An excursion guide to areas of very low grade metamorphism in the Lake District and the Rhinns of Galloway

R.J. Merriman, N.J. Fortey and B. Roberts

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Introduction

As a contributor to BGS Core Programme surveying in Lower Palaeozoic slate terranes in the British Isles, the Mineralogy and Petrology Group has carried out extensive surveys of very low grade metamorphism (VLGM) in metasedimentary rocks. An important, integral part of this work has been the continued collaboration of Dr Brin Roberts of the University of London and his colleagues Patrick Daly and Steve Hirons.

During 1989 the International Geological Correlation Programme established Project 294 on "Very Low Grade Metamorphism". The first conference of this project, entitled "Phyllosilicates as indicators of very low grade metamorphism and diagenesis" was held in July 1990 at the University of Manchester, and was convened by RJ Merriman (BGS), Dr G Droop (University of Manchester) and NJ Fortey (BGS) The conference drew together diverse workers from different continents, thus enabling wide reaching exchange of expertise and the resolution of discrepencies in practises employed to investigate VLGM.

In addition, the joint BGS-London University group welcomed the opportunity to lead a post-conference excursion to review patterns of VLGM in the English Lake District and Southern Scotland. As with the conference itself, the support given by the Survey's staff was amply rewarded in terms of "state-of-the-art" expertise gained, contacts established and overall enhancement to the prestige of the Survey.

Preparation of an excursion guide provided the chance to set out and review results obtained on the field areas to be visited, and to discuss their interpretation. The guide is reproduced here as a Mineralogy and Petrology report in order to keep a permanent record of its contents and to make them more widely available.

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Itinerary

Friday 6 July

Depart Manchester at 16.30: drive to The Horseshoe Hotel, Ambleside, Lake District.

Saturday 7 July

Stop 1. Borwick Fold Hill; Bannisdale Slates, Silurian, Ludlow

Stop 2. Allen Heads Quarry; Conniston Grits, Silurian, Lower Ludlow.

Stop 3. Applethwaite Slate Quarry; Brathay Flags, Silurian, Lower Wenlock

Stop 4. Lunch at Brotherswater.

Stop 5. Troutbeck; Skiddaw Slates; Ordovician, Arenig.

Stop 6. Mungrisedale and ; Skiddaw Slates, Ordovician, Arenig.

Stop 7. River Caldew; hornfelsed Skiddaw Slates, Skiddaw Granite aureole.

Return to Ambleside.

Sunday 8 July

Stop 8. Chaple Stile Quarry; Borrowdale Volcanic Group, Ordovician ?Caradoc

Stop 9. Kirkstone Gallery; coffee.

Drive to Scotland.

Stop 10. Lunch at Southwaite Services M6.

Stop 11. Isle of Whithorn; Carghidown Formation, Llandovery, Silurian.

Drive to The Downshire Arms Hotel, Portpatrick, Rhins of Galloway.

Monday 9 July

Stop 12. Corsewall Point; Corsewall Formation, Caradoc, Ordovician.

Stop 13. Portpatrick; Portpatrick Formation, Caradoc, Ordovician.

Stop 14. Port Logan; Port Logan Formation, Llandovery, Silurian.

Stop 15. Lunch at Logan Botanic Garden.

Stop 16. Grennan Slate Quarry; Port Logan Formation, Llandovery, Silurian.

Stop 17. Clanyard Bay; Moffat Shale Group, Llandovery, Silurian.

Stop 18. Mull of Galloway; Carghidown Formation, Llandovery, Silurian.

Return to Portpatrick

Tuesday 10 July

Party returns to Manchester, arriving at approximately 15.00 hours. Arrangements will be made for one minibus to leave the hotel very early (~06.30) to reach Manchester by midday.

Introduction

It is widely accepted that in the early Lower Palaeozoic the various terranes of the British Isles lay close to a triple collisional junction. Here, two major continental terranes, Laurentia and Baltica, collided with a third microcontinental terrane comprising southern Britain and nearby Europe, which is referred to as Eastern Avalonia (Soper et al. 1987; Soper and Woodcock, in press). The Iapetus ocean, which separated Laurentia and Eastern Avalonia, became a zone of closure. The site of closure is now taken to be represented by the Iapetus suture, a notional suture line trending NE–SW and lying within the Solway Basin. In Newfoundland, evidence for closure of Iapetus in the middle to late Ordovician is reported (Williams & Hatcher 1983; Pickering et al. 1988), but in Britain it is now generally accepted that closure occurred in the Silurian (Barnes et al. 1989; Soper & Woodcock in press). As a consequence of closure, two contrasting Lower Palaeozoic terranes are now juxtaposed. To the northwest of the Iapetus suture, the Scottish Southern Uplands terrane comprises a succession of predominantly thickly bedded volcaniclastic and terrigenous turbidites with subordinate graptolitic shales, ranging in age from middle Ordovician to late Silurian. Southeast of the Iapetus suture, the Lower Palaeozoic of the English Lake District consists of a succession of early Ordovician to late Silurian mudrocks, calc-alkaline volcanics and turbidites. Regional low grade metamorphism on both sides of the suture ranges from late diagenetic to epizonal. The purpose of this excursion is to examine the relative influences of lithology, deformation and burial conditions on low grade metamorphism in two contrasting geodynamic environments generated by closure of Iapetus.

Summary of the geology and metamorphism of the English Lake District

Introduction

The English Lake District has had a long history of quarrying and underground mining. Quarrying operations have worked slate, limestone, roadstone and granite as well as coal and iron ore. Slates for roofing and building were (and are) produced from grey Wenlockian mudstones at Kirkby-in-Furness and from green Caradocian andesitic tuffs at Broughton Moor, Chapel Stile, Kirkstone, Honister and other sites. The famous Cumbrian green slates are seen in buildings and walls throughout the area, and often give excellent displays of sedimentary structures on cleavage planes.

Geology

The Lake District is a large inlier of early Ordovician (Tremadocian) to late Silurian (Pridoli) sedimentary and volcanic rocks emerging from beneath the Carboniferous and Permian strata that cover most of Northern England. These rocks are also seen in the smaller, fault bounded Cross Fell inlier NE of the main inlier (Figure 1). Outcrops of Silurian to middle Devonian granites are surface expressions of a composite batholith known from gravimetric surveys (Lee, 1984) to underlie much of the Lake District.

Following tradition, the sedimentary-volcanic succession of the Lake District is split into three main divisions (Figure 1). These comprise turbiditic sandstones and monotonous silty mudstones and slates of the Tremadoc–Llanvirn Skiddaw Group (the "Skiddaw Slates"), calc-alkaline volcanic and volcaniclastic rocks of the Llanvirn to lower Caradoc Eycott and Borrowdale Volcanic Groups, and calcareous mudrocks and turbidite sandstones of the middle Caradoc to Pridoli Windermere Group.

The ca. 5 km thick sediments of the Skiddaw Group developed extensive slump folds and gravity slide structures (Webb & Cooper, 1988). Although lacking volcanic rocks, deposition was contemporaneous with early Ordovician arc volcanism further south in the Welsh basin, and an inter-arc or back-arc setting is probable. In common with early Ordovician mudrocks of the Welsh basin, Skiddaw Group mudrocks are paragonite bearing and rich in chlorite-mica stacks formed by diagenetic alteration of detrital biotite and other ferro-magnesian mineral grains of volcanic derivation (Milodowski & Zalaziewicz, in press). Recent mapping of the Skiddaw Group has identified a major WSW–ENE sinistral shear displacement, the Crummock Water fault, across which discordant sets of synsedimentary structures have become aligned (Cooper & Molyneux, 1990), and which is one of a set of major sinistral strike slip faults found on both sides of the Iapetus suture.

Interpretation of the geological history of the Eycott and Borrowdale Volcanic Groups is currently under revision. It is generally agreed that the characteristics of the outcrop of the latter group indicates subaerial calc-alkaline volcanism. This structurally complex sequence of lavas, pyroclastics, volcaniclastic sediments and high level intrusions, ca. 4 km thick, is marked by volcanotectonic faulting during prolonged subsidence (Branney, 1988). Overstep of the base of the BVG indicates that emergence and erosion of the underlying Skiddaw Group occurred before the onset of volcanism. The exposed part of the Eycott Volcanic Group is ca. 2 km thick, but more of this group lies concealed beneath the cover rocks. Once again, an unconformable base and volcanotectonic faulting can be demonstrated (D. Millward, pers. comm.).

Much of the volcanic sequence was preserved beneath the unconformable base of the mudstones and impure limestones of the lower part of the Windermere Group. Deposition of these rocks persisted until middle Wenlock time, when northerly derived turbidites mark the onset of subsidence and rapid sedimentation which continued until the Lower Devonian (Acadian) folding and cleavage development (Soper et al. 1987). The group is ca. 7 to 8 km thick. Windermere Group mudrocks lack both paragonite and chlorite-mica stacks, in common with mudrocks of the Southern Uplands. However, the thick upper part of the group is dominated by sandstones and siltstones with few true mudrocks.

In considering the thickness of the succession it is important to note that the unconformable bases of the volcanic rocks and Windermere Group mark periods of erosion. Therefore, depths of burial were not accumulative throughout the succession as three separate periods of subsidence and sedimentation took place.

The age of the main Caledonian WSW–ENE subvertical slaty cleavage is well constrained in the Windermere Group. Here it cleaves late Ludlovian sediments but is cut by the middle Devonian Shap Granite (N J Soper, field excursion, 1989). Strong cleavage of the same trend can be traced northeastwards into the Borrowdale Volcanic Group. In the Skiddaw Group the situation is less clear since cleavage here is patchy and often weak. A steep main Caledonian cleavage is accompanied by a NNW–SSE steep cleavage and a late (post-granite) sub-horizontal cleavage. Soper and Roberts (1971) correlated the main cleavage with its counterpart further south but the age and origin of the NNW–SSE cleavage remains uncertain.

