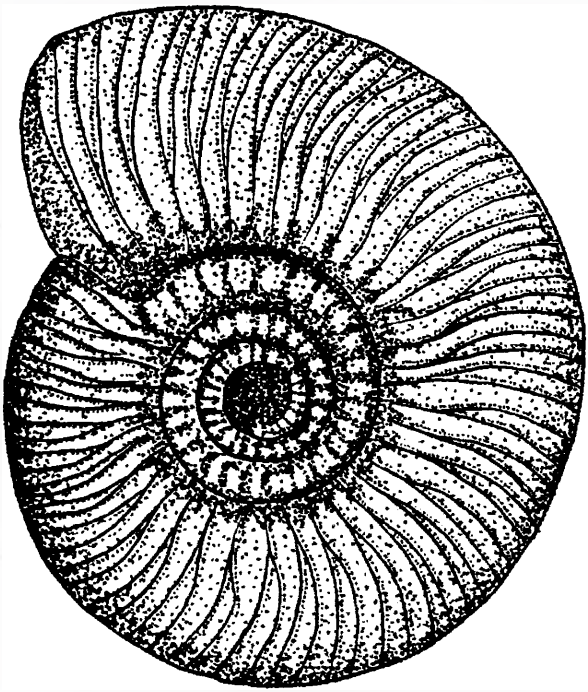
THE CUMBERLAND GEOLOGICAL SOCIETY



PROCEEDINGS

Volume 6 2000-2001 Part 4

ISSN 0967-2443

THE CUMBERLAND GEOLOGICAL SOCIETY

PROCEEDINGS 2000 - 2001

Volume 6 Part 4

Published by the Cumberland Geological Society

May 2002

ERRATUM.

Proceedings Cumberland Geological Society, Vol 6, part 4, 2000-2001.

Page 530, Article on the Bowder Stone. We regret there is an error in the conversion of tonnes/tons in the 8th line. The final sentence of this paragraph should read :
Laboratory measurement of samples of the andesite give a specific gravity of 2.65 and thus a calculated total weight of 1273.8 tonnes (1253.7 tons) – i.e. just over 517 tons lighter than Pocklington calculated.

CONTENTS

EDITOR'S NOTES 484

ORIGINAL ARTICLES 485

A thermal contraction crack in bedrock at Braithwaite, Cumbria 485
D. K. Farrow, M. G. Burnley, S. P. Oxford and A. Palmer

Garrigill: evidence of global warming, ancient and modern 497
Dr B. Webb

Building and decorative stones in Whitehaven 505
M. Fox

The building stones of Penrith and district 511
E. Skipsey

The Bowder Stone, Grange-in-Borrowdale, Cumbria 525
Dr R. A. Smith

On the genesis of shear-zone-hosted gold mineralisation in south Eastern Desert, Egypt 540
Dr W. E. G. Taylor & Dr Y. A. El Kazzaz

The Solway region in the late Pleistocene 553
Dr R. P. K. Clark

EXCURSION REPORTS 2000 587

Borrowdale Volcanic Group rocks in Cat Gill in the footsteps of James Clifton Ward - Dr R. A. Smith 587

The Furness of John Bolton: Lindal, Plumpton, Gleaston and Stank – D. A. Kelly 588

Thomas Hay: Glenridding – Dr R. P. K. Clark and Dr R. A. Smith 591

Watch Hill and Elva Plain through the eyes of Tom Eastwood – D. Dickins 593

In Charles Edmonds' Day: Longlands and Clints – M. B. Dodd 596

The Carboniferous limestones of Yewbarrow and Beck Head – Dr I. Burgess 598

List of other excursions held in 2000 602

EXCURSIONS 2001 603

LECTURE REPORTS 2000 – 2001 604

Eruptions on the volcanic island of Montserrat: monitoring and understanding an explosive volcano - Dr S. Loughlin 604

A tale of two volcanoes: Mount St Helens and Kilauae - Dr R. A. Smith 606

Limestone pavements in Cumbria – their origin and conservation - S. Webb 608

Other lectures 610

LECTURE REPORTS 2001 – 2002 611

Dry stone walls - Dr E. Robinson 611

Volcanic eruptions under Iceland's glaciers – H. Tuffen 612

Rivers, landforms and man – a system in equilibrium? - Dr S. Bradley 614

Mam Tor – C. Arkwright 616

The ice age in Lakeland - Dr R. A. Smith 620

A geologist in the Andes of Ecuador - Dr R. Hughes 622

ANNUAL GENERAL MEETINGS 624

ANNUAL DINNERS 625

THE SOCIETY SMALL AWARDS FOR STUDENTS 626

OBITUARY NOTICE 627

LIST OF SOCIETY OFFICERS AND COUNCIL – 2001 and 2002 628

EDITOR'S NOTES

I would like to thank the following people who have contributed to the production of these Proceedings: the authors of the original articles; those who have submitted lecture and excursion reports; the members of the Editorial Board; those who have provided technical references for the original articles; my predecessor Chris Thompson for his advice and guidance.

The Proceedings is a biennial publication that caters for contributions on all aspects of geology and geomorphology of northern England. Contributions are welcome and should be submitted to the Editor. As well as full papers, the Society would be interested to receive shorter communications on the geology of Cumbria; these might include descriptions recording temporary exposures or other items of interest to the general readership of the Proceedings.

David Kelly

Editor

Published by the Cumberland Geological Society May 2002

General Secretary: Dennis Dickins

[redacted]

ISSN 0967 - 2443

ORIGINAL ARTICLES

A THERMAL CONTRACTION CRACK IN BEDROCK AT BRAITHWAITE, CUMBRIA

Della K. Farrow, Martin G. Burnley, Stephen P. Oxford and Adrian Palmer

Abstract

A fissure interpreted as a thermal contraction crack observed in Skiddaw Group bedrock at Braithwaite has been used to make palaeoenvironmental inferences for the period of Late Devensian ice wastage. It is suggested that cracking was induced by the rapid reduction in air temperature resulting from the wastage of the Late Devensian ice sheet where air temperatures in the ice marginal region were in the order of -10°C. This is the first observation of a thermal contraction crack formed in bedrock in England.

Introduction

Thermal contraction crack is the general term used to denote a fissure that forms in the ground as a result of severe and repeated winter cooling (French, 1996). Depending upon the severity of this cooling such a fissure may extend for a depth ranging from a few centimetres to several metres. The formation of such cracks is facilitated by perennially frozen ground that is associated with permafrost regions. In these areas the coefficient of expansion/ contraction of ice is greater than that of either bedrock or frozen sediments such that once ice has formed in the ground it hastens the development of contraction cracks.

In Britain the presence of thermal contraction structures, such as ice wedge casts and ice wedge polygons have been used to indicate a permafrost palaeoenvironment (Worsley, 1966; Rose *et al.*, 1985; Ballantyne and Harris, 1994). The distribution of these structures shows two distinct groups (see Fig. 18.2 of Rose *et al.*, 1985). The first group occurs predominantly in East Anglia and southern England, and lies outside of the maximum extent of the Late Devensian ice sheet. The second group is situated in the highlands of Wales and eastern Scotland, but most are outside of the limit of the glaciers and ice caps that developed during the Loch Lomond Stadial.

One area where thermal contraction cracks have not been noted is in the Lake District. A fissure, formed in Skiddaw Group bedrock, has been recorded at an altitude of 108m OD in the village of Braithwaite (NY 223254), which is located 3km west of Keswick, Cumbria. Reasons for the interpretation of this crack as a thermal contraction feature are given and inferences are made about the periglacial environment of the north-westLake District during the wastage of the Late Devensian ice sheet.

