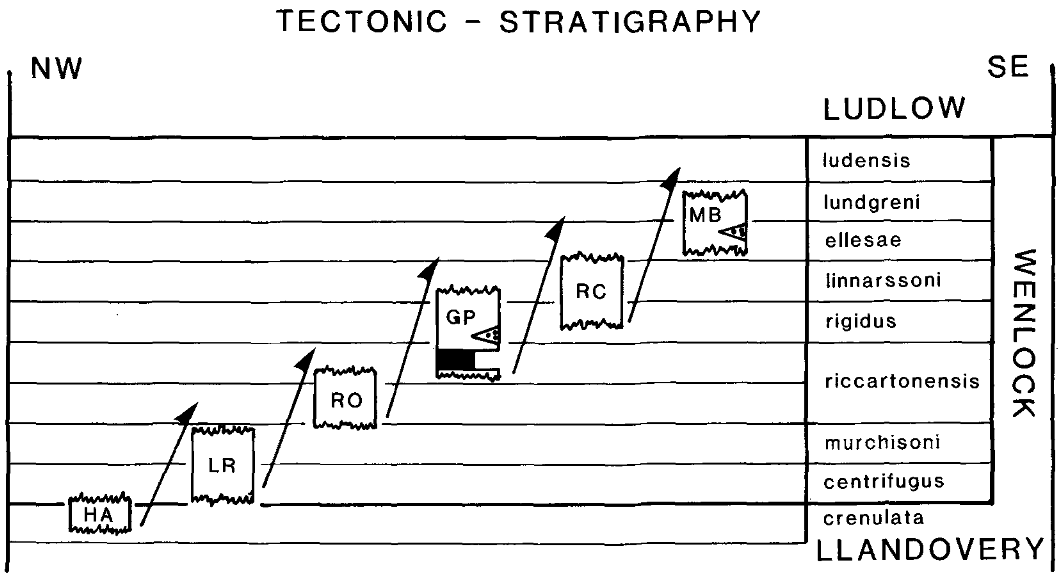


FIG. 4. Stratigraphic diagram showing age ranges of different accreted units with sense of overthrusting. Abbreviations as in fig. 3. The Raeberry Castle Formation is now known to be of Wenlock and not Llandovery age (Kemp and White, in press).

fold phase in the Southern Uplands/Longford-Down terrain, F1, comprises typically SE-verging anticline-syncline fold pairs and is consistent with SE-directed overthrusting during progressive accretion (Anderson and Cameron, 1979; Stringer and Treagus, 1981). In the Upper Llandovery and Wenlock rocks of the central and southern belts, F1 is associated with a regionally penetrative cleavage (S1) which transects fold axial planes (Stringer and Treagus, 1980). Later minor folding (F2 and F3) is