Fitton & Hughes (1970) interpreted the Eycott and Borrowdale Volcanics as products of southeasterly directed subduction of the Iapetus oceanic lithosphere which originally floored the basin which separated the Lake District from Laurentian terranes further north. This view was supported by faunal evidence of wide separation of the two terranes until the middle Silurian (Fortey et al. 1989), and evidence for derivation of Lake District sediments from the Southern Uplands only from the middle Silurian onward (Furness, 1965). Soper & Hutton (1984) reconstructed the pattern of plate movements in the Caledonides, placing the Lake District on the NW side of the East Avalonian microcontinent which collided with the Laurentian continent. Middle Silurian (Wenlock) collision was followed by a period of sinistral transcurrent movements on WSW–ENE trending faults and eventually the Lower Devonian (Acadian) orogeny. This last event caused the Caledonian folding and cleavage seen throughout much of the paratectonic Caledonides, and involved major and widespread crustal shortening. In the Lake District, sinistral transpression during the shortening can be deduced from the arcuate trend of fold-cleavage transections in the Windermere Group (Soper et al. 1987). Interpretation of the Ordovician-Silurian tectonics of the Southern Uplands as a SE-directed rising thrust stack (Stone et al. 1987) has led to the view that the late Silurian sedimentation and subsequent deformation of the Lake District involved southwards migration of a foreland basin across the line of closure of the Iapetus ocean into the Eastern Avalonian terrane (Barnes et al. 1989).

Metamorphism in the Lake District

The first direct determination of regional metamorphic grade in the Lake District was probably by Bergstrom (1980) for the lower Windermere Group using conodont maturation indices. Values of 5 (300–400°C) and, locally, 4 (190–300°C) suggest epizonal or upper anchizonal metamorphism. Later, Thomas (1986) studied illite crystallinity by measuring the Weber Hb .rel index for 2–6 micron fractions from sedimentary rocks and the mineralogy of basic volcanic rocks, concluding that the area had undergone anchizonal or prehnite-pumpellyite facies burial metamorphism probably at more than one stage related to its history of successive burials. Oliver et al. (1984) and Allen et al. (1987) also record prehnite-actinolite facies metamorphism in parts of the Borrowdale Volcanic Group underlain by granitic plutons.

Oliver (1988) presented graptolite reflectance measurements mostly for the Windermere Group. These results show a down-sequence pattern of increasing reflectance from diagenetic values (122.3) in the Bannisdale Slates (Ludlow) to upper prehnite-pumpellyite facies values (6.4–8.5) for the Brathay Flags and underlying Stockdale Shales (Wenlock and Llandovery respectively). Oliver (1988) comments that the values for the Bannisdale Slates are at variance with anchizonal illite crystallinity values recorded by Thomas (1986), probably because the illite data is influenced by the component of detrital mica in the rocks.

A Kubler index survey of the Skiddaw Group was made as part of the BGS Regional Geological Survey of the Lake District (Fortey, 1990). This revealed considerable variation, some of which could be attributed to post-tectonic fault displacements and local contact induration. However, a broad pattern of diagenetic to low epizonal variation remained which was difficult to account for by a single metamorphic event. The <2 micron fractions of the higher grade metapelites consist of 2M muscovite and chlorite with minor amounts of quartz and feldspar. In addition, mixed layer muscovite-paragonite occurs in many samples, and variation in this phase is believed to account for much of the Kubler index variation within a general 0.19–0.35 $\Delta° 2\theta$ range. The <2 micron fractions of the lowest grade mudrocks (Kubler index >0.42 $\Delta° 2\theta$) contain poorly ordered 1Md illite together with chlorite and very minor quartz. Some samples also contain pyrophyllite or, rarely, kaolinite. At outcrop (eg Excursion stop 5) these latter rocks are soft and are poorly cleaved. Most belong to the Tarn Moor Mudstone, the youngest part of the Skiddaw Group, and include tuff bands and probably a dispersed tuffaceous component. Thin sections show that these rocks often have well developed bedding-parallel fabrics, contain chlorite-mica stacks of very low chlorite content and carry fracture pockets of probable pyrophyllite. Some also display a penetrative fabric not easily seen at outcrop. It was suggested by Fortey (1990) that burial metamorphism had been partially overprinted by regional metamorphic effects related to folding and cleavage development, and that high heat flow during volcanism and later granite emplacement were additional factors.

Recent results (unpublished) have involved the Furness, Windermere, Cautley and Cross Fell areas (see Figure 2). At Cross Fell, the Kubler index varies from formation to formation with 'sharp changes and apparent inversion of metamorphic grade (Figure 3). Low anchizonal values were obtained from the oldest and youngest formations in the local succession, but mudstones in intervening formations gave diagenetic values in which apparent metamorphic grade increased upwards through the succession. The oldest rocks, of the Skiddaw Group, and the youngest, the Brathay Flags, are essentially terrigenous fine sandstones and silty mudstones. The intervening formations include shaley Llanvirn mudrocks which may have a significant volcanogenic clay component, and Ashgill mudrocks carrying a strong cleavage. The inlier, which is poorly exposed, is cut by numerous normal and reverse faults. It is conceivable that lateral movement has juxtaposed fault slices from different crustal settings, but such faulting is not documented. Similar apparent inversions in grade occur at Furness and Cautley. In the Furness area the inversion takes place across an unconformity, not a fault.

The results suggest that crystallinity varies with lithology, underlining the view that a survey of white mica crystallinity should concentrate on samples of terrigenous mudrock, avoiding sandstones or volcanogenic mudstones. Clearly, in the Lake District this restricts the extent of possible sampling, and it becomes difficult to know which of the Skiddaw Group lithologies provides the best data from the metamorphic viewpoint. The presence of interlayered paragonite-muscovite in many samples of otherwise suitable mudrocks implies that the middle to upper anchizonal crystallinity values obtained from them give an underestimate of the "true" grade. Paragonite-free mudrocks in Bouma sequences give epizonal Kubler indices, and correlating these with the data for mudrocks of the Brathay Flags suggests that both the Skiddaw and the Windermere Groups underwent upper anchizonal to epizonal regional metamorphism. However, this is based on selective use of the results, and it raises the problem of reconciling this inferred grade with the somewhat lower grades and metavolcanic facies shown by Thomas's (1986) data.

In contrast, very restricted variation was observed in Kubler indices (0.26–0.32$\Delta°$ 2θ) from siltstones in the Bannisdale Slate (Ludlow) sampled along a ca. 20 km cross strike section in the Windermere area (Figure 2) [eg Excursion Stop 1]. The older Brathay Flags (Lower Wenlock) gave similarly uniform but higher grade values (0.20–0.22 $\Delta°$ 2θ) for silty mudstones again sampled over a wide area [eg Excursion stop 3]. Low epizonal values for the Brathay Flags are in agreement with the conodont maturation indices suggesting that they are giving a true estimation of the grade of metamorphism. The difference between the crystallinities of the formations could be due simply to different degrees of burial. As already pointed out, Oliver (1988) obtained diagenetic graptolite reflectance values for the Bannisdale Slate, and concluded that the crystallinity data of Thomas (1986) were influenced by mica of detrital origin. The range of reflectance values suggests a temperature range of perhaps 100°C over a stratigraphic thickness of 4–5 km, giving a geothermal gradient of 20–25°C/km during late Silurian burial.

Alternatively, in view of the strong cleavage present throughout the Bannisdale Slate cross strike section it is difficult a priori to accept a grade no higher than diagenetic for these rocks. New mica growth during metamorphism associated with the folding and cleavage formation should be dominant in the <2 micron fractions so that the limited variation in the Kubler indices along the section implies an even degree of metamorphism across the southern Lake District. The difference in crystallinity between the Bannisdale Slate and the Brathay Flags could thus result from a lithological control such as differences in the kinetics of new mica growth during metamorphism rather than different degrees of metamorphism.

The conclusions of this discussion are that:

1. An upper anchizonal to epizonal grade of metamorphism, or its metabasic volcanic equivalent, has affected much of the area, and that this was established during the Lower Devonian regional metamorphism.
2. Some of the variation observed in Kubler indices reflects lithological controls which either affect the process and kinetics of new mica growth or the susceptibility of the rocks to retrograde alteration, possibly during uplift or deep weathering.

The first conclusion is less simple than it seems. The Skiddaw Group is generally more indurated but less uniformly cleaved than the Windermere Group [eg Excursion stop 6], possibly reflecting a greater degree of de-watering or a higher geothermal gradient during metamorphism. Much of it is underlain by granitic rocks, and most of the areas giving very low grade Kubler indices are those in which the gravimetric survey indicated that granite is very deep or absent. Is this merely a coincidence? Also, if the geothermal gradients were indeed different, why should the resulting grade of metamorphism be the same in both groups. Another coincidence?

Besides very low grade regional metamorphism, the Lake District contains some good examples of contact metamorphism around the high level granite intrusions. The contact aureole around the cupola of the Skiddaw Granite is a classic example in which concentric zones of increasing intensity of metamorphism are present. An outer zone of bleached slate and spotted hornfels gives way via successive andalusite, biotite and cordierite isograds to an inner zone of cordierite-biotite-hornfels. Garnet occurs only rarely. Sillimanite has not been recorded, suggesting a relatively high structural level. At the Grainsgill locality (Excursion stop 7) hornfelsic alteration of Skiddaw Group sandstone preserves synsedimentary chevron folding. Greisen-like alteration of the granite is associated with a W-As rich swarm of quartz veins, and has also affected the hornfels causing retrogressive chlorite-sericite-muscovite alteration.