Description

The crack is an elongate, two-dimensional, wedge-shaped feature, filled with allochthonous material that has formed entirely within slightly weathered,

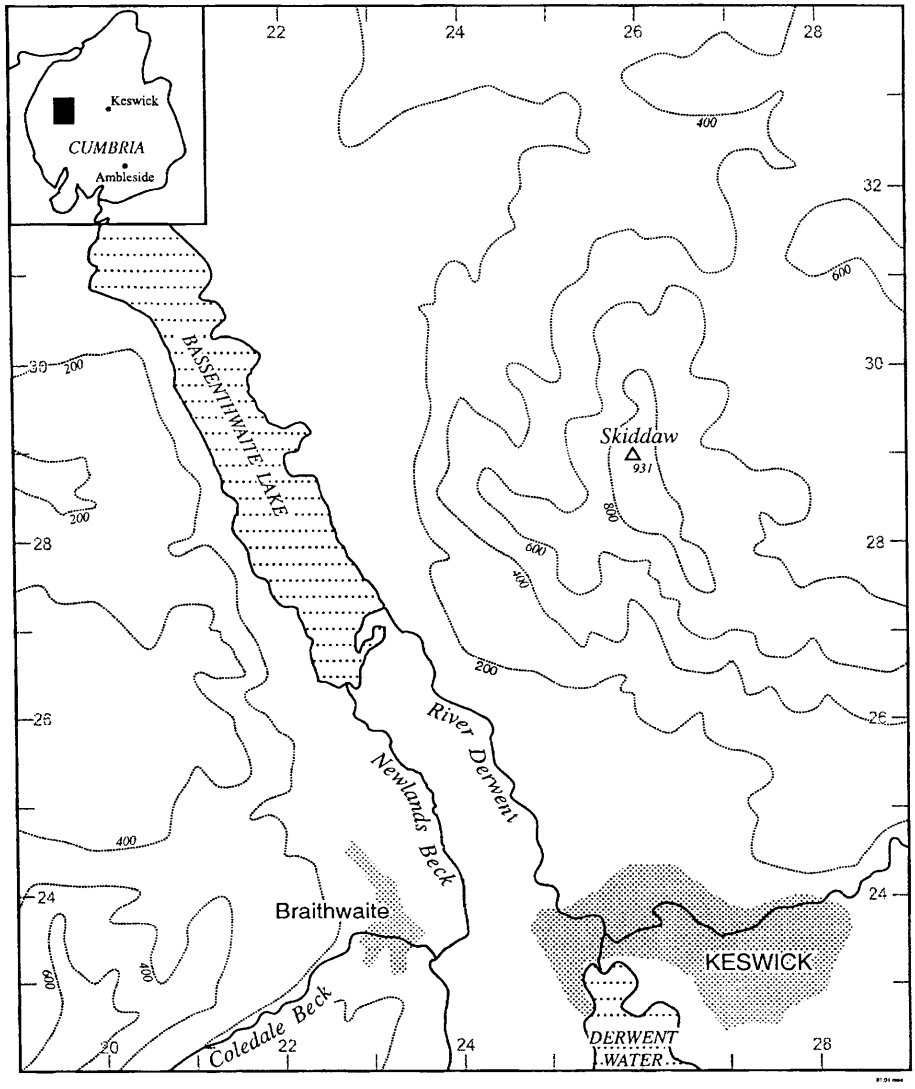


Figure 1 - Location of the study site, Braithwaite, Cumbria. Scale and orientation are shown by the National Grid Co-ordinates.

fissile slate. It is 2.2m in depth (length) and has a maximum width of 10cm at the top tapering to 2cm at the bottom (Figs. 2a; 2b and 3). It is independent of the cleavage of the slate being at an angle of 35° to the cleavage planes. There is no evidence of upturned adjacent rock strata.

The infill is a gravely, clayey diamict that consists predominantly of fine gravel, sand and clay with a reddish brown colour (Munsell colour: 5YR 5/6). Particle size analysis shows that gravel (nothing is larger than 8mm) is the dominant sediment size, comprising 86.3% of the sample (Fig. 4). Of the remaining sediment 9.0% is sand, 1.1% silt and 3.6% clay. If the gravel component is removed then the relative proportions of the remaining non-gravel fractions are: sand 65.3%, silt 8.0%, and clay 26.4% (Fig. 5) indicating clearly that there is no mode of silt and hence no loessic component, as may have been expected (Rose *et al.*, 2000). Observation of the gravel sized component of the infill shows that there is no preferential clast orientation, yet the clasts in this diamict are very angular and are composed entirely of slate. This material is considered to be mainly frost shattered material that has been washed into the fissure from upslope. Colluvium overlies the crack.

Process of Formation

As slate is a fissile rock that fractures readily along its cleavage planes it is unlikely that the crack described here was produced by repeated freeze-thaw action. A fracture produced by this process would be expected to follow the cleavage lines of weakness. Therefore a mechanism is required whereby fracture can take place but where the cleavage planes will not act as lines of weakness. Consequently, it is suggested that the slate must have been frozen into a wholly competent massive rock, and then subjected to rapid cooling, which caused contraction and cracking. Accordingly the fissure recorded at Braithwaite is interpreted as a permafrost thermal contraction crack.

The only other known examples of wedge-shaped features that have formed in bedrock have been recorded in carbonaceous shales overlying the Charlestown Main Limestone at Cults, Fife (McManus, 1966), and in Mercia Mudstone cliffs at Swanbridge, South Glamorgan (Harris, 1989). At Swanbridge, Harris (1989) has described fourteen fissures that have depths ranging from 0.60m to 2.76m. There is no relationship between these fissures and structural properties such as faults. He therefore suggests that the fissures in South Wales were not formed through tectonic activity. As each of the wedges is characterised by adjacent, upturned rock strata, he proposes that they are the product of ice wedge development and so these features are interpreted as ice wedge casts. McManus (1966) also interprets a 5m fissure as an ice wedge cast with similarly described properties such as fractured, upturned rock strata directly adjacent to the fissure. In common with the Braithwaite contraction crack the features at both of these localities have formed in fissile, well-jointed lithologies, although the Braithwaite feature does not exhibit upturned rock strata. It is suggested that the Braithwaite fissure developed in response to

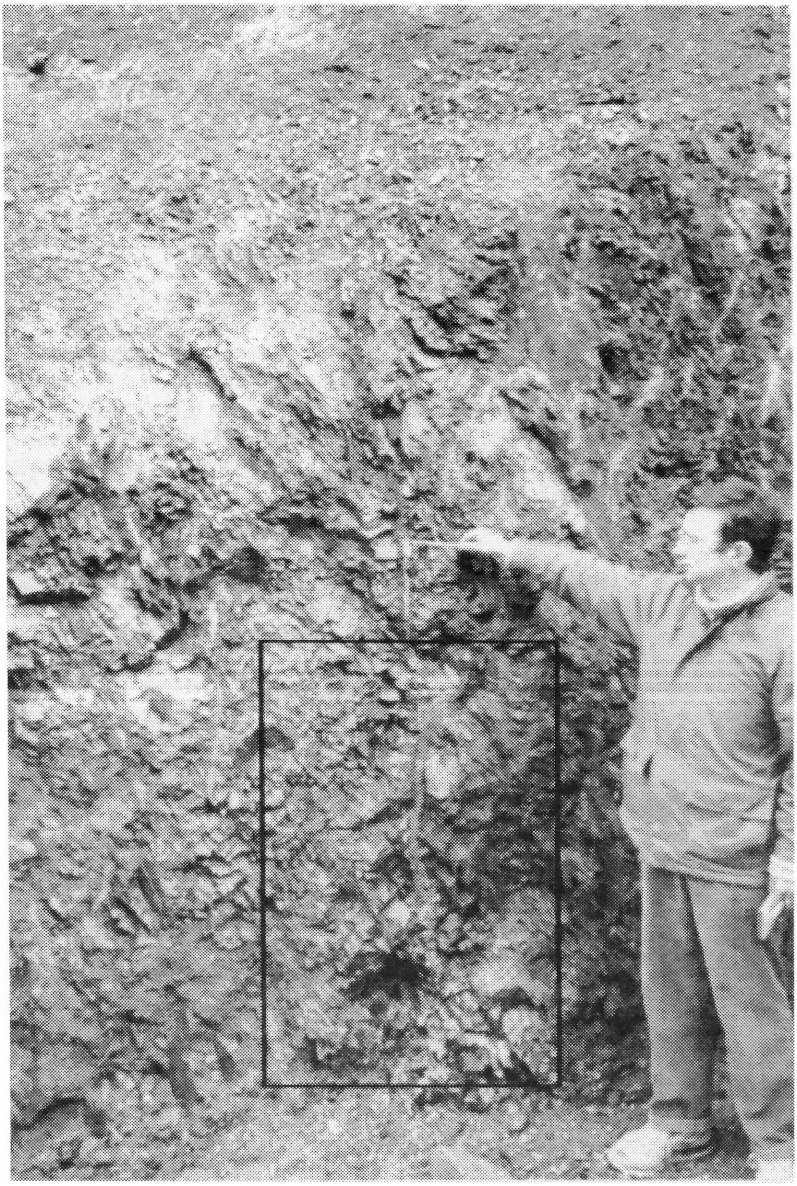


Figure 2a - Thermal contraction crack cutting across the bedding planes of well foliated Skiddaw Group bedrock. Colluvium obscures the top of the crack.