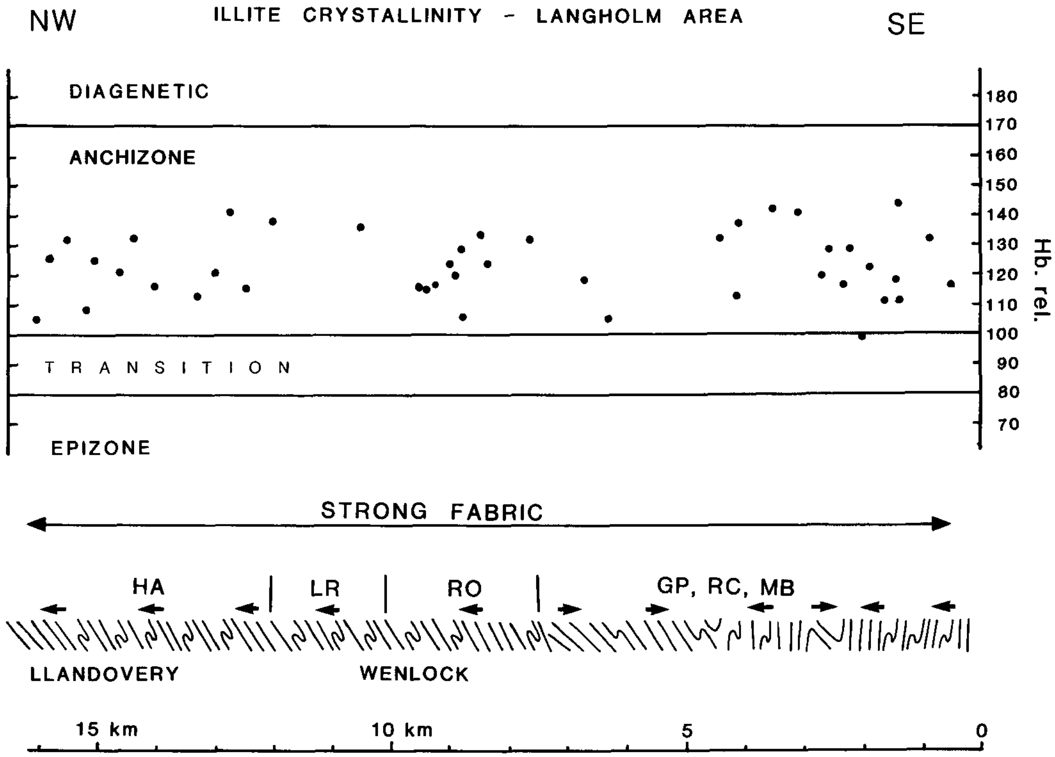


FIG. 5. Illite crystallinity values for Langholm traverse with synoptic structural section. A broad transition is indicated at the anchizone/epizone boundary as Hb. rel. values < 100 occur in prehnite-pumpellyite-bearing sediments elsewhere in the Southern Uplands (Oliver *et al.*, in press). These low values may be due to detrital micas and the true boundary is probably near 100 Hb. rel.

only locally developed and in the hinges of late folds S1 may be crenulated (Cameron, 1981). These minor, later fold phases are of uncertain origin.

In the Langholm traverse F1 folding and S1 cleavage occur uniformly throughout (fig. 5). However the youngest (last) accreted packets in the Kirkcudbright traverse lack a penetrative cleavage with only a compaction fabric present (fig. 9) and F1 folding is less frequent. The S1 cleavage develops and increases in intensity northwestward (fig. 10) and F1 folding becomes more common.

The results of the structural studies raise a significant problem in that the last (youngest) accreted packets in the southern belt of the Kirkcudbright area (fig. 3) were found to represent the least deformed sediments in the Southern Uplands, lacking a penetrative cleavage and with only rare folding. This is in apparent contradiction to models such as that of Phillips *et al.* (1979) which propose an increase in deformation intensity and number of fold phases towards the Iapetus suture.

The objective of the metamorphic studies was therefore to shed light on the structural history of this region.

Mineralogy. X-ray diffraction studies show that the mudstones comprise dominantly illite, chlorite, quartz, and albite. The interbedded fine to very fine grained turbidite greywacke or calcareous sandstones contain mainly quartz, albite, and K-feldspar and varying amounts of carbonate as bioclastic material, micritic and sparry fragments, and cement with minor illite and chlorite as matrix. Because of the compositionally mature nature and variable carbonate content of the sandstones, studies of low-grade metamorphism were necessarily confined to the mudstones.

Methodology. In the Langholm area samples for illite crystallinity and b_0 analysis were collected over a 15 km wide by 16 km cross strike traverse area. In the Kirkcudbright area, samples were collected over a 0.5 km wide by 13 km cross strike traverse area at intervals between 50 and 150 m. In all cases the finest grained Te muds were sampled to minimize the occurrence of detrital micas (where