Another example of contact alteration is the Crummock Water Aureole, a linear, 7 x 1 km zone of bleaching, induration, chloritic spotting and tourmalinisation developed over a concealed dyke-like granitic intrusion emplaced along the trend of the Crummock Water Fault (Cooper et al. 1987). Pelites in this aureole take on a lepidoblastic bedding fabric, although chlorite-mica stacks and locally detrital grains are still recognisable in thin section. Paragonite contents are variable, locally matching that of muscovite. The micas are the 2M polytype. Kubler indices reach 0.19–0.21 $\Delta° 2\theta$ where paragonile is absent, consistent with a model of metasomatic recrystallisation indicated by the presence of tourmalinisation and other geochemical changes. Chlorite is abundant, whereas biotite is a very minor constituent.

Summary of Southern Uplands geology and metamorphism

Geology

Following the pioneering work of Peach and Horne (1899), the Southern Uplands lying south of the Southern Upland Fault, has been traditionally divided into Northern, Central and Southern Belts (Figure 4). The Northern Belt is characterised by the presence of Ordovician strata only; the strata of the Central Belt are mainly of Llandovery age; and the strata of the Southern Belt are mainly Wenlock in age. Belts are separated from each other by major strike-parallel faults. Thus the Northern and Central Belts are separated by the Orlock Bridge–Kingledores Fault with a possible sinistral displacement in excess of 400 km (Anderson and Oliver, 1986); and the Central and Southern Belts are separated by the Riccarton Line. The three belts are further cut by near-vertical parallel faults giving 12 or more major slices or tracts.

Although the succession is dominated by turbidites, lithological variations are present from belt to belt. Thus the Northern Belt succession consists mainly of volcaniclastic and terrigenous turbidite sandstones, graptolitic shales and occassional basic lavas and cherts. The Central Belt consists mainly of terrigenous and volcaniclastic turbidite sandstones and subordinate graptolitic shales. Finally, the Southern Belt comprises mostly terrigenous turbidite sandstones and graptolitic shales.

Beds presently are steeply dipping to vertical and within each fault-bounded tract mostly young to the NW. However the successions comprising each tract, overall, become younger to the SE (Figure 5). Each fault-bounded tract has extensive, along-strike continuity and most completely traverse the terrane from WSW to ENE. Each thick sequence of turbidite sandstones is characteristically underlain by graptolitic shale — the Moffatt Shale Group (Figure 5).

The terrane has been interpreted as an accretionary prism by. McKerrow et al. (1977) and by Leggett et al. (1979). Each fault-bounded tract is taken to represent a succession of fore-arc sediments sliced off the oceanic plate as it was subducted to the NW beneath a continental margin. Accretion developed under the toe of the SE-aggrading prism as a series of slices bounded by continent-dipping thrust faults. As the prism developed, earlier accreted slices were steepened by backward rotation and acquired a pattern of very low grade metamorphism related to burial (Oliver and Leggett 1980).

In the past decade, BGS surveys in the Southern Uplands and research in the Irish extension of this terrane have produced alternatives to the accretionary prism model. Both Murphy and Hutton (1986) and Stone et al. (1987) pointed out that the arrangement of faults previously interpreted as characteristic of subduction and accretion constitutes an imbricate thrust stack, and that the tectono-stratigraphic pattern can equally well be generated by thin-skinned, SE directed thrusting. Moreover, palaeocurrent evidence from volcaniclastic turbidites indicates that fresh andesitic detritus was derived from the south, implying the existence of a volcanic arc situated on the oceanic side of the fore-arc region. An alternative model thus envisages a back-arc setting for the Southern Uplands, which simultaneously received quartzose turbidites from a mature continental landmass to the north and turbidites, rich in fresh volcaniclastic detritus, from an ensialic volcanic arc to south (Styles et al. 1989). Following oblique collision, initiated in the Llandovery, under-thrusting of the Laurentian marginal basin by Eastern Avalonia generated a SE-propagating thrust stack. An associated middle Wenlock, southward migrating foreland basin is envisaged by Barnes et al. (1989) as developing ahead of the rising thrust stack on the leading edge of Eastern Avalonia. There is claimed to be firm evidence of a sedimentary link in the Late Wenlock between the Southern Uplands and the Lake District (Soper and Woodcock, in press).

Metamorphism in the Southern Uplands

Studies of metabasic volcanic rocks and volcaniclastic turbidites show that prehnite-pumpellyite facies metamorphism is widely developed in the Northern and Central Belts of the Southern Uplands (Oliver and Leggett, 1980). Illite crystallinity, illite b parameters and graptolite reflectance data derived from two loW-density sampling traverses across the Southern Belt indicate consistent anchizonal grades in the northeast but late diagenetic grades in the southwest of the Southern Belt (Kemp et at., 1985).

White mica crystallinity studies of low grade pelitic rocks were initiated in 1986 as part of the BGS Southern Uplands Regional Geological Survey. These studies, which use a sampling density of 1–2 pelite samples per square kilometer, have closely followed geological mapping and revision of areas in the southwest part of the Northern and Central belts. Initially, computer-generated metamorphic maps were derived from data plotted on 1:50,000 scale. The maps showed rapid changes in grade across the traces of some, but not all, of the proven strike-parallel faults and, in general, isocrysts were oblique to the strike.of the bedding. Consequently the maps were re-drawn by hand, treating proven faults (both strike-and dip-parallel) as potential metamorphic discontinuities. A simplified and reduced version of unpublished metamorphic maps is shown in (Figure 6), and a brief, preliminary synthesis of the data is presented here. (A full account of the metamorphic history will be presented in BGS 1:50,000 sheet memoirs and appropriate scientific journals; metamorphic maps will appear as part of the marginalia of BGS 1:50,000 geological maps).

Interpretation of the isocryst pattern

Within fault-bounded tracts, the oblique intersection of the isocryst surfaces with bedding planes, the absence of systematic variation in grade with younging direction of strata, and the fact that lowest grade rocks include the oldest tract (Corsewall Formation) in the Northern Belt as well as younger rocks within the Central Belt, precludes an interpretation in terms of a simple burial-related metamorphism followed by thrusting or subduction. Rather, the isocryst pattern suggests that beds were inclined, probably steeply, during metamorphism.

One working hypothesis, in terms of the subduction model, could evoke a modified burial metamorphism with essentially depth-controlled, approximately horizontal isocryst surfaces developing in a set of steeply inclined, strike fault-bounded packets of strata. Little or no post-metamorphic movement on the strike faults results in continuity of metamorphic grade across the faults; but subsequent movement (eg sinistral strike-slip) results in discontinuities. If this movement were coupled with a rotation of packets about axes approximately normal to the strike-parallel faults then the pattern observed could be generated. Late Palaeozoic NW–SE trending normal faults, eg the Loch Ryan Fault, up-throwing to the east, necessarily expose deeper, and therefore higher grade, metamorphic levels.

Mudstones in the Central Belt of late diagenetic grade merit further comment. In these tracts beds young to the SE rather than NW. McCurry and Anderson (1989) interpret such tracts as having been obducted rather than subducted whereas Stone et al. (1987) would interpret them, in terms of thin-skinned tectonics, as backthrust tracts. In each model, the tracts would have been less deeply buried than adjacent tracts and hence are of lower metamorphic grade.

Highest grades are found within the Hawick Group, Central Belt, where epizonal (low-greenschist facies) grades are associated with a well-developed slaty cleavage and often associated with steeply plunging folds. Although detailed studies of the Southern Belt are incomplete, data to hand suggest that grade falls towards the southeast, as already reported by Kemp et al.. (1985).

The primary pattern is overprinted by contact metamorphic effects associated with late Silurian and early Devonian granitoid intrusions. Concentric patterns of metamorphic grade are developed around the Cairnsmore of Fleet, Creetown and Portancorkrie intrusions, where biotite-cordierite hornfelses are found in the inner aureoles. Elsewhere smaller intrusions may generate epizonal or high-anchizonal concentric aureoles. Other concentric and ellipsoidal patterns of steep metamorphic gradient, ranging up to epizonal grade, may indicate concealed minor intrusions.

Lake District itinerary

This first part of the field excursion will examine metamorphosed sedimentary and volcanic rocks in the Lake District inlier. The first morning will be concerned with lithologies of the Windermere Group, and the following afternoon with the older Skiddaw Group. Lunch will be taken during a road traverse across the intervening Borrowdale Volcanic Group, but time will prevent us from taking a close look at these rocks. However, the first location on the second day will be one of the slate quarries working cleaved tuffs of this group, before the party sets off for the Southern Uplands. In drawing up these notes, we are indebted to Lawrence et al. (1986), Millward et al. (1978) and A.H. Cooper (personal communication) for background information.

Saturday July 7th

Stop 1 — Bannisdale Slate at hilltop exposure near to Borwick Fold farm [SD 446 971]

The first three stops of the excursion are in successively older rocks of the Windermere Group. At Stop 1, a close-spaced, sub-vertical fracture cleavage is developed throughout thinly bedded pale grey siltstones and fine sandstones. The rocks belong to the ca. 3 km thick Bannisdale Slate (Middle Ludlow), distal turbidites deposited by rapid sedimentation during subsidence of the late Silurian foreland basin. Cleavage is approximately axial planar to open minor folding with a gentle easterly plunge, though a small clockwise transection relative to fold hinges can be demonstrated. The locality lies within the belt of ENE to E trending periclinal folds and strong cleavage which extends across the southern Lake District, related to Lower Devonian sinistral transpression. A sample of grey siltstone from here gave a Kubler index of 0.29 $\Delta° 2\theta$, close to values measured from 22 other samples of cleaved Bannisdale Slate collected on a 20 km cross strike traverse across this belt. This uniformity of crystallinity is in contrast with.the variability found in the Skiddaw Group. The mineralogy of the <2 pm fraction is 2µm muscovite, chlorite, quartz, albite and calcite.