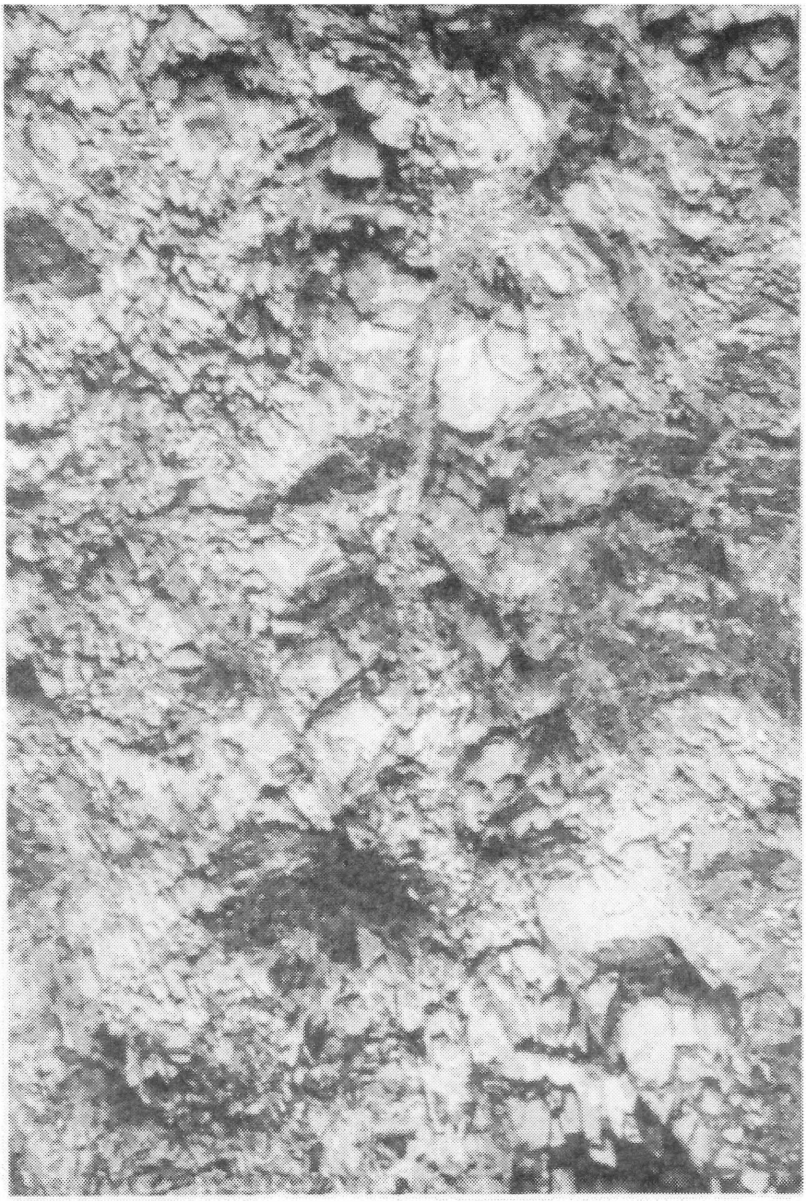


Figure 2b - The contact between the edge of the thermal contraction crack and the bedrock is clearly defined, with no upturned strata evident in the adjacent rocks.

slightly different palaeoenvironmental conditions compared with those that formed the wedges in eastern Scotland and South Wales.

Typically, ice wedge casts in Britain are found in unconsolidated or fine grained sediments such as sands and gravels, sand, clay or peat (Ballantyne and Harris, 1994). In areas of active wedge formation, such as the western Arctic coast of Canada (Mackay, 1993), development occurs where the mean annual air temperature (MAAT) is in the order of <-6°C (Péwé, 1966; Murton *et al.*, 2000). Cracking in perennially frozen bedrock requires either a lower MAAT (Lachenbruch, 1962), or a rapid reduction in air temperature (Mackay, 1993). Either of these conditions will enable the tensile strength of the icy rock to be overcome thereby causing cracking.

Ballantyne and Harris (1994) estimate that at sea level the MAAT during the latter stages (c. 14.5 -13ka BP) of the Dimlington Stadial in central England was in the order of -10°C. With these temperatures continuous permafrost would have been present in the Derwent Valley, and elsewhere in the Lake District. However during the Loch Lomond Stadial the MAAT at sea level in the Lake District is estimated to be in the order of 1°C (Sissons, 1979; 1980) with the nearest corrie glaciers having developed at Grasmoor, approximately 5km southwest of Braithwaite. From studies into the rate of contemporary ice wedge cracking on Garry Island, Northwest Canada, Mackay (1993) has observed that a continuous temperature reduction of 1.8°C per day over a four day period was sufficient to crack frozen lake sediments. While it is not possible to calculate changes in temperature from a fossil feature, is suggested that similar conditions would have been necessary to form the contraction crack at Braithwaite.

Palaeoclimatic inferences

Following the deglacierization of the Late Devensian ice sheet from the Derwent valley during the latter stages of the Dimlington Stadial (c. 14.5 -13ka BP) the slate, which had been insulated by the warm-based ice-sheet (Boulton *et al.*, 1991), would have been exposed to intense atmospheric cooling. If the estimated sea level MAAT in Central England during this deglaciation period was -10°C (Ballantyne and Harris, 1994) then it would be plausible to suggest that at Braithwaite the MAAT was ≤-10°C. The subsequent rapid reduction in temperature experienced by the slate during the process of deglacierization would have caused thermal contraction and hence cracking.

As the width of the crack ranges from 10cm to 2cm it is suggested that it represents a single contraction event, rather than a series of similar events. If the feature had developed due to successive cooling events, possibly associated with the accretion of ice crystals within it, then it would be expected that the top of the crack would be larger as cooling permeated downwards. Also adjacent rock strata would become deformed and upturned as cooling progressed. In this instance the contraction crack cuts abruptly across the cleavage planes of the slate implying that freeze thaw processes were not responsible for the formation of this feature.

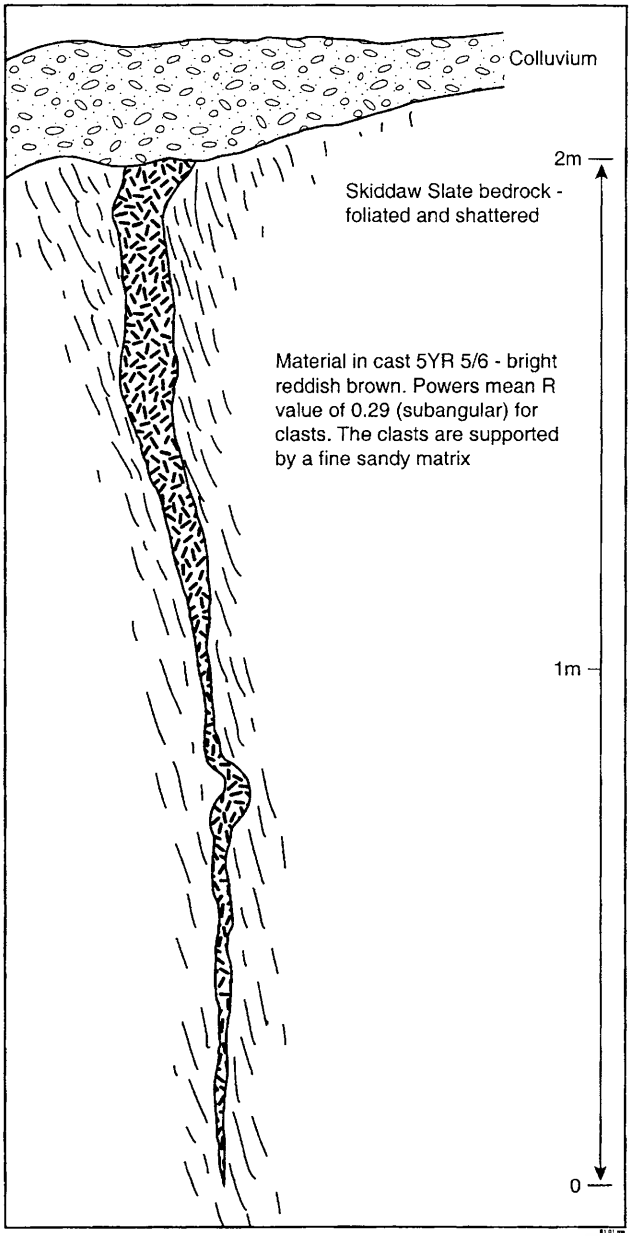


Figure 3 - Schematic representation of the thermal contraction crack showing that there is no preferred orientation of the infill sediment.