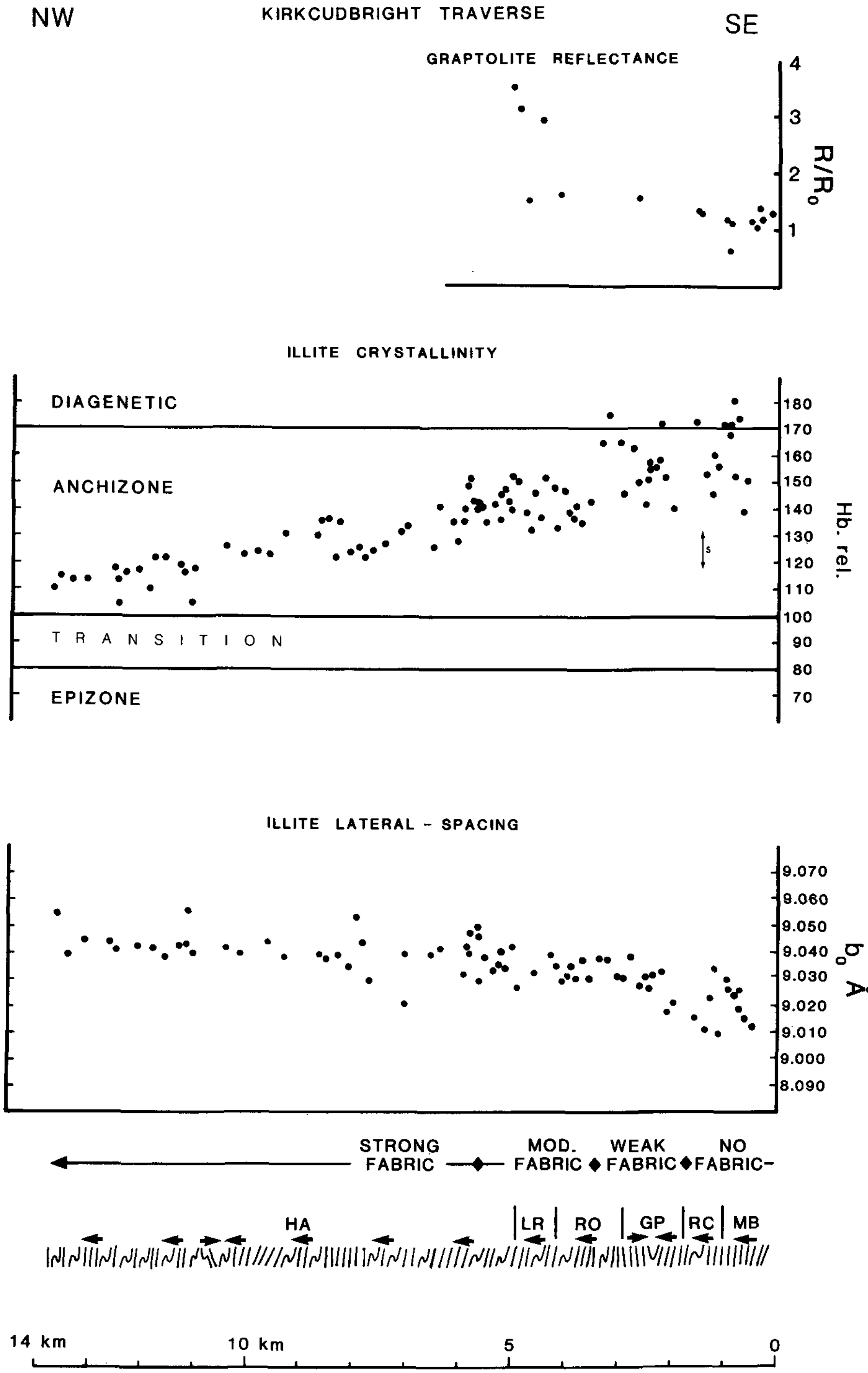


FIG. 6. Kirkcudbright traverse: lower plot, b_0; middle plot, illite crystallinity; top plot, graptolite reflectance, R_0 max. One standard deviation indicated on right of illite crystallinity plot.

siltstones were analysed, higher crystallinity values were obtained). Samples were ground in a Tema for 10 seconds, placed in an ultrasonic bath for 10 min., then separated into 2–6 μm and < 2 μm size fractions. Illite crystallinity was measured on sedimented samples using the method of Weber (1972*a*, *b*). For each sample, the illite peak was scanned five times and the quartz reference peak three times. Analysis was undertaken on a Phillips PW 1010 diffractometer with Cu-$K\alpha$ radiation at 40 kV, 20 mA, using 1° divergence slits and run at a scan speed of half a degree 2θ/minute and sensitivity of 4×10^2. Standard deviations (shown in fig. 6) were assessed by repeated measurements of the same sample and by measurements of samples prepared from different parts of the same hand specimen. Results shown in the text figures are based on the 2–6 μm fraction. The < 2 μm fraction had up to 20% higher Hb. rel. values (lower crystallinity) for the transitional diagenetic samples but essentially the same values as those of the 2–6 μm fraction in the mid-anchizone, supporting the conclusions of Weber (1972*a*, *b*).