The hilltop site gives a panoramic view in which the hill country of the Windermere Group is in contrast with the more rugged uplands of the Borrowdale Volcanic Group to the north and west. Small old workings on the hilltop were for flaggy building stone.

Stop 2 — Coniston Grits at Allen Heads quarry. [NY 415 011]

The beds exposed in this old roadstone quarry are steeply inclined turbidites belonging to the ca. 2 km thick Coniston Grits (Lower Ludlow) which underlie the Bannisdale Slates. Bouma sequences, some > 2 m thick at this site, are dominated by massive greywacke sandstone beds, but also possess silty and muddy tops in which slaty cleavage is developed. The beds strike 055° and dip 70° SE; cleavage strikes 050° and is sub-vertical. Sedimentary structures here include grading and ripple-drift lamination. The sandstones are muscovitic, highly feldspathic and locally rich in rock fragments including rhyolitic lavas and flow foliated lavas of more basic character. The Windermere Group is thought to have extended northwards over the older rocks of the sequence, and Furness (1965) considered that a lithological correlation exists between the Coniston Grits and the Hawick Group of the Southern Uplands.

Stop 3 — Brathay Flags at Applethwaite quarry. [NY 423 034]

This quarry lies within the Brathay Flags (Lower to Middle Wenlock), a ca. 300 m thick sequence of uniformly grey silty mudstones, much of which display a fine, regular carbonaceous banding. The beds were deposited as distal turbidites, probably in a deep water. Some 50 m, of silty mudstones, striking 070° and dipping about 40° SE, is exposed in this quarry , which lies on the SE limb of the ENE trending Nan Bield anticline, a major Caledonian structure. A sub-vertical penetrative cleavage is present throughout the quarry, trending approximatley 070°, and was the basis for the rough slate worked at this site. Kubler indices of 0.20 and 0.22 $\Delta° 2\theta$ were measured on two samples whose <2µm mineralogy comprises 2µm muscovite, chlorite and quartz. Several K-bentonitic tuff bands, up to 4 cm thick, occur at 0.5–1.0 m spacings in part of the exposed succession. Most have a 'sandy' character due to the presence of feldspar and pyrite crystals set in an illitic groundmass, but at least one is distinct in consisting of remnants of illitic material invaded by calcite veining. Kubler indices for two of the tuffs are 0.24 and 0.31$\Delta° 2\theta$, only slightly lower grade than the enclosing mudrocks.

The Party are warned that the quarry faces are unstable, and are asked to avoid the high rear faces of the quarry, and to hammer spoil material rather than the dangerous rocks faces.

Stop 4 — Road traverse across the Borrowdale Volcanics, and lunch stop at the Brotherswater Inn. [NY 403 119]

The route crosses the outcrop of the Borrowdale Volcanic Group, an area of rugged, glaciated mountains. Broadly speaking, the lower part of the volcanics is dominated by basalt and andesite lavas, but dacitic ignimbrites become more abundant upwards. Tuffs and volcaniclastic sediments occur very widely. The volcanics are potassic, calc-alkaline rocks whose more silicic members contain almandine phenocrysts. They are the remnants of a major subaerial volcanic edifice cut by numerous volcanotectonic faults related to caldera subsidence according to Branney (1988). On the ascent of the Kirkstone Pass the route crosses the axis of the Nan Bield anticline. To the left (NE) is the Kirkstone Slate Quarry, working cleaved andesitic tuffs comparable with those to seen at Stop 8. On the descent the Haweswater Syncline is crossed, and the hills west of the lunch stop at Brotherswater are predominantly SE dipping tuffs. These open, rather gentle major folds have been attributed to the Caledonian. orogeny, though some have argued for a volcanotectonic origin. Further north, at Ullswater, the valley bottom consists of Skiddaw Group grey mudstones lying beneath the lavas and tuffs of the lower part of the volcanic sequence which form the surrounding hills. Rounded hills NE of the lake are of un-metamorphosed Devonian red conglomerates deposited after the climax of the Caledonian orogeny. However, the excursion route turns north to cross the last outcrops of the volcanics and reach an area where thick glacial till masks soft, low grade mudrocks of the Skiddaw Group.

Stop 5 — Skiddaw Slate at Troutbeck stream section. [NY 385 270]

Stops 5 to 7 show aspects of metamorphism within the Skiddaw Group. At Stop 5 a late diagenetic grade is indicated by illite crystallinity data from grey shales in the upper part of the Skiddaw Group at a locality south of the Causey Pike Fault. Stop 6 (a and b) is in more typically upper anchizonal to epizonal Skiddaw Slate north of this transcurrent fault. Stop 7 is in the contact metamorphic zone around the Skiddaw Granite.

At Stop 5 a shallow gorge has exposed conspicuously soft, tightly folded dark grey shaley mudstones. Numerous isoclinal minor folds with sub-horizontal hinges lack an axial planar cleavage. Thin sandstone beds may pass around closures without rupture, but numerous detached sandstone lenses lie within the mudstones more generally. Siliceous nodules occur locally in the mudstones. Thin sections show the presence of chlorite-mica stacks, unusually rich in the mica component, and the presence of a weak crenulation cleavage. Accompanying sandstones possess a calcite cement marked by the presence of microscopic spherules of probable biogenic origin. Varying bedding orientations of strike:145°/dip:45°NE and strike: 064°/dip: 56°NW were measured at different points here. Lower Arenig fossils have been recorded (S Molyneux, personal communication), but interpretation of the rocks as mudflow deposits similar to the Late Arenig Buttermere Formation, further west, implies that the fossils could be derived. Similar rocks, the Tarn Moor Mudstones at Mosedale Beck and other locations nearby are known to be of Llanvirn age. A crosscutting cleavage striking about E-W and dipping at moderate angles northwards can be demonstrated and has influenced development of the gorge. A ca. 1 m thick felsitic dyke (not analysed) in the north wall of the gorge is not present in the southern side, implying some fault displacement along the gorge. Kubler indices for 5 mudstone samples range from 0.45 to 0.82 $\Delta° 2\theta$. The <2µm fractions consist of 1Md illite with minor irregular interlayered smectite, chlorite and traces of quartz. One sample also contains kaolinite, and this mineral, or more commonly pyrophyllite, was recorded in mudstone from a number of sites in the upper part of the Skiddaw Group. Variable Kubler indices reflect different degrees of development of a low angle broadening of the 10■ peak. Glycolation results in sharpening and lessening in the intensity of the 10 ■ peak The locality is in many ways typical of areas of sub-anchizonal grade in the Skiddaw Group. The origin of such zones has not been satisfactorily determined, and current discussions centres on whether the low grade simply means that the rocks have not undergone metamorphism, or whether they have suffered retrogression related to hydrothermal activity.

Stop 6 — Skiddaw Slates at Mungrisedale.

If time permits, two stops will be made in this area.

1. Loweswater Flags in old quarry at Mungrisedale village [NY 363 305].
2. Kirkstile Formation at Bowscale End [NY 360 314].

In the first, steeply dipping beds of hard, dark grey siltstone and fine sandstone of the Lower Arenig Loweswater Flags Formation strike 100–120°, and are accompanied by massive sandstone beds about 0.6 m thick. A steep cleavage lies sub-parallel with the beds, but is not conspicuous. An open, sideways-closing, minor S fold has developed about a gently dipping thrust plane. Also, the rocks are cut by prominent 060° striking joints dipping 30° NW and carrying E–W trending slickensides which plunge gently eastwards. A Kubler index of 0.27 Δ° 2θ was measured here, in a <2µm fraction consisting of 2µm muscovite, chlorite, quartz and albite. Rocks at both Stop localities lie within 2 km of the outer aureole of contact metamorphism around the Skiddaw Granite, and therefore may have been contact indurated.

The second part of Stop 6 is in exposures on the open fellside at Bowscale End in folded dark grey pelites and fine interbedded sandstones, attributed to the Kirkstile Formation (Arenig). Two sets of penetrative cleavage are indicated by fine crenulation fabrics, seen on lustrous mudstone bedding surfaces, trending 260° and 340°. A Kubler index of 0.32 Δ° 2θ was measured here in a <2µm fraction consisting of interlayered muscovite-paragonite, chlorite and minor quartz. Cleavages in the upper anchizonal to epizonal rocks of the Skiddaw Slate are generally poorly developed in sandstone beds, and are rarely truly penetrative, in contrast with that in the Windermere Group. The reasons for this contrast could involve some degree of pre-cleavage burial induration at a high geothermal gradient, in a back or intra-arc setting, prior to Caledonian tectonism.

Stop 7 - Hornfelsed Skiddaw Slate at Grainsgill. [NY 327 326]

Exposures at the confluence of Grainsgill with the River Caldew are in contact metamorphosed rocks of the Skiddaw Group in contact with the Lower Devonian Skiddaw Granite. The tough hornfelses preserve and enhance the sedimentary interlamination of pelite and fine sandstone. The beds are generally sub-vertical and strike E–W, but this is repeatedly modified by minor chevron folding attributed to soft sediment deformation. The darker, pelitic laminae are rich in cordierite, andalusite, orthoclase and biotite. A later generation of coarse grained muscovite is also present, and may be related to greisenitic alteration widespread in the granite. The aureole has a classic mineral zonation in which an outer zone of spotted bleached rocks passes through chiastolite, biotite and cordierite 'isograds' inwards to the contact. Chloritoid has been recorded from its outer part, and garnet is a rare constituent, but sillimanite is not known to occur. The Skiddaw Granite is a sparsely orthoclase-phyric two-mica variety having some features of an S-type granite although O'Brien et al. (1985) favour a subcrustal origin. Primary biotite is rare owing to extensive chloritisation related to greisenitic alteration which is widespread in this granite. Quartz-muscovite greisen occurs in zones centred on N–S steeply inclined quartz veins which cross the granite and penetrate adjacent rocks, in particular the Carrock Fell gabbroic complex which forms the northern side of the Caldew–Grainsgill valley. Tungsten in the forms of wolframite and scheelite was mined have until recently, occurring in veins along with arsenopyrite and a range of other sulphides and sulphosalts. The hills north of here are noted for occurrences of a wide range of rare authigenic minerals of vanadium, lead, etc.