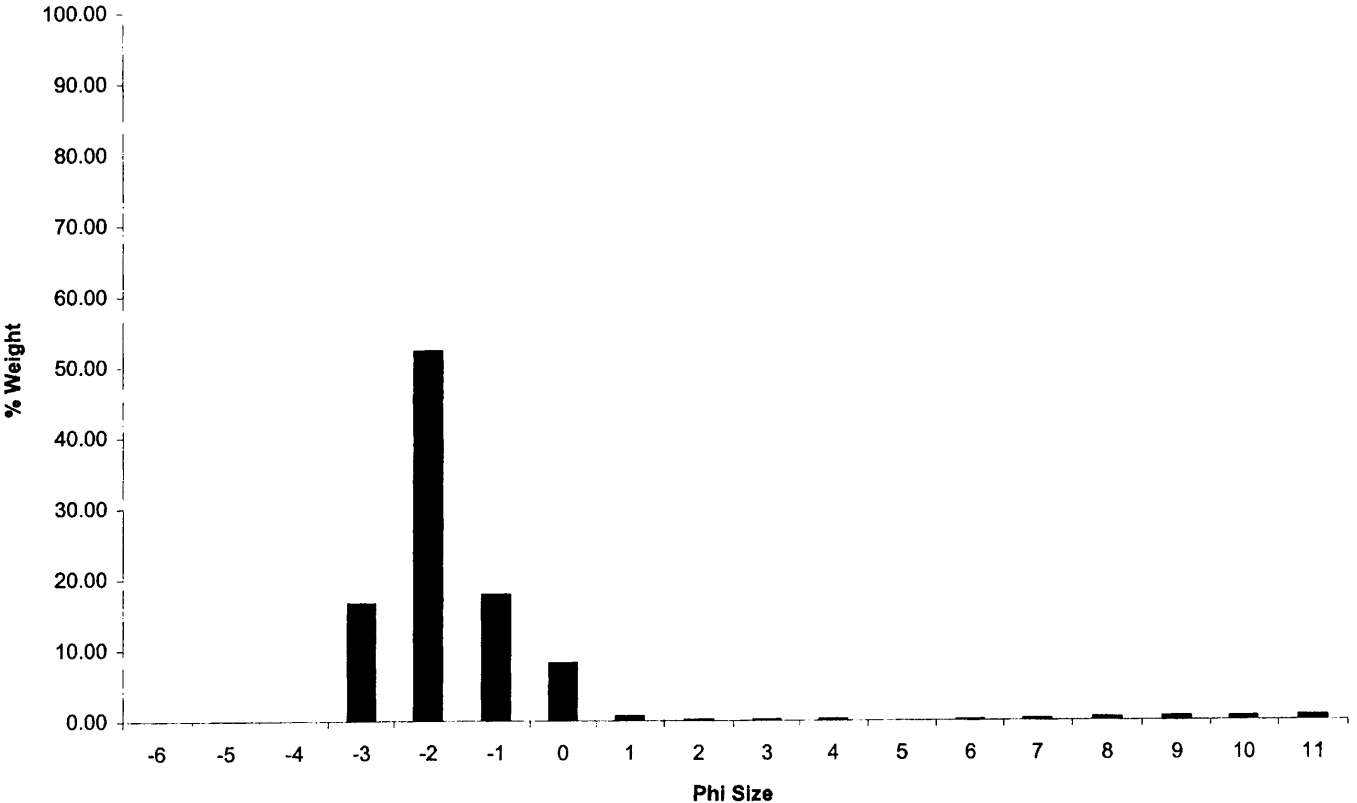


Figure 4 - Particle size analysis of the thermal contraction crack infill sediment.

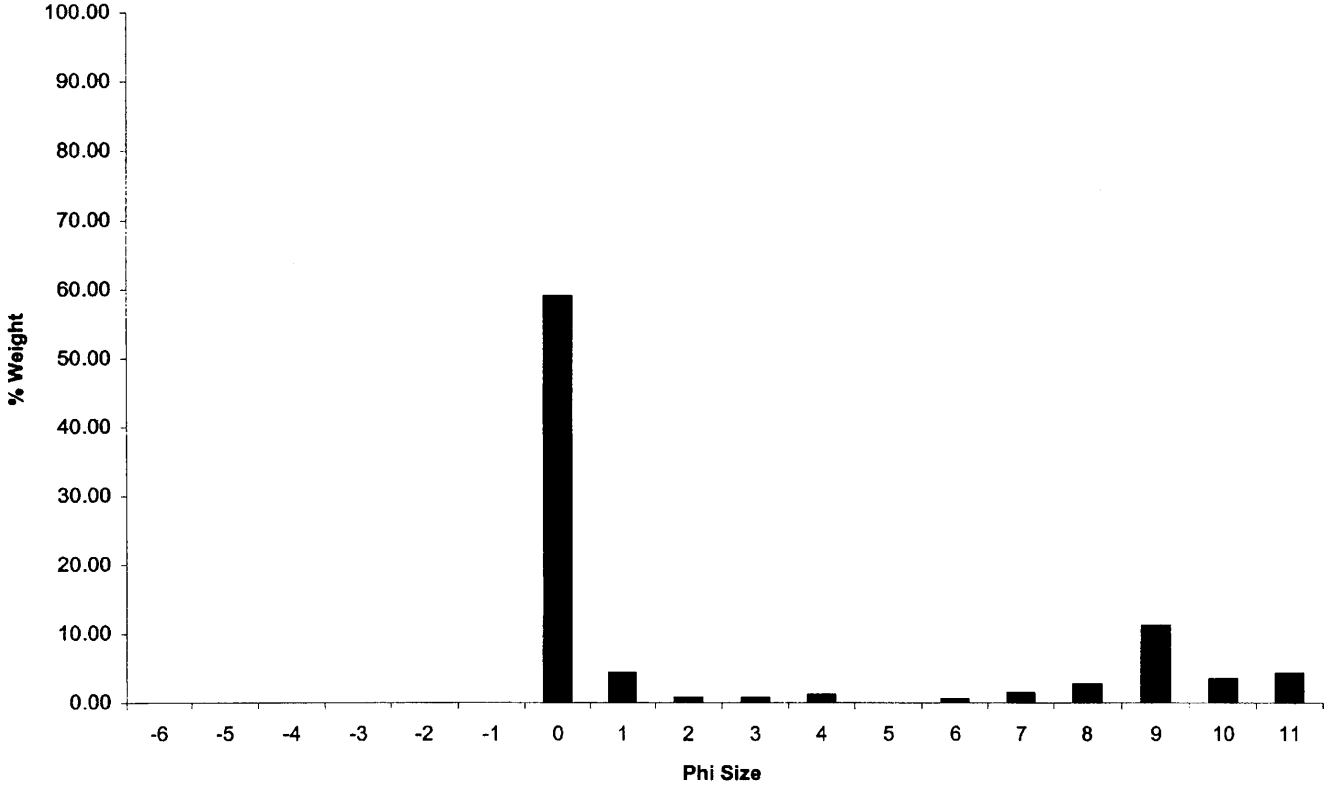


Figure 5 - Particle size analysis of the thermal contraction crack infill sediment with the gravel fraction removed.

This interpretation also agrees in part with McManus (1966) who argues that the Scottish ice wedge developed as a result of stress release over an extensive area. However he provides no further comment as to the cause of this stress release, although it is suggested that the ice wedge formed after a period of glaciation in the area; an obvious source of stress release is the process of deglacierization. Harris (1989) on the other hand correlates the South Wales ice wedges with similar features recorded at Oldbury upon Severn, Gloucestershire (Allen, 1984) and infers from this that his features were formed under permafrost during the Dimlington Stadial.

However the Braithwaite feature differs from those at Cults and Swanbridge regarding its infill. In these cases all of the clasts, whether local or far travelled lithologies, are vertically aligned, while at Braithwaite there is no preferred clast orientation. McManus (1966) suggests that the orientation of the clasts in the Cults ice wedge was caused by alternate freezing and thawing, which led to frost heaving within the wedge. By comparison, this supports the suggestion that the environment in which the contraction crack formed was not dominated by repeated freeze-thaw action. Instead, it is likely that once the contraction crack had formed, the diamict was washed into the open fissure during summer melting of the active layer. This would explain the dominance of the gravel and clay sized particles in the infill.

Conclusion

The Braithwaite feature is interpreted as a thermal contraction crack formed after the mlting of the Late Devensian ice sheet from the Derwent valley during the latter stages of the Dimlington Stadial. It developed as a result of a relatively rapid reduction in air temperature, immediately following the deglacerization of the site, and the exposure of the locality to atmospheric cooling. This suggests that the Derwent valley experienced mean annual air temperatures of at least -10°C while the Late Devensian ice sheet was melting and that in these circumstance ice wastage was likely to have been caused by snow starvation, rather than a rise of temperature.