Illite crystallinity. In the Langholm area (fig. 5), no stystematic variation is present in crystallinity values and the regional average is 125 Hb. rel. corresponding to middle anchizone conditions. These relatively constant crystallinity values are associated with a regionally penetrative S1 cleavage and common F1 folding throughout the area. The greater scatter than for mid-anchizone grade in the Kirkcudbright traverse (fig. 6) is due to variation along the broader (15 km) strike width of the Langholm traverse.

In the Kirkcudbright area (fig. 6), illite crystallinity values increase from mean Hb. rel. values of 161 in the youngest, most south-easterly block, to 114 at the north-western end of the traverse corresponding to a north-westward increase, from transitional diagenetic to advanced anchizone conditions. The distribution of crystallinity values (fig. 6) indicates that this increase is apparently systematic, so that, although mean Hb. rel. values differ from one tectonostratigraphic unit to the next, the values of adjacent units are not statistically different. The broad scatter of crystallinity values at the low-grade end probably reflects greater variation at lower temperatures. Illite poly-

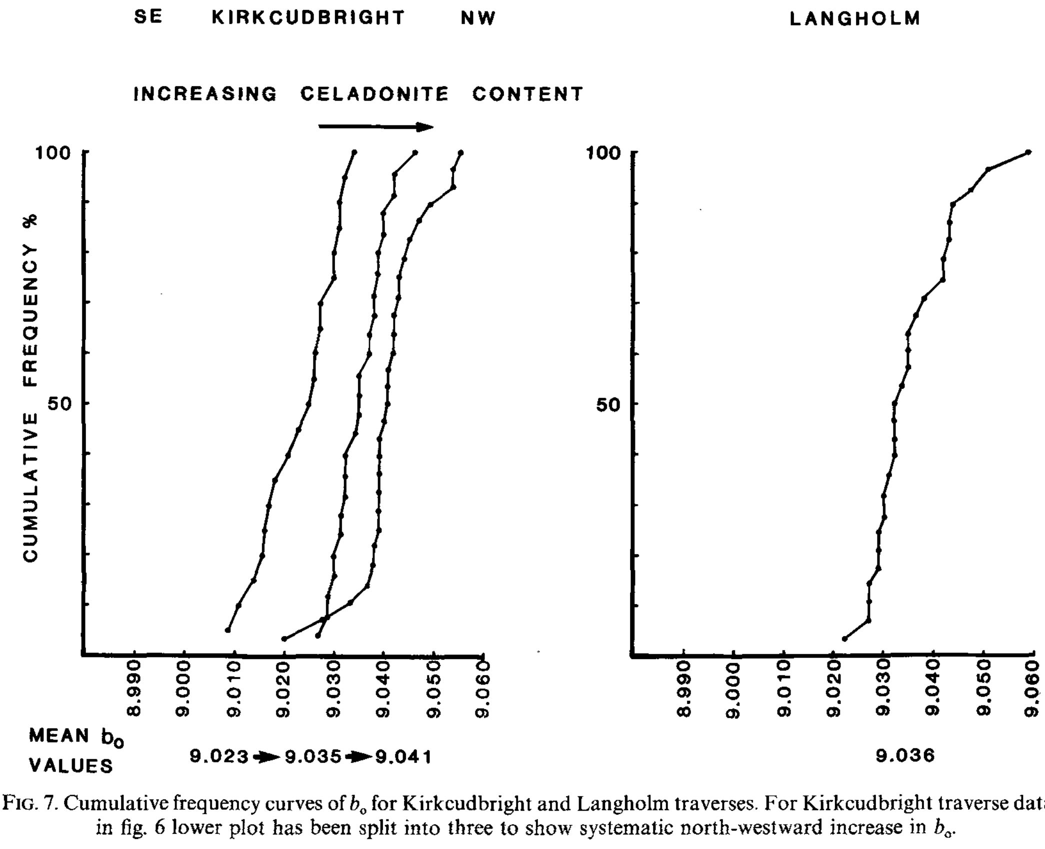


FIG. 7. Cumulative frequency curves of b_0 for Kirkcudbright and Langholm traverses. For Kirkcudbright traverse data in fig. 6 lower plot has been split into three to show systematic north-westward increase in b_0.

morph studies, using the method of Maxwell and Hower (1967), indicate the presence of over 50% 1*Md* structure in the SE while in the NW, the 2*M* structure is dominant. The increase in illite crystallinity is associated with a gradual north-westward development and increase in intensity of the S1 cleavage (figs. 9, 10). Additionally from kilometer 9 north-westward, S1 is locally crenulated in hinges of post-F1 folds (fig. 11). The increase of cleavage and general deformation intensity with illite crystallinity could be related either to a temperature increase during progressive deformation or merely result from the effect of dynamic recrystallization associated with deformation at constant temperature.