On the return to Ambleside the route passes through St Johns in the Vale, where prominent S-inclined benches in the hillside west of the valley are created by the contrast between basic lavas and softer interbedded tuffs of the lower part of the Borrowdale Volcanics.

Sunday July 8th

Stop 8 - Green slate quarry at Chapel Stile, Langdale. [NY 324 049]

This locality can be considered to represent a number of sites at which high quality roofing slate has been worked in the Lake District. The quarry, operated by the Burlington Slate Company, is one of three still in operation. It is sited in massive, pale green water-lain andesitic tuffs of the Tilberthwaite Tuff Formation, part of the upper Borrowdale Volcanic Group. Bedding is locally visible, and strikes more or less uniformly at 140°, dipping at about 26° to the NE. A variety of sedimentary structures can be seen including load castes and flame structures as well as local intraformational unconformities. The penetrative slaty cleavage strikes at about 050° and dips 60° NW.

In addition, a prominent set of joints lies approximately perpendicular to the cleavage and at an acute angle to bedding. Within the volcanic rocks as a whole, cleavage is best developed in the massive tuffs, and poorly developed in compact lavas.

Stop 9 — Coffee stop at Kirkstone Gallery prior to the drive to the Southern Uplands. [NY 343 034]

Before embarking on the 2–3 hour drive into southern Scotland, we shall take the opportunity to visit the excellent cafeteria and the gallery of the Kirkstone Slate Company where a variety of mementos can be obtained. After leaving here the route will be N across the Borrowdale Volcanics via Thirlmere and across the Skiddaw Group on to the Lower Carboniferous limestones and Permo-Triassic red sandstones of the Vale of Eden around the town of Penrith.

Stop 10 — Lunch stop at Southwaite Services, M6 Motorway.

Southern Uplands itinerary

On Monday July 9, the excursion will make a traverse (Stops 12–18) through the imbricate sequence of the Northern and Central Belts, from the oldest to youngest tracts, examining the effects of lithology and deformation on the grade of metamorphism. For logistical reason the first stop in the Southern Uplands (Stop 11) will be made on Sunday July 8 at the Isle of Whithorn. Here the party will be introduced to the lithologies and the style of deformation to be examined the following day.

In collaboration with Professor D R Peacor, Department of Geological Sciences, University of Michigan, electron microscope studies have been made of three samples representing typical late diagenetic, anchizonal and epizonal pelites encountered on the Rhins of Galloway. Some results of this, as yet, unpublished work are included in the notes for appropriate stops, and a selection of SEM and TEM lattice fringe electron micrographs will be available for discussion on the evenings of 8 and 9 July.

Stop 11 — Isle of Whithorn. [NX 481 359]

Greywacke sandstones and shales of the Carghidown Formation (Hawick Group; Llandovery, *griestoniensis — crenulata* biozones). Two styles of folds can be seen in the rocks exposed at the southeast of the Isle of Whithorn. The first folds are tight to isoclinal upright folds which plunge at low angles (~5°) to the east. These folds are here related to soft-sediment deformation of the succession; note how partly lithified sandstones beds were also imbricated and disrupted whereas relatively ductile mudstones have flowed around dismembered sandstones. A second set of folds with more-or-less vertical axial surfaces plunge steeply to the east. These folds are characterized by straight limbs and gently curved hinges. Their geometry suggests generation by sinistral shear. Cleavage, approximately axial planar, is associated with the 2nd fold phase, and can be seen to transect the axes of the 1st folds in a clockwise sense by 10–15°.

XRD analysis of <2µm separations from the cleaved mudstones show that $2M_1$ white mica and chlorite are abundant, with minor albite, ankerite and quartz. Kubler indices range from 0.28–0.36$\Delta°$ 2θ, suggesting mid-to high-anchizonal grades.

Monday July 9th

Stop 12 — Corsewall Point. [NW 982 728]

Greywacke sandstones, conglomerates and mudstones of the Corsewall Formation (Leadhills Group; Ordovician, N. gracilis biozone). These are the oldest rocks examined on the traverse though the Rhins of Galloway, and lie immediately north of the Glen App Fault. Close to the old jetty, conglomerates and coarse sandstones with thin silty mudstones dip at 85° towards the NW. Grading in the sandstones indicates that the succession youngs towards the northwest. The conglomerates are totally unsorted mass-flow deposits. They contain abundant granitoid cobbles and boulders, up to 0.5 m across which have been dated by Elder (1987) at 1200 Ma, 600–700 Ma and 470–490 Ma. A link with exposed plutons in Newfoundland is suggested by Elder (1987). Other rock types present include intermediate and acid gneiss, amphibolite, metadolerite and red chert. Rip-up clasts of mudstone can be seen in the base of some sandstone beds. Thin sections of the sandstones show abundant feldspar and metabasic lava clasts with detrital epidote and hornblende, in a matrix largely composed of mafic phyllosilicates; some metabasic clasts consist of albite-actinolite-sphene intergrowths. Note the thin Tertiary basic dyke trending at 304°.

Approximately 15 m east of the jetty, alongside a stone wall, a slot is eroded along a small tear fault. Here, dark grey-green occasionally reddened, laminated silty mudstones are interbedded with steeply dipping sandstones and conglomerates. The mudstones may show a poorly developed spaced cleavage dipping less steeply than bedding. Scanning electron microscope (SEM) study of the silty mudstone, using back-scattered electron images (BSEI), show grains of quartz, albite, K-feldspar, biotite flakes (<0.5 mm), magnetite and rare chromite, in a phyllosilicate matrix which lacks an obvious fabric. X-ray diffraction (XRD) analysis of the <2µm separations shows that the matrix is mainly composed of 'corrensitic' chlorite characterized by a broad relatively intense 14■ peak, and 10■ illite, which gives a Kubler index of 0.6Δ° 2θ. Similar, late diagenetic grade Kubler indices were obtained from other mudstone samples from the Corsewall Formation. Transmission electron microscope (TEM) lattice fringe images show that the dominant phyllosilicate has a 14■ periodicity, whereas 10■ celadonitic illite is much less common, as was indicated by XRD. Phyllosilicate crystallites are thin (5–25 layers thick) and commonly show layer terminations and other defects; curved crystallites are common. The TEM textures are consistent with the diagenetic grade determined by XRD.

Stop 13 — Portpatrick.

Greywacke sandstones and mudstones of the Portpatrick Formation (Leadhills Group; Ordovician, **P. linearis** biozone). Stop 13 begins at a disused quarry south of the harbour [NX 000 537]. Here massive graywacke sandstone beds are deformed by a monoclinal fold, so that the north and central part of the quarry face are in the vertical limb, and the hinge zone and horizontal limb form the southern side of the face. The hinge of the fold plunges at 18° towards 040°; slickensided surfaces in the hinge indicate accommodation by bedding plane slip. Grading in the sandstones demonstrates younging towards the northwest. Cleavage in the mudstone interbeds is less steep than bedding on the vertical limb, but more or less vertical in the hinge zone, probably fanning across the fold. The greywacke sandstones are predominantly volcaniclastic and contain significant amounts of fresh pyroxene. Secondary albite, chlorite, calcite and minor pumpellyite occur in volcanoclasts and in the sandstone matrix. XRD analysis of the <2µm fraction from a mudstone sample shows 10■ white mica, chlorite and minor albite. The Kubler index of 0.36Δ° 2θ indicates an anchizonal grade.

On the north side of the harbour the Portpatrick Formation is strongly deformed in a narrow E-W trending shear zone [NW 996 543]. Behind the paddling pool, beds dipping steeply northwards show well developed slickensides plunging 25° towards 265°. Quartz and carbonate veins are common, some the result of hydraulic fracturing. As these beds become involved in the shear zone which trends 088° alongside the disused (Victorian) sewer outfall, the mudstones and some fine sandstones develop phyllonitic and mylonitic fabrics with phacoidal fragments of coarse sandstone. Kubler indices of 0.26A° 20 were obtained from slates within the shear zone, indicating that localized input of strain energy has advanced the grade to the anchizone-epizone boundary.

Detailed SEM and TEM studies were made of a shale from the Portpatrick Formation, collected from outcrops 4 km SE of Portpatrick. The shale, which gives a Kubler index of 0.35Δ° 2θ, shows a strong bedding-parallel fabric of abundant albite and detrital mafic phyllosilicates, minor quartz, TiO grains and apatite; secondary phyllosilicates in the matrix are also predominantly oriented bedding-parallel. TEM lattice fringe images show crystallites of 14■ chlorite and subordinate 10■ phengite, the latter ranging from 10 to 300 layers in thickness. Thicker crystallites tend to be straight and defect-free whereas thin crystallites may be curved and show layer terminations and stacking defects. Nannometric folds are recorded and commonly show recrystallization in the fold hinge.

Stop 14 — Port Logan. [NX 094 404].

Greywacke sandstones and mudstones of the Port Logan Formation (Gala Group; Silurian, Llandovary turriculatus - crispus biozones). Strata dip steeply (-70°) to the NW, but bottom structures and grading show that they are overturned, younging to the SE. Soft sediment deformation has disrupted the sandstone beds and resulted in mud injection into fractured blocks. Thin sections show that the sandstones are predominantly quartz-rich, with minor volcanic detritus, in a matrix of white mica and chlorite; calcite forms a patchy cement. The mudstone give a Kubler index of 0.63Δ° 2θ, and <2 μm fractions are composed of illite (?I/S) and chlorite. The late diagenetic grade of these mudstones suggest minimal burial. McCurry and Anderson (1989), have suggested that the Port Logan tract has been obducted rather than subducted with the result that strata were overturned and young southwards. In terms of the model of Stone et al. (1987), the tract has been back-thrusted.