References

ALLEN J.R.L. 1984. Truncated fossil thermal contraction polygons in the Mercia Mudstone Formation (Trias), Oldbury upon Severn, Gloucestershire. Proceedings of the Geological Association, 95, 263-273.

BALLANTYNE C.K. AND HARRIS C. 1994. The Periglaciation of Great Britain. Cambridge University Press.

BOULTON G.S, PEACOCK J.D. AND SUTHERLAND D.G. 1991. Quaternary. In G.Y. Craig (ed.) The Geology of Scotland (third edition). The Geological Society, London. p503-537.

FRENCH H.M. 1996. The Periglacial Environment (2nd edition). Longman.

HARRIS C. 1989. Some possible Devensian ice-wedge casts in Mercia Mudstones near Cardiff, South Wales, Quaternary Newsletter, 58, 11-13.

LACHENBRUCH A.H. 1962. Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost. Geological Society of America Special Paper, 70, 69pp.

MACKAY J.R. 1993. Air temperature, snow cover, creep of frozen ground, and the time of ice-wedge cracking, western Arctic coast. Canadian Journal of Earth Sciences, 30, 1720-1729.

McMANUS J. 1966. An ice wedge and associated phenomena in the Lower Limestone Series of Fife, Scottish Journal of Geology, 2, 259-264.

MURTON J.B., WORSLEY P. AND GOZDZIK J. 2000. Sand veins and wedges in cold aeolian environments. Quaternary Science Reviews, 19, 899-922.

PÉWÉ T.L. 1966. Palaeoclimatic significance of fossil ice wedges. Biuletyn Peryglacjalny, 15, 65-72.

ROSE J., BOARDMAN J., KEMP R.A. AND WHITEMAN C.A. 1985. Palaeosols and the interpretation of the British Quaternary stratigraphy. In: K.S. Richards, R.R. Arnett and S. Ellis (eds) Geomorphology and Soils. George Allen and Unwin, London, 348-375.

ROSE J., LEE J.A., KEMP R.A. AND HARDING P. 2000. Palaeoclimate, sedimentation and soil development during the Last Glacial Stage (Devensian), Heathrow Airport, London, UK. Quaternary Science Reviews, 19, 827-847.

SISSONS J.B. 1979. The Loch Lomond Stadial in the British Isles. Nature, 280, 199-203

SISSONS J.B. 1980. The Loch Lomond Advance in the Lake District, northern England. Transactions of the Royal Society of Edinburgh: Earth Sciences, 71, 13-27.

WORSLEY P. 1966. Fossil frost wedge polygons at Congleton, Cheshire, England. Geografiska Annaler, 48A, 211-219.

Acknowledgements

The authors wish to thank to Jim Rose and an anonymous referee for constructive comments on an earlier draft of the paper. Thanks are also extended to Justin Jacyno of Royal Holloway, University of London for his cartographic assistance.

Della K. Farrow
[redacted]

Stephen P. Oxford
[redacted]

Martin G. Burnley
[redacted]

Adrian Palmer
[redacted]

GARRIGILL, EVIDENCE OF GLOBAL WARMING, ANCIENT AND MODERN

Dr Barry Webb

During the last decade we have become much more aware of the effects of global warming. Our climate has become wetter, and sea level is rising at a rate that has forced a radical change in coastal defence policy. It is now agreed that human activity has exacerbated global warming, but to what extent, is still hotly debated. The localities described below will not provide an answer, but are useful to demonstrate some of the techniques used to investigate the effects of global warming in the past.

Superficially, the Carboniferous rocks of the Alston area seem to have little in common with the alluvial deposits that cover the valley floors. The former were deposited in a largely marine environment nearly 350 million years ago, the latter on land, from the close of the Pleistocene ice ages (some 10000 years ago) up to the present day. There is, however, a link. Ice ages also occurred in the Carboniferous period and both sets of deposits may preserve evidence of the climate change from glacial to more temperate conditions. The Garrigill area provides some good localities for examining such evidence whilst enjoying an afternoon's stroll through its attractive North Pennine scenery. The 1:25000, O.S. Outdoor Leisure Map 31, North Pennines, is recommended.

The Ashgill stream section

Ashgill is a good place to examine the Alternating Beds between the Tynebottom and Scar limestones. The section exposes three minor cyclothems, indicating marine transgressions and regressions linked to changes in relative sea level (Figure 1). Such changes are commonly due to local subsidence and infilling of the sedimentary basin, but global, eustatic changes must also have occurred.

The Ashgill section provides an interesting exercise to illustrate how these effects may be separated. It can be visited by starting in the small village of Garrigill situated on the River South Tyne, 5km from Alston. Walk along the minor road towards Tynehead, past the church to Low Crossgill (NY747408). You will see the impressive Ashgill Force (Figure 2) on this walk.

Ashgill is best reached along the footpath from Low Crossgill. This crosses the South Tyne at Windshaw Bridge which spans the head of a spectacular little gorge cut into the shale overlying the Tynebottom Limestone. The path continues along the east bank of the South Tyne towards the confluence with Ashgill. A little before the confluence (NY753405) a small alluvial terrace is visible which, when traced south, can be shown to be a remnant of a quite impressive, but rather eroded alluvial fan emanating from Ashgill. It was probably this fan which forced the South Tyne across to the western side of the valley, where it now flows in another gorge cut into the shale. The original course is exposed in Ashgill as a low point in the bedrock some 30m east of the

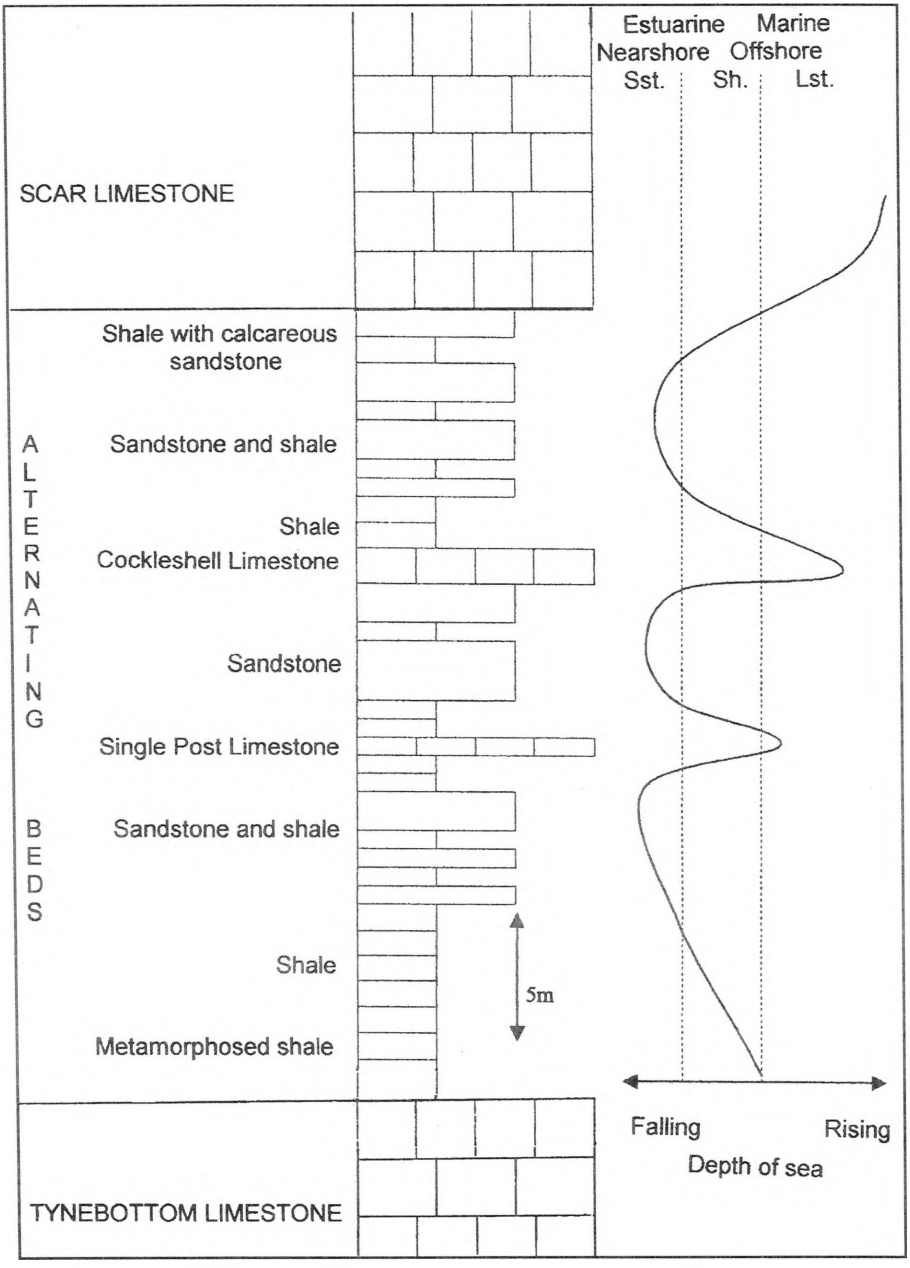


Figure 1 - Schematic section of the Alternating Beds at Ashgill.

present gorge. This is a convenient point to examine the basal shale of the Alternating Beds, but, if you wish to see the contact with the underlying Tynebottom Limestone, a detour to the south is necessary. Ashgill can be crossed by a footbridge a little upstream, from where footpaths lead across the fields to a footbridge over the South Tyne at (NY755401).