Graptolite reflectance. Graptolite reflectance data from the Kirkcudbright area (fig. 6), confined to the Wenlock rocks in which organic carbon is preserved, confirms a northward increase in temperature associated with increasing illite crystallinity values.

Illite lateral spacing (b_o). The lateral spacing of K-white micas (b_o), which is a measure of celadonite content, is dependent on pressure, temperature, and composition (Velde, 1965, 1967) and has been used to characterize facies series and *P–T* gradients (Sassi and Scolari, 1974). More recently this method has been extended to anchizonal material (Kisch and Padan, 1981).

In the Langholm area, the mean illite lateral spacing is 9.036 Å and does not vary markedly (figs. 6, 7). In the Kirkcudbright area illite lateral spacing values increase systematically to the northwest from mean values of 9.023 Å in the SE to 9.041 Å in the NW (figs. 5, 7). The illite crystallinity and graptolite reflectance values for the Kirkcudbright traverse show a systematic increase in temperature to the NW. The lack of variation of lateral spacing in the Langholm traverse in mudstones of the same age and identical facies to those in the Kirkcudbright traverse (providing a compositional control) suggest that the variation in lateral spacing in the Kirkcudbright traverse represents a northward increase in pressure. The studies of Velde (1965, 1967) suggest that with a normal geothermal gradient, celadonite content (lateral spacing) should remain constant or decrease with increasing temperature for a given composition. The increase in celadonite content with temperature increase (fig. 6) suggests a relatively high *P*, low *T* trajectory which would be expected for subduction zone metamorphism.

Discussion

The overall variation in temperature and pressure indicated above is best explained by the exposure at the present erosional surface of rocks which descended to different structural levels within the accretionary pile. A northward passage into progressively deeper structural levels in the Kirkcudbright area (indicated by increasing illite crystallinity, celadonite content and graptolite reflectance) is associated with increasing development of cleavage, an increase in intensity of folding and from km 7, local refolding of F1, and crenulation of S1. Hence, the intensity of deformation and occurrence of post F1 folding appears to be related to structural depth and not to proximity to the Iapetus suture as proposed by Phillips *et al.* (1979).

The preservation of different structural levels in the two traverse areas probably relates to differential slip along original accretionary fault zones during rotation and uplift caused by progressive accretion (fig. 8) and/or the impingement of the Lake District arc terrain on the subduction zone in late Wenlock or early Ludlow times (Leggett *et al.*, 1983). The contrast between the two traverses may be explained by invoking bulk rotation without slip between packets in the Langholm area such that

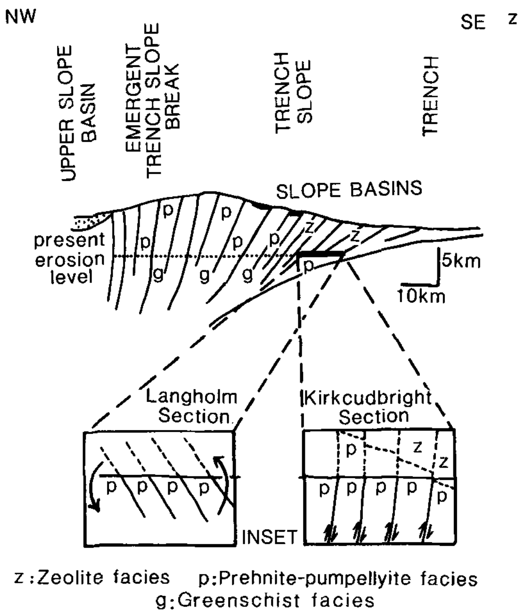


FIG. 8. Schematic cross-section of the Southern Uplands in late Wenlock times showing disposition of accreted units and metamorphic grades. INSET: present-day outcrops at Langholm and Kirkcudbright—bulk rotation of packets at Langholm may have occurred without slip between packets, thus exposing only prehnite-pumpellyite (anchizone) facies. Differential slip at Kirkcudbright has juxtaposed prehnite-pumpellyite facies (anchizone) rocks against zeolite facies (diagenetic zone) rocks.

the present erosional level exposes only anchizone-grade rocks (fig. 8). In the Kirkcudbright area, differential slip between and/or within packets during rotation to the vertical has juxtaposed advanced anchizone-grade rocks against progressively lower-grade rocks to the southeast (fig. 8). The systematic increase in crystallinity values in the Kirkcudbright traverse suggests that slip was distributed fairly evenly and that no one fault surface was exploited to the exclusion of others.