Stop 15 — Lunch at Logan Botanic Garden [NX 097 429]

The garden is famous for its exotic plants, ferns and Australian gums).

Stop 16 — Grennan Slate Quarry [NX 127 394]

Slates and sandstones of the Port Logan Formation (Gala Group; Silurian, Llandovery, crispus biozone). The quarry works cleaved mudstones, which are split along the bedding-parallel fabric to provide cladding and, formerly, local roofing slates. The succession comprises plane laminated, pale grey calcareous mudstones and slates with thin (<1 m) sandstone beds dipping steeply (83°) to the north. Bottom structures on the sandstones indicate that younging is towards the south. A set of kink bands plunging 5° towards 077° deform the bedding-parallel cleavage. Diagenetic carbonate nodules are flattened to oblate spheroids within the bedding-parallel cleavage. In thin section the slate shows a well developed fabric of detrital muscovite, quartz and feldspar, together with secondary white mica (?phengite) and chlorite, oriented parallel to bedding lamination. Three typical slate samples all gave epizone/anchizone indices of 0.26Δ° 2θ, and show $2M_1$ white mica (?phengite) and chlorite, with minor albite, rutile and quartz in <μm fractions. More calcareous mudstones and slates show a range of diagenetic values from 0.41–0.57Δ° 2θ, but essentially possess the same mineralogy as the higher grade slates. Further work is in progress to assess the effects of early diagenetic carbonate cementation on phyllosilicate recrystallization.

Stop 17 — Clanyard Bay [NX 098 377]

Dark grey and black shales of the Moffat Shale Group (Silurian, Llandovery), with numerous thin (<10 cm), pale grey metabentonites. The beds are approximately vertical striking at 095°. A bedding-parallel cleavage is developed in the shales, which show, small-scale folds and boudinage. Metabentonite beds show folds, along-strike thichness variation, and were more ductile than the shales during deformation. Underlying greywacke sandstones, south of the shale outcrop, dip 48° towards the NNW and also young towards the NW. A porphyritic microdiorite dyke, -1.5 m thick and trending 065°, is clearly post-tectonic.

XRD analysis shows that the shales typically contain 2M white mica and chlorite, with minor albite and quartz, in <2 gm fractions; Kubler indices of 0.26–0.27Δ° 2θ suggests that the grade is high anchizone. The metabentonites consist of mixed-layer illite/smectite, with up to 5% smectite, and traces of chlorite; the Kubler index of 0.55Δ° 2θ indicates a much lower 'grade' than the enclosing shales. A thin section of the metabentonite shows scattered chips (<0.3 mm) of altered lava, feldspar, apatite and rare zircon in the phyllosilicate matrix.

Stop 18 — Mull of Galloway [NX 157 304].

Greywacke sandstones and slates of the Carghidown Formation (Hawick Group; Silurian, Llandovery, griestoniensis-crenulata biozones). In the cutting behind the lighthouse the sequence of thinly-bedded, carbonate-cemented sandstones and plane-laminated silty slates is essentially vertical, striking at 056°. Bottom structures on the sandstone beds indicate younging towards the NW; when restored to the horizonal, these structures suggest that currents flowed from north to south. A vertical slaty cleavage strikes at 074°. The sequence is cut by a thin (<10 cm) spherulitic felsite dyke with flow-banded margins and a flow-folded centre.

In thin section the greywacke sandstone clasts are predominantly of quartz (including quartzite, quartz schist, and rare granophyre, all < 2 mm), with microcline, muscovite, chloritized biotite, a few maffic and felsic lava clasts, and accessory tourmaline and zircon. The phyllosilicate matrix is extensively replaced by a calcite cement. BSEI of a slate sample show an anastomosing cleavage enclosing grains of quartz, albite and detrital phyllosilicates, including chlorite/mica stacks. Oriented TiO pseudomorphs appear to represent original heavy mineral-rich laminae. XRD analysis of <2 μm fractions indicate that 2μm mica (phengite) and chlorite are the dominant phyllosilicates, with minor albite, quartz and rutile. Kubler indices of 0.22–0.28Δ° 2θ indicate high anchizone-epizone grades suggesting that the rocks may have been carbonate-poor at the time of metamorphism. TEM lattice fringe images show intergrown chlorite and mottled phengite crystallites ranging from 15 to over 300 layers in thickness. Chlorite generally contains fewer crystal defects than phengite.

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Accommodation (dinner, bed and breakfast)

Nights of July 6th (Friday) and July 7th (Saturday):

The Horseshoe Hotel, Rothay Road, Ambleside, Cumbria, LA22 OEE [05394–32000]

Nights of July 8th (Sunday) and July 9th (Monday):

The Downshire Arms Hotel Portpatrick Wigtownshire Scotland [077681–300]

List of excursion party from 'Phyllosilicates' conference Manchester University, July 1990