A small collapsed adit lies just downstream from the bridge, with good specimens of quartz and purple fluorspar in the spoil heap. At the entrance to the gorge below, the Tynebottom Limestone is exposed in the riverbed. It is overlain by pale, speckled mudrocks rather different from the typical dark shale slightly higher in the succession. This is an effect of contact metamorphism. In this area the Whin Sill lies immediately below the Tynebottom Limestone. The effects on the limestone are not so readily noticeable.

Returning to the Ashgill footbridge, the rocks overlying the Tynebottom Limestone can be examined near the waterfall just downstream. Typical, unmetamorphosed shale can be examined a little downstream from the waterfall. The thicker, darker layers represent fine muddy sediment, deposited from suspension in quiet, still water. The thinner, paler layers are silty and, being slightly coarser grained, would have required some current activity to wash them into the area. Indeed, the discontinuous, lenticular shape of many of these, are sections through current ripples. The generally undisturbed nature of the layering indicates little activity by burrowing organisms, suggesting either a lack of oxygen in the water, or, more likely, a high rate of sedimentation. Occurring immediately above the limestone, these are likely to be offshore deposits, but, being siliciclastic, they represent land-derived sediments, presumably emanating from an estuary. The coarser layers were probably deposited during times of flood, when river levels were particularly high and currents strong.

At the top of the waterfall, flaggy, fine-grained sandstones are interbedded with the silty shale and are also clearly rippled, as can be seen on some of their surfaces. The symmetrical form of these ripples suggests that they were formed by wave, rather than current, action. In places, infilled burrows penetrate the sandstones, evidence both that something did live here, and that sand deposition was probably intermittent. These thicker, coarser grained beds must have been deposited closer to source, but there is no evidence that they fill discrete channels; they are more likely to have been deposited when the river was in flood, spreading coarser sediment across the whole estuary. Immediately upstream, the sandstones become predominant, with sporadic thicker beds. They influence the topography, giving rise to a small scarp and bench feature and to the next small waterfall above the fence. Above this waterfall the succession becomes more shaly and is, at first, not well exposed. The next waterfalls, some 25m upstream, are capped by the Single Post Limestone, and the underlying beds can be examined in the shallow gorge below them. They comprise shale and sandstone with at least one lenticular sandstone bed representing a small infilled channel.

If these rocks were laid down in a river estuary, as the evidence suggests, then this is a major change from the fully marine conditions in which the underlying Tynebottom Limestone was deposited, and implies a decrease in water depth (Figure 1). Such shallowing is not unexpected, and can be simply explained by the seaward progradation of the land-derived sediments. Any sedimentary basin will become filled in this way.

The Single Post Limestone is less than 0.5m thick. It is unequivocally marine, and indicates clearer water, farther from land. It would seem that after deposition of the sandstones, water depth abruptly increased again (Figure 1) resulting in a marine transgression. This rapid flooding event marks the start of a minor cyclothem.

The next waterfall upstream exposes a 3m sandstone unit with shale beneath it. There must be some 2m of shale between the Single Post Limestone and this sandstone. Clearly, this indicates a marine regression as land derived sediments again prograded into the area, with the coarser sediments indicating the shallowest conditions, nearest to land.

The waterfall by the bridge exposes more sandstone and is capped by the Cockleshell Limestone. Again we must be seeing the results of a rapid increase in water depth after deposition of the sandstone. Such an abrupt rise is almost certainly a result of intermittent basin subsidence. The resultant flooding and marine transgression mark the start of another minor cyclothem.

The Cockleshell Limestone is nearly 1.0m thick and gets its name from the prominent gigantoproductid brachiopod shells which can be seen in it (just above the bridge on the south side). The slightly greater thickness of this limestone compared to the Single Post, suggests that this marine transgression was more marked than the former.

On the north side of the bridge some 12m of shale with interbedded sandstone is exposed. Where visible in the streambed, the sandstones can again be seen to be rippled. This indicates yet another regression, as land derived sediments prograded into the area.

South of the bridge lie the crushing floor and storage hoppers of Ashgill mine whose collapsed adit can be found a little closer to Ashgill Force. Above the mine track, on the south side, and amongst the trees on the north side, the Scar Limestone of the next cyclothem forms prominent cliffs extending along the valley sides to the force itself. This gorge is the result of recession of Ashgill Force, the power of the falling water causing rapid erosion of the underlying shale, and consequent collapse of the limestone, blocks of which are clearly evident in the stream bed beneath.

Going up to the force (beware, its stability is highly questionable, and the wet rocks can be very slippery) the beds beneath the limestone can be



Figure 2 - Ashgill Force.

examined. They are predominantly shale, but, approaching the limestone, they include a few thin beds of calcareous sandstone. These contain some fossils, including brachiopods, gastropods and crinoid stems, which have weathered out leaving characteristically shaped holes. This shows that these beds, and the associated shale, were deposited under marine conditions. The water appears, once again, to have begun to deepen. This third transgression was the most marked of all, with 12 - 15m of Scar Limestone deposited before land derived sediments reappear some distance above the force (Figure 1).

It is interesting to consider these cyclothems from a sequence stratigraphic point of view. Sequence stratigraphy attempts to define major cycles of rise and fall in relative sea level, many of which can be correlated world wide and are considered to be eustatic. The deposits of a major cycle are termed a sequence. Minor cycles, such as these cyclothems, are termed parasequences. As stated above, the flooding event marking the base of a parasequence is probably the result of local subsidence. It is the changes in successive parasequences that enable possible eustatic effects to be isolated. The rate at which sea level rises will vary, being at a maximum midway between the lowstand and highstand levels. It is around this time that the rate of rise can outpace deposition. The sea will increasingly transgress onto the land, and successive parasequences will show deeper water facies increasing, and shallow water facies decreasing. Such changes are characteristic of the transgressive systems tract. As the rate of rise slows down and starts to reverse, deposition again dominates and the highstand sequence tract is characterised by progradational parasequences in which shallow water facies increase at the expense of the deeper water ones. Falling water and lowstand tracts also occur in a complete sequence, but these stages of the major cycle commonly result in local erosion or non-deposition.

From the Single Post Limestone upwards, the Ashgill parasequences show increasing thicknesses of limestone. This suggests they form part of a transgressive systems tract. The parasequences are no doubt the result of intermittent local subsidence, but, since they form part of a transgressive systems tract, it is likely that they were laid down during a time of increasingly rapid eustatic rise.

Glacial control on eustatic sea level has been demonstrated for the Quaternary, and is thought to have been important throughout much of Earth history. During the Carboniferous ice ages the climate fluctuated, and warm periods would lead to melting of the ice, producing a eustatic rise in sea level. The Ashgill section nicely illustrates some of the effects this may have produced, although, of course, the extremely limited data render the argument entirely speculative.

Returning to the footbridge downstream, a path leads northwards, up the scarp of the Scar Limestone and onto the bench at its top near Ashgillside

(NY754406). It then continues along the bench to Pasture Houses and down to Garrigill Bridge (NY745416).

The Garrigill alluvial fan

With global warming at the end of the Pleistocene ice ages, ice melted from the Alston area leaving the hills more rounded, valleys somewhat widened, and the ground swathed in poorly consolidated boulder clay. River levels must have fluctuated enormously, from zero during the winter freeze, to high flood at times during the spring thaws. In flood conditions the rivers would carry vast quantities of coarse sediment derived from the boulder clay on the slopes, and would dump this as soon as the flow began to wane. This commonly occurred where valleys widen out and the rivers were less constrained. Garrigill village is built on the fairly flat top of a large alluvial fan, deposited where the South Tyne valley opens out after its more constricted upper reaches. The streams which deposited such fans, were braided rather than meandering. The sudden dumping of their sediment load, when flow began to wane, largely filled in the channels and new ones were eroded during the next flood. As the climate ameliorated further, and flash floods became less common, the streams switched channels less often and eventually stabilised, eroding a single channel through the fan deposits and into the bedrock beneath. Since fans generally slope away from their centres, the stabilised streams commonly flow round the edge of the fan. The South Tyne now occupies a gorge, incised along the eastern edge of its fan, which can easily be viewed from Garrigill Bridge.

Major fans can extend for considerable distances down valleys. Several in the Alston area terminate rather abruptly, with a marked slope to their downstream edges. This leaves the edge prone to further erosion. Once stabilised, the streams cut back into this edge, producing a lower, secondary fan in front of the original one, and may erode the original until it is preserved merely as terraces along the valley sides (as was seen with the Ashgill fan). Walking north out of Garrigill towards Leadgate, the road, at first pretty level, abruptly drops to a lower level at the southern end of the village. This is the eroded edge of the main alluvial fan, with a secondary fan below. A remnant of the main fan is preserved as a mound rising above the secondary fan opposite the old Girls' School (NY742418). Looking back from a point a little before the old Girls' School, the eroded edge of the main fan is quite clear, with the farm and houses built on its top. Its curvature suggests that although the South Tyne is now entrenched along its eastern side, in the past it must have sometimes flowed along the western side. The shallow traces of abandoned channels on the surface of the secondary fan also bare this out.

Some 100m farther on, where the road bears off to the left, the South Tyne can be crossed by a footbridge. From the footbridge, the secondary fan can be seen to extend on downstream. The river has cut across it here, and now runs along its western margin. The river has also clearly cut down into the secondary fan and is flanked on its eastern side by an even lower terrace, which must have developed at a time when the river was actively switching its channel position.

Soil analyses and studies of old maps have shown that this rejuvenation was a direct result of interference with the river flow by mining activity here, and farther upstream, in the latter half of the 19th century (Aspinall, et al. 1986). Clearly the balance between stability and channel switching is a delicate one. Although the lower terrace is stabilised by vegetation, bare patches show it to be composed of similar material to the present riverbed. Some 100m downstream from the bridge, the river has cut into what is, probably, a remnant of the main fan along its west bank. The downstream end of this erosion scar shows a good section through the fan deposits below about 0.3m of soil. At the base, about 1m of the underlying glacial boulder clay is exposed. It comprises rather angular pebbles and cobbles scattered irregularly in a grey clay matrix. Above this, some 1.5m of rounded pebbles, cobbles and small boulders are set in a brown, gravely and silty matrix. The lowest 0.3m of this deposit lacks matrix. This indicates that it was deposited under relatively stable river conditions, when continuous water flow could carry away the finer material (it is very similar to the present riverbed deposits). The overlying, poorly sorted material with matrix present, is a flash flood deposit. Imbrication of many of the flatter cobbles indicates a strong current flowing down the valley. This current must have ceased quite abruptly and completely to dump its entire bedload, including the finer grained material. This is typical of a braided fan deposit where, at the end of a flood event, the river switches to a completely new channel.

Low, elongate mounds of clean cobbles in the present riverbed are one of the results of several, quite severe, flash floods in the last few years, which reactivated a number of previously stable braided streams in the Alston area. As the mining of last century demonstrated, these features are in a delicate balance.

It is too soon to tell if the present reactivation can be blamed on global warming, but if this is so, then many similar upland areas in Britain can expect increasing problems with erosion control.

Reference

ASPINALL, R. J., MACKLIN, M.G. AND BREWIS, T. 1986. Metal mining and floodplain sedimentation at Garrigill, and their influence on terrace and floodplain soil development. *In* Macklin, M.J. and Rose, J. (eds). Quaternary landforms and sediments in the northern Pennines: field guide, 35-45. British Geomorphological Research Group and Quaternary Research Association.

Dr Barry Webb
[redacted]

BUILDING AND DECORATIVE STONES IN WHITEHAVEN

Margaret Fox

Why study town centre geology?

Town centres offer the opportunity to see rocks in use. There is often great variety in a small area, with different stones used for different purposes. Igneous rocks are usually polished, so textures are clearer than in the field. In Whitehaven there are at least three significantly different granite textures. Students can practise determining the 'way up' of sandstones and weathering characteristics can be noted.

Suitable local rocks tend to dominate. In Whitehaven these are red, pink and yellowish sandstones. Other features such as cracking and subsidence due to subsurface mining may be apparent and local industry reflects locally available materials.

Studying building/decorative stones closely may attract attention, but this can give an excellent opportunity to 'spread the word' about our interest. This paper describes a walk around the town centre and describes the principal decorative and building materials encountered.

The Children's Memorial

This look at Whitehaven starts by the Children's Memorial at the back (Duke Street) side of St Nicholas Gardens. The memorial serves to remind us that the underlying geology includes coal, with eight principal seams dipping seaward at about 1 in 12. Mining had started at Arrowthwaite at least by the 13th century. In 1560, land at Whingill and Howgill, was granted for digging coal. By the 17th century, the main coal market was Ireland and the pier was built in 1634. The area of Whitehaven known as Ginns derives its name from the wind and horse-driven water ginns used for drainage.

The main seam is here about 38 m below ground. In the 18th century there were 45 to 50 pits in the area from Mirehouse to Bransty and Moresby. The nearest were James, behind St James' Church, and Duke, which was somewhere near the multi-storey car park. On 31st January 1791, waste water broke into one mine drowning two men, one woman and five horses. The ground behind Somerset House (the last building on Duke Street before the park) subsided and several buildings collapsed.

Looking at the memorial, it is interesting to reflect on the ages of the children. The youngest boy was only eight years old; the youngest girl was eleven. These youngsters and others like them were sacrificed for Whitehaven's prosperity.

Next, looking closely at the granite, the crystal shape, size and size variation and the overall colour are noteworthy. This is classed as Balmoral Red and was reported to have come from the Aberdeen area. However most

'Balmoral Reds' these days are imported from Scandinavia. The original intention had been to use a local rock, but nothing suitable was available.

Roofing

Whitehaven developed in the 17th and 18th centuries as a result of the prosperity brought by coal and the nearby iron. Sir John Lowther acquired much of the land and was able to control development, so that Whitehaven was one of the earliest planned towns, laid out on a gridiron pattern. King, Duke, Lowther, Scotch and Irish Streets had well-spaced houses in large gardens, but by the end of the 18th century the gardens were built over with dark alleys of houses for the workers.

Originally Whitehaven's houses had thatched roofs but by the end of the 17th century most were of slate. Although there were obviously sources of slate in the Lake District which are well represented, there is also a fair amount of purplish or dark grey Welsh slate. This is hard, strong, totally impermeable, frost resistant and light in weight but rather brittle. In general it can be split more thinly than the Lake District slates, commonly 3/16 or 1/8 of an inch. Welsh slate was used from the 14th century in Cheshire, but its use grew rapidly in George III's reign when there was a fashion for concealing roofs behind parapets. Being thin and impermeable, the Welsh slate could be laid at a low pitch if adequately lapped. Lowther Street has some examples of roofs behind parapets.

Until about 1840 Welsh slate was sold by weight in a range of sizes and could be laid in diminishing courses as the Lake District slates tend to be, partly for aesthetic reasons. However increased demand led to size standardisation and sales by number, with up to 75% wastage. Transport to Whitehaven by sea from North Wales would have been relatively cheap and easy, possibly more economical than bringing slate overland from Lake District sources.

Artificial roofing slates only date back to the 1970s, whilst roofing tiles have a much longer history, having been used by the Romans. By looking at the roofs along Duke Street and the streets either side of the gardens examples of Lake District, Welsh and artificial slates can be seen. Tiles are not evident in the town centre.

Thompson tombs

Passing through St Nicholas Gardens towards the tower, three granite tombs can be found on the Church Street side. These contrast with the sandstone of the majority of the tombstones lying on the Duke Street side and indicate the family's perceived importance. The granite has a matrix of quartz and feldspar with occasional large white feldspars and some needle-like magnesium-iron minerals. The source is unknown, but it has been suggested that it resembles Rubislaw granite.

St Nicholas Church

The church was built in 1883 of Triassic St Bees Sandstone from Beggarghyll Quarry near Egremont. The quarry is now a garden, but a drop of water on a small sample taken from the quarry remained on the surface, indicating low porosity. St Bees is one of the more reliable red sandstones, most of which tend to blister and flake. Examples of cross-bedding can be seen, for instance to the left of the main door.

The strength of a sandstone depends on its matrix. Ideally this would be siliceous, making it chemically inert. Fine-grained and homogenous stone can be cut easily in any direction and is known as 'freestone'. When cut, dressed and squared for facing it is known as 'ashlar'.

The use of rough stone and bricks faced with stone can be seen in more isolated parts of the building, for example the north-east corner. Brick, presumably from one of the brickworks that operated locally in the 19th century, was probably cheaper than stone.

At the Lowther Street end of the gardens rubbly limestone boulders, a Cumbria in Bloom tablet in slate and an urn of Shap granite can be found. The urn has polished and unpolished sections, showing the effect of polishing on apparent colour. In rain the two parts are barely distinguishable. Shap granite is recognisable by its large, pink, well-shaped feldspar crystals (described by one mason as 'spam'). Twinning is common and there are some end sections.

Lowther Street – north-east side

Leaving the gardens by the gate opposite the main door and turning left (south-east) along Lowther Street, the Clydesdale Bank is faced with a fine-grained, yellowish sandstone of unknown source. The window sills are of a coarser, paler stone. Places where water tends to lie need a stronger stone.

The side wall of the HSBC is pebble-dashed with a mixture of grains. These tend to be angular so are probably from broken or crushed stone rather than natural gravel.

The Post Office and the NatWest Bank are both of fine-grained, red St Bees Sandstone, which saws well and is carvable. The actual quarries are not known. Close examination suggests that they are from different quarries or different levels in the same quarry.

Again, examples of sedimentary structures can be found and can be used to check whether the blocks are the right way up. For maximum strength, blocks should be laid the same way up as in the quarry. In particular they should not be used on edge, which would allow water to more easily percolate between layers.

Continuing along Lowther Street, Hillary's has Lake District green slate slabs hanging on one wall.

Lowther Street Methodist Church

On the corner of Lowther Street and Scotch Street stands the former Methodist Church, built in 1887 at a cost of £10 000. The construction is known as 'random granite'. Granite is generally hard to saw, so this method would have minimised working.

The granite has pink orthoclase feldspar phenocrysts, white oligoclase feldspar, quartz and biotite, with the feldspars in approximately equal amounts. This is another example of Shap "granite" although it has less quartz than a true granite. Masons use the term "granite" for almost any igneous rock that takes a polish, including gabbros and gneisses. Similarly any rock that splits into thin pieces may be known as slate, and masons' "marbles" can include serpentinite and some limestones such as the Frosterley Marble.

Variations within the granite can be found. The darker red variety occurs at the side of master joints and results from percolating fluids during cooling. There are also dark grey xenoliths of foreign material incorporated into the melt.

The pinkish Whitehaven Sandstone came from the quarries at Bransty. A drop of water placed on the surface sinks rapidly into the stone, so it is very subject to freeze and thaw effects and is deteriorating badly. Lines of holes in the stone, seen on the arch to the right of the gate, are due to the weathering out of mudstone clasts, which are common in some layers of the sandstone.

Civic Hall and Library

Across Lowther Street from the Methodist Church is the Civic Hall, built in the 1960s. The brick is Staffordshire Blue, made with clays from the Carboniferous Etruria Marls, which are found above the productive Coal Measures.

The source of the sandstone is not known, but similar markings can be found in the Countess Pit Sandstone, outcropping towards Parton.

The distinctive feldspars of the Shap Granite stand out in the crushed material coating pillars and incorporated into paving in front of the Civic Hall.

Lowther Street – south-west side

Returning north-west along Lowther Street, Dixons store is faced on the lower levels with a remarkably homogenous creamish sandstone which is said to have come from Lamb Hill, a quarry outside Whitehaven towards Howgate. At higher levels, best seen from across the road, is red sandstone from St Bees.

Green marble in the step apparently came from a quarry near Milan in about 1910 and the white marble is said to have been cut from old washstand tops.

When building renovations are being carried out, it may be possible to see more of the actual structure. The local building method, which persisted for a long time, was to use cobbles or quarry stone laid in clay, then pointed with lime. Other buildings in town are faced or rendered brick. In the late 17th century, Sir John Lowther tried to encourage the use of brick by loans and example, but without much success. There were fears for the viability of the harbour if too much stone were taken from the headland. From about 1750 facing in stucco became popular. This was often marked as false ashlar as a cheap substitute for stone, but ashlar courses were normally graded whereas stucco tended to be marked evenly throughout.

Continuing north-west along Lowther Street, another roughly equigranular red granite is found on the Cumberland Building Society. This is similar to that used for the Children's Memorial, but close examination suggests a different source.

What's New? has an example of 'Emerald Pearl' larvikite. This intermediate syenite is distinctive because the high temperature sodium/potassium anorthoclase feldspar shows blue schillerisation, a play of light due to inhomogenities in the crystal. There is no quartz and the ferromagnesian minerals occur in clots. The type area is Larvik in southern Norway, where it is of Permian age, but some larvikites come from South Africa.

On the corner of King Street the Bradford and Bingley Building Society is faced with its corporate image, a granite with rapakivi texture, which comes from Eastern Finland. The potassium feldspar is intergrown with quartz, zoned with magnesium-iron minerals and surrounded by sodic feldspar. Occasional equigranular patches can be seen.

King Street

Towards the south-west end of King Street, the Halifax Building Society displays its corporate image granite. This is a grey granite imported from Italy in the late 1980s and shows a slight lineation. Replacement tiles are obviously from a different source.

Heading north-east along King Street, Burton's on the left has another example of Emerald Pearl larvikite and Contemporary Menswear on the right has the lighter Blue Pearl larvikite, with very noticeable schillerisation.

Travel Care on the left has a small remnant of another granite. This is mainly intergrown quartz and pink feldspar with minimal dark minerals and poor crystal forms.

Inland Revenue Building

The recently built Blencathra House, off Tangier Street by the harbour, is of artificial materials. Artificial stone is usually a mixture of sand or stone dust with cement and suitable colouring matter, sometimes with a concrete core. The best

examples take care with texture, even making impressions from real stone. Artificial stone has obvious advantages if a number of identical sections are required, but may not always be cheaper than natural stone if only one or two pieces of a particular shape are needed.

Here the facing bricks are known as Furness Whitehaven Blend and the cast stone with needle gun/ashlar finish came from the Birmingham area. The colour was decided in conjunction with the planning office.

Harbour

The original harbour was constructed from Whitehaven Sandstone. However, the source of the large area of new flags has not been determined.

A final note

Limited availability and high cost mean that natural stone is less likely to be used on new buildings in this country. Only the larger chains and richer institutions can still afford to face in a corporate image stone, but even artificial materials have geological origins.

The locations described in this article were visited by the Society during a field excursion on July 11th 2001. However, for town centre geologists, building stone trails can become frustrating as buildings change hands and new owners make changes. Two of the best examples of "Blue Pearl" larvikite have disappeared since this route was originally researched. On the other hand, special projects can sometimes bring unexpected "exposures" of local and exotic stones. The Millennium Labyrinth in Holy Trinity Gardens would repay a visit for its decorative stones, including examples of gneiss, as well as its calming properties.

Margaret Fox
[redacted]

THE BUILDING STONES OF PENRITH AND DISTRICT

Eric Skipsey

The varied sequence of rock types found in Cumbria has had a marked influence on the buildings in the towns and villages of the county. Each town and village contains in its buildings the same materials, colours and textures that characterise the surrounding countryside. For instance, Ambleside, Hawkshead and Coniston are typified by the forbidding dark blue-grey or near black Silurian flagstones and slates, matching the ragged outcrops in the crags, walls and bridges. Similarly tuffs from the Borrowdale Volcanic Group locally known as 'Lakeland Green Slate' more than any other typify Keswick, according to Smith (p.244). The town of Kendal is completely different as the building stone was hewn from the limestone quarries of Kendal Fell – a cool, silver-grey place giving Kendal its old name of '*the auld grey town*'. In contrast to the Lake District settlements, Penrith and the villages of the Eden Valley glow with warm red sandstone buildings which is reflected in its soils and abundant old quarries (Millward & Robinson, p.204).

In medieval times the demand for stone was for the construction of castles, cathedrals, churches and bridges while humbler buildings were made of wood with thatch roofs. With growing prosperity in the 17th century, stone became one of the materials for medium sized as well as large houses and it is with this period that the earliest houses are associated. The ideal building stone is one that incorporates good weathering properties and agreeable colour and texture with a consistency fine enough to provide smooth surfaces and crisply carved details. Unfortunately, the Penrith Sandstone was too coarse in texture and suffered from weathering to provide a material for high quality architecture. The coming of the railway marked an important milestone since it enabled a wide range of building materials to