The restriction of significant deformation in the higher structural levels to boundaries between accreted packets accords well with recent evidence from present-day accreting margins, where high pore fluid pressures suppress penetrative deformation during early accretion (von Huene and Lee, 1983). Progressive de-watering, which would accompany the descent to deeper levels, would favour a change in deformation mechanisms from grain boundary sliding to pressure solution. The development of cleavage only at lower structural levels after the initiation of folding suggests that this time lag may be responsible for the non-coplanar nature of the cleavage and consequently that non-coaxial deformation occurred during descent to lower structural levels within the accretionary pile.

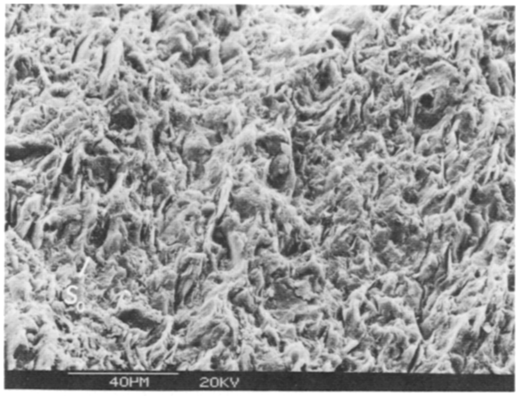
Conclusions

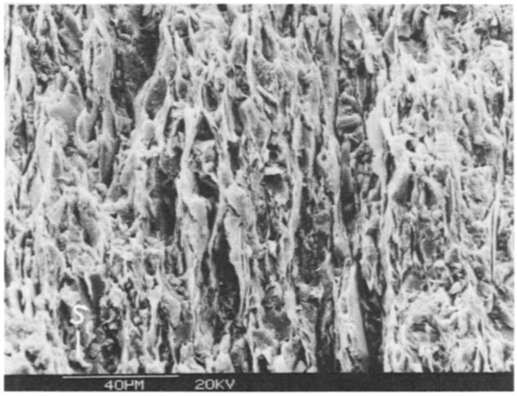
1. Deformation intensity in the Southern Uplands terrain is related to structural depth within the accretionary complex. More intense deformation and cleavage formation generally occurs at relatively deeper structural levels. The development of cleavage appears to coincide with the onset of anchizone conditions (cf. Kisch, 1983). Accreted packets preserved at higher structural levels show little internal deformation and relatively low-grade metamorphism.

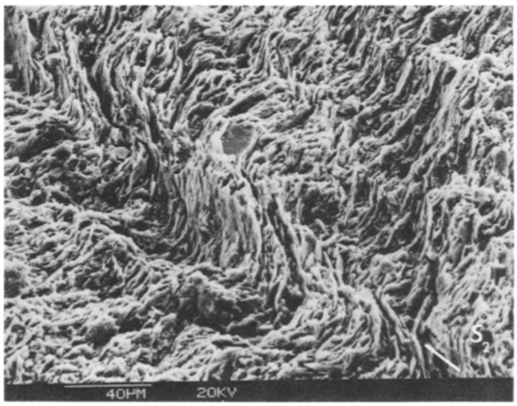
2. The grade of metamorphism in the Southern Uplands generally increases from SE to NW. This confirms evidence that the earliest accreted packets underwent the greatest uplift, having formed an emergent trench-slope break (Cockburnland) from the Upper Llandovery, Walton (1965). However, the special circumstances of the Bail Hill Volcanic Group, namely its topopography, prevented its accretion to deeper levels, thus preserving its zeolite facies metamorphism.

3. Large numbers of samples, close sample spacing and consistent lithology are required for detailed studies of low-grade metamorphism in structurally complex paratectonic areas.

4. Graptolite reflectance is a useful parameter for assessing low-grade metamorphism. It is probably more sensitive than conodont colour alteration.