Dr Fernando Alvarez

Daisy Barbosa Alves

Dr P Arkai

Dr R E Bevins

Dr Covadonga Brime

Dr D D Eberl

Dr N J Fortey

Professor R L Freed

Professor M Frey

Mrs Eveline Hayes

Dr W L Huang

Professor Warren D Huff

Professor J C Hunziker

Wei Teh Jiang

Professor H J Kisch

Professor B Kubler

Kenneth J T Livi

Dr F T Madsen

Mr R J Merriman

Dr Takashi Miki

Dr Ph Muchez

Dr Robin Offler

Dr T C Pharaoh

Raymond Beiersdorfer

Dr B Roberts

Dr D Robinson

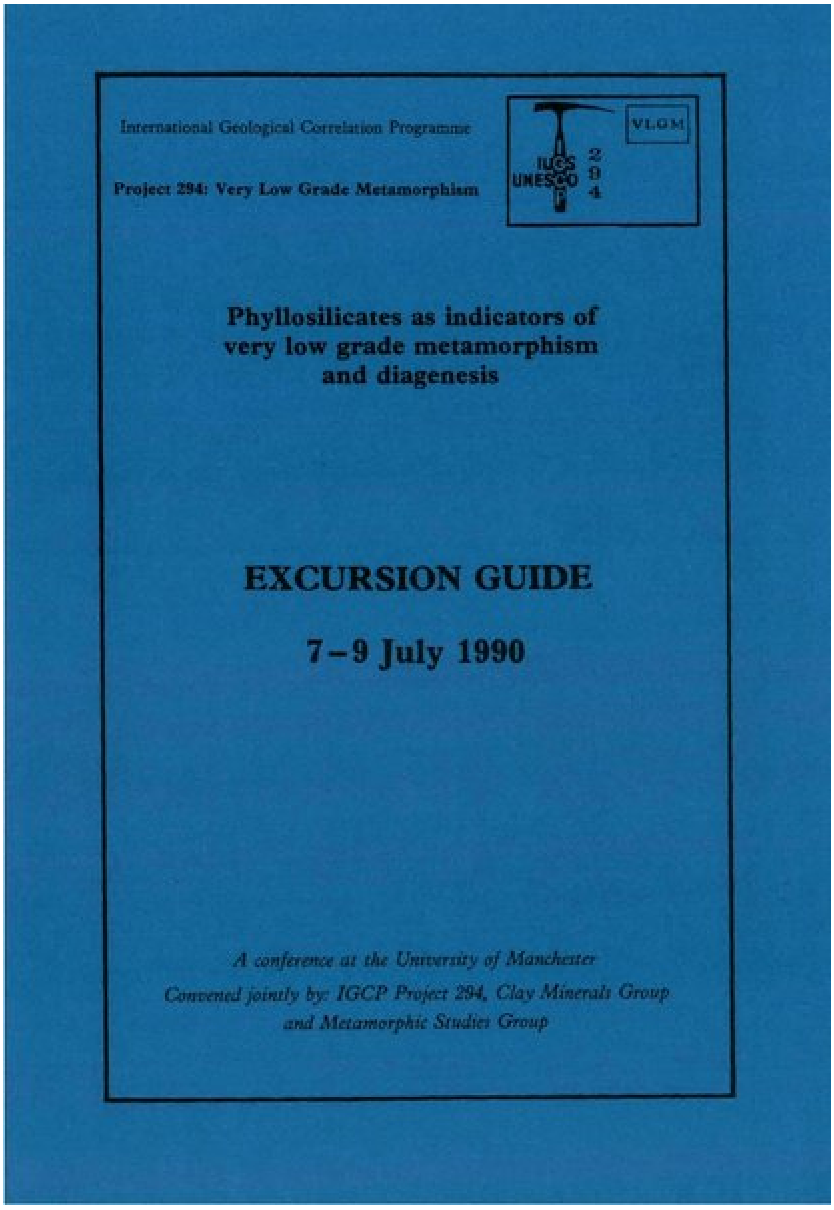
Dr P Schiffman

Yen Hong Shau

Vaclav Ing Suchy

Dr Istva'n Viczia'n

Ms Chao Yang International Geological Correlation Programme


International Geological Correlation Programme

Project 294: Very Low Grade Metamorphism

Phyllosilicates as indicators of very low grade metamorphism and diagenesis

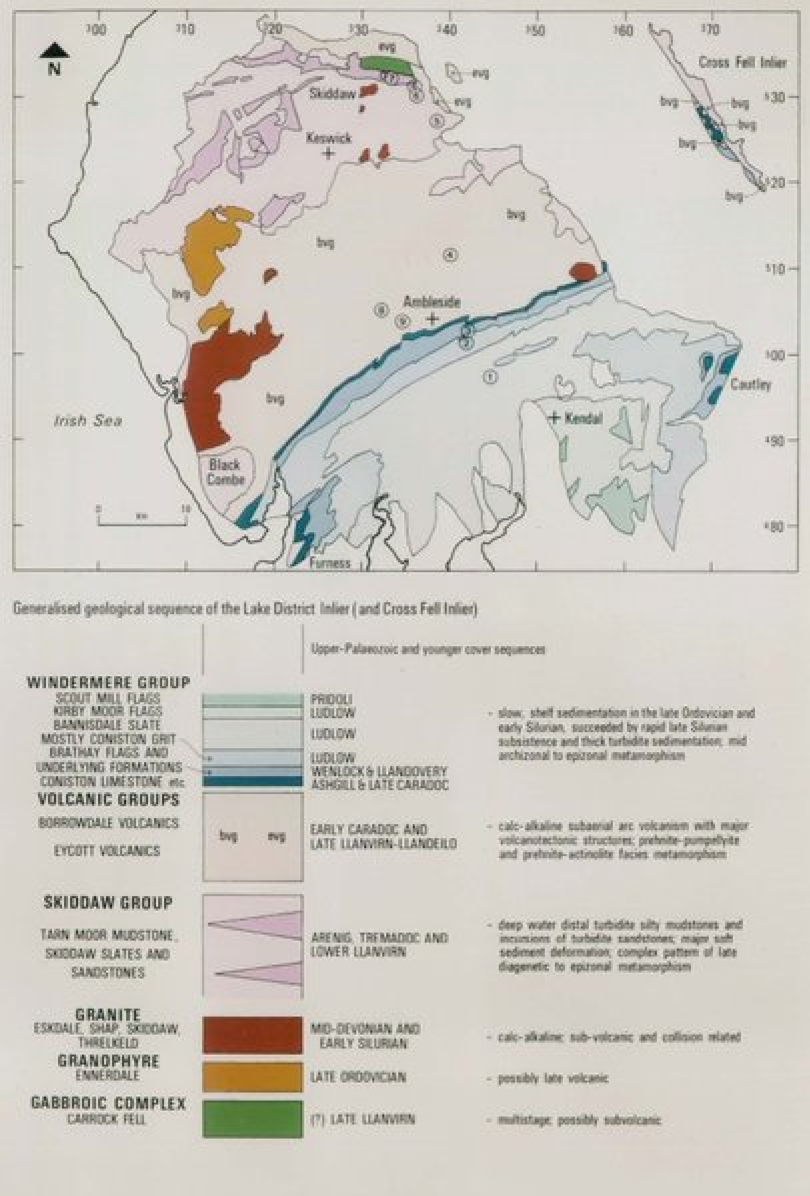
EXCURSION GUIDE

7–9 July 1990

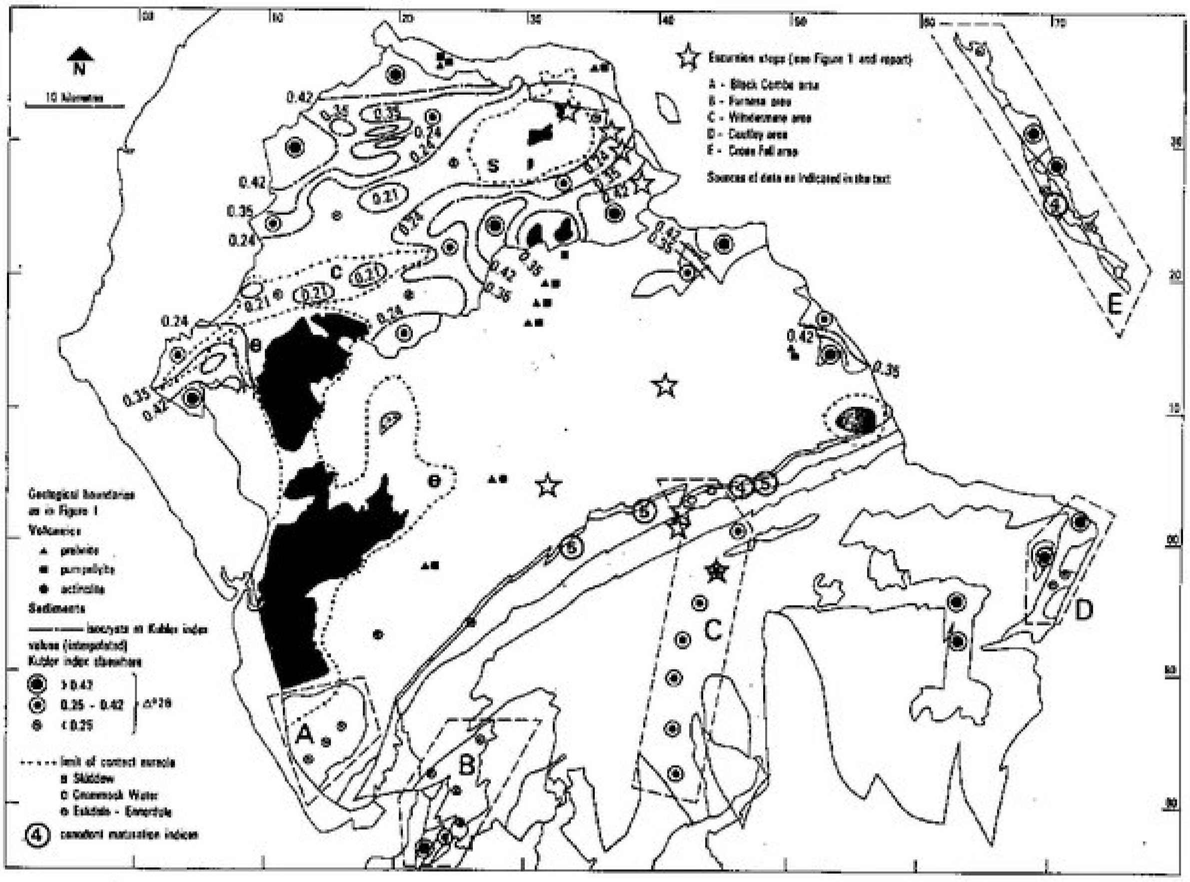
A conference at the University of Manchester

Convened jointly by: IGCP Project 294, Clay Minerals Group and Metamorphic Studies Group

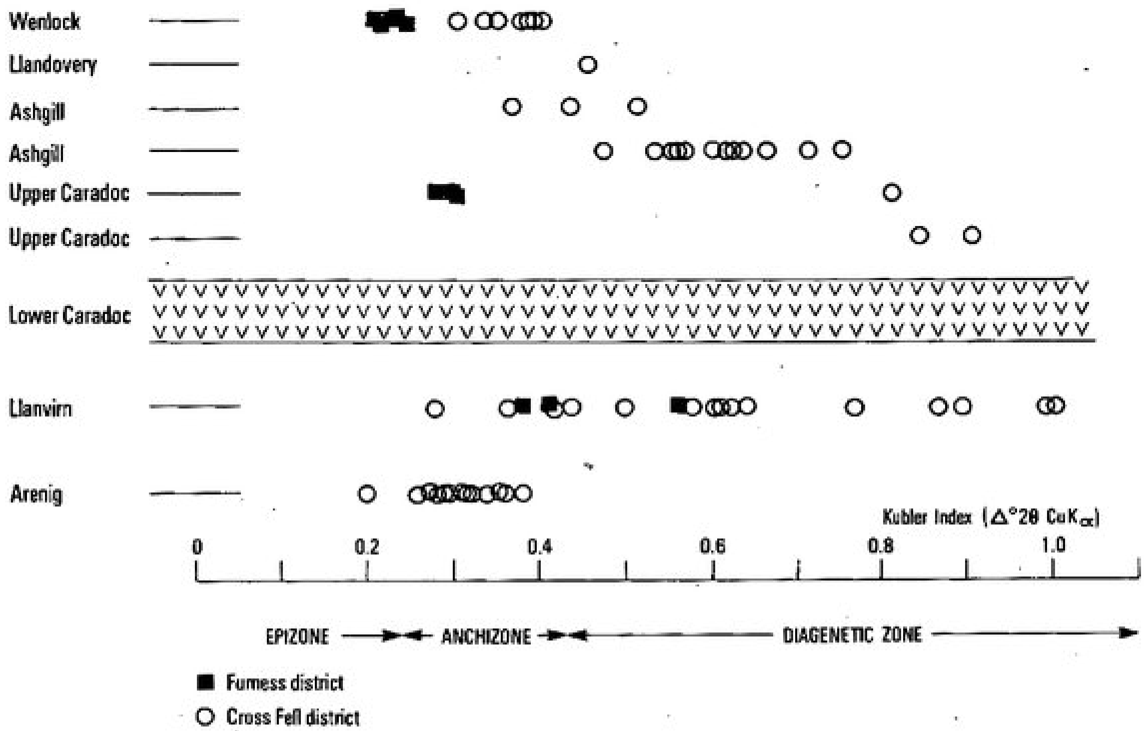
(Front cover).



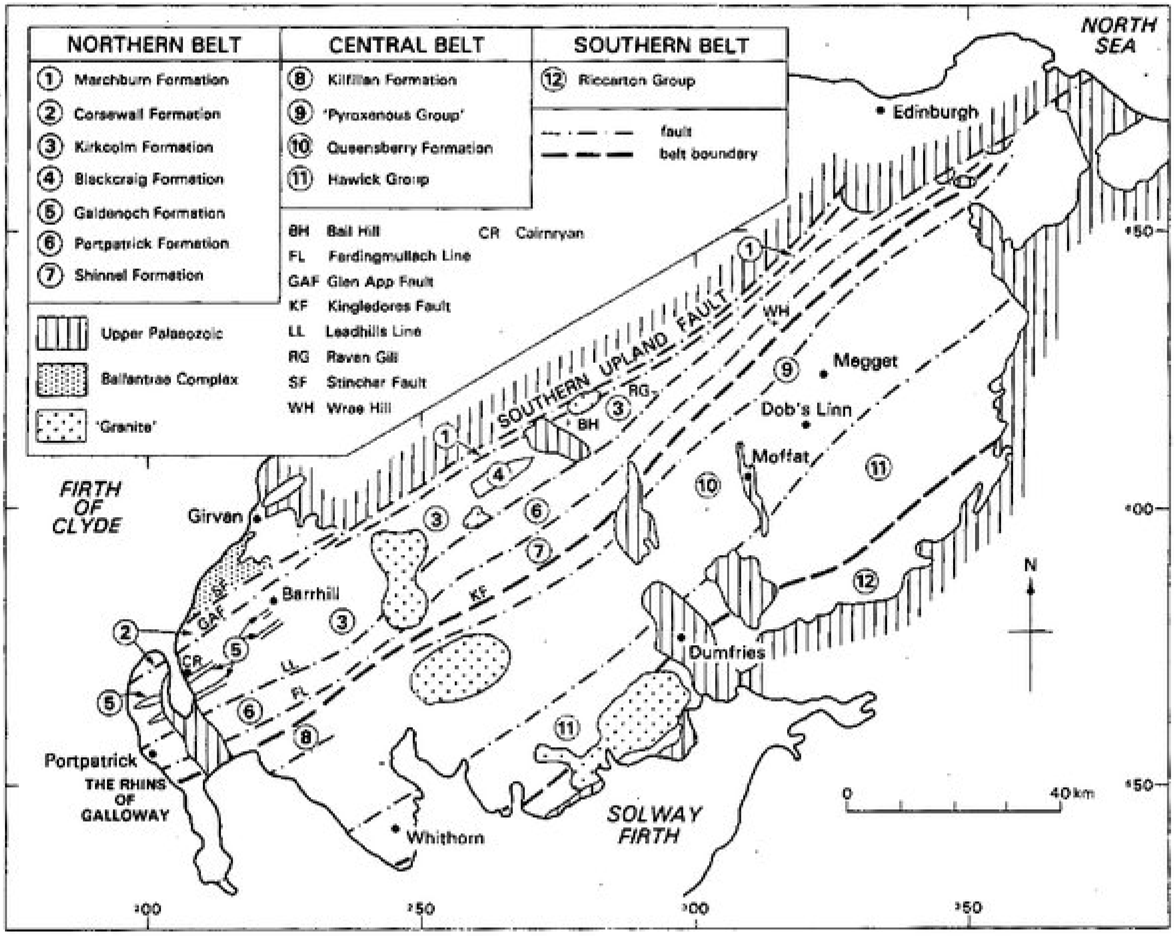
(Figure 1) Geological sketch map of the Lake District.



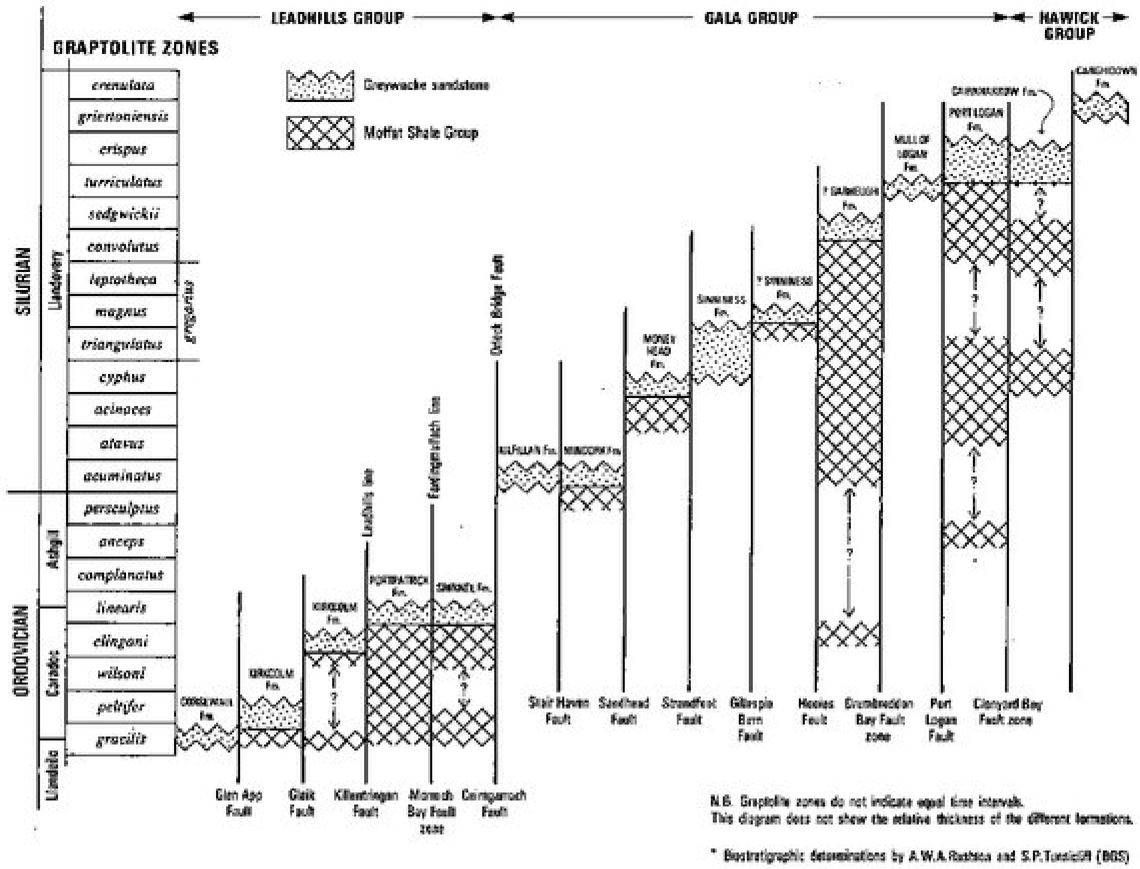
(Figure 2) Metamorphic map of the Lake District.



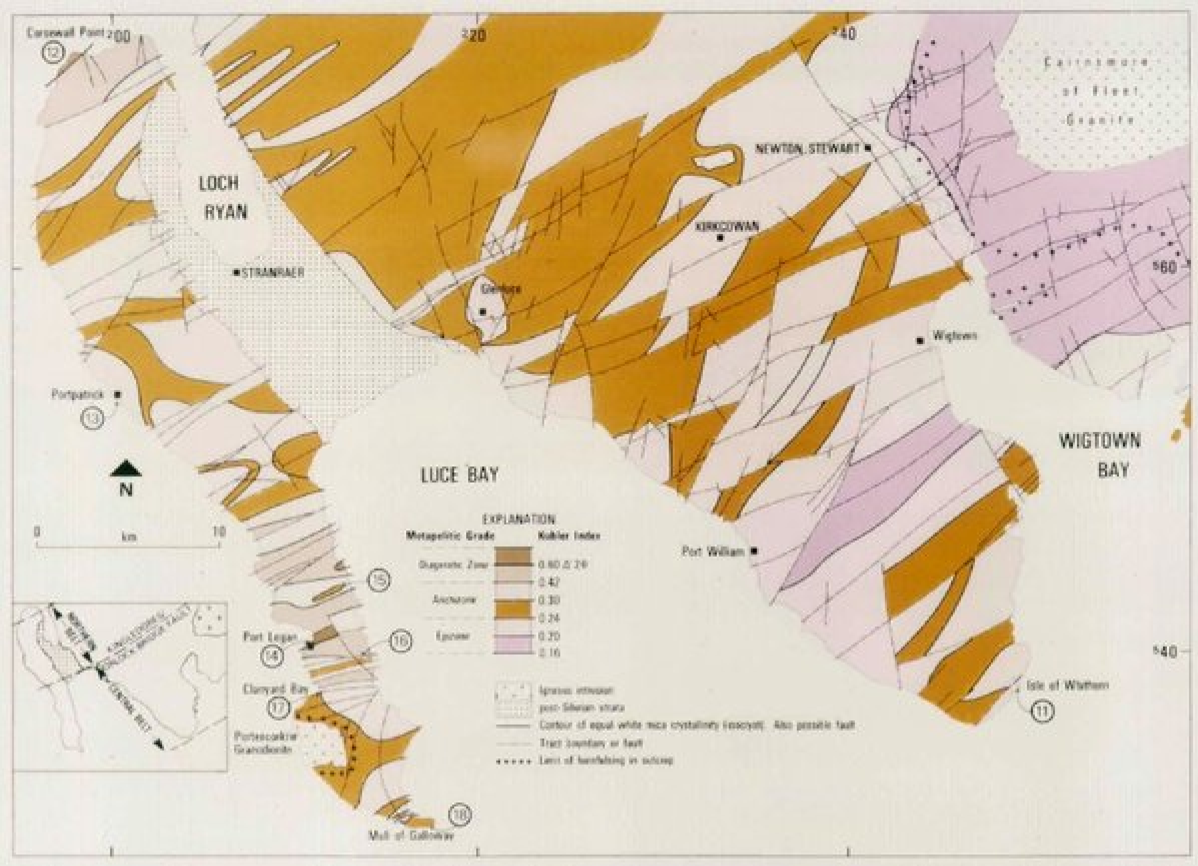
(Figure 3) Kubler indices plotted against stratigraphic horizon, for mudrocks from the Cross Fell and Furness areas.



(Figure 4) Outline geology of the Southern Uplands.



(Figure 5) Simplified biostratigraphy of the Rhins of Galloway area arranged in tectonostratigraphic units.



(Figure 6) Metamorphic map of the Galloway and Kirkcudbright region of the Southern Uplands.