FIGS. 9–11. Scanning electron micrographs. FIG. 9 (*top*). S_0 compaction fabric from km 1.1 of Kirkcudbright traverse. FIG. 10 (*centre*). S1 cleavage from km 6.3 of Kirkcudbright traverse. FIG. 11 (*bottom*). S2 crenulation of S1 cleavage from km 11.9 of Kirkcudbright traverse.

5. To date, there have been few studies of low-grade metamorphism within ancient accretionary complexes. The results of this study show that these can be a powerful tool to complement

structural work and aid interpretation of the accretionary process.

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REFERENCES

Anderson, T. B., and Cameron, T. D. J. (1979) In *The Caledonides of the British Isles—reviewed.* (A. L. Harris, C. H. Holland, and B. E. Leake, eds.). Geol. Soc. Lond. Spec. Publ. **8,** 263–7.

Bergstrom, S. M. (1980) *Geol. För. Stockh. Förh.* **102,** 377–92.

British Standards Institution (1981) *Petrographic analysis of bituminous coal and anthracite.* Part 5. *Method of determining microscopically the reflectance of vitrinite.* BS 6127, 1–7.

Cameron, T. D. J. (1981) *J. Earth Sci. R. Dublin Soc.* **3,** 53–74.

Chandra, D. (1965) *Econ. Geol.* **60,** 621–30.

Craig, G. Y. (1983) *The Geology of Scotland.* 2nd edn. Scottish Academic Press, Edinburgh.

Hepworth, B. C. (1981) Unpubl. Ph.D. thesis, University of St Andrews.

——Oliver, G. J. H., and McMurtry, M. J. (1982) In *Trench Fore Arc Geology* (J. K. Leggett, ed.). Spec. Pub. Geol. Soc. Lond. **10,** 521–34.

Kemp, A. E. S., and White, D. E. *Geol. Mag.* (in press).

Kisch, H. J. (1974) *Proc. K. Ned. Akad. Wet,* Amsterdam, B, **77,** 81–118.

——(1983) In *Diagenesis in Sediments and Sedimentary Rocks,* **2** (G. Larsen and G. V. Chilingar, eds.). Elsevier, Amsterdam, 289–493.

——and Padan, A. (1981) *Terra Cognita* **1,** 54–5.

Leggett, J. K., McKerrow, W. S., and Eales, M. H. (1979) *J. Geol. Soc. Lond.* **136,** 755–70.

————and Soper, N. J. (1983) *Tectonics* **2,** 187–218.

Maxwell, D. T., and Hower, J. (1967) *Am. Mineral.* **52,** 843–57.

Oliver, G. J. H. (1978) *Nature,* **274,** 242–43.

——and Leggett, J. K. (1980) *Trans. R. Soc. Edinburgh, Earth Sci.* **71,** 235–46.

——Smellie, J. L., Thomas, L. J., Casey, D. M., Kemp, A., Evans, L. J., Baldwin, J. R., and Hepworth, B. C. (1984) Ibid. **75,** 245–58.

Paproth, E., and Wolf, M. (1973) *Geol. Palaeontol.* **8,** 469–93.

Phillips, W. E. A., Flegg, A. M., and Anderson, T. B. (1979) In *The Caledonides of the British Isles—reviewed* (A. L. Harris, C. H. Holland, and B. E. Leake, eds.). Geol. Soc. Lond. Spec. Publ. **8,** 257–62.

Sassi, F. P., and Scolari, A. (1974) *Contrib. Mineral. Petrol.* **45,** 143–52.

Stringer, P., and Treagus, J. E. (1980) *J. Struct. Geol.* **2,** 317–31.

————(1981) *Scot. J. Geol.* **17,** 129–48.

Velde, B. (1965) *Am. J. Sci.* **263,** 886–913.

——(1967) *Contrib. Mineral. Petrol.* **14,** 250–8.

von Huene, R., and Lee, H. (1983) *Mem. Am. Assoc. Petrol. Geol.* **34,** 781–92.

Walton, E. K. (1965) In *The Geology of Scotland* (G. Y. Craig, ed.). Oliver and Boyd, Edinburgh, 161–227.

Watson, S. W. (1976) Unpubl. Ph.D. thesis, Univ. St Andrews.

Weber, K. (1972*a*) *Neues Jahrb. Mineral. Monatsh.* 267–76.

——(1972*b*) *Neues Jahrb. Geol. Palaeontol. Abh.* **141,** 333–63.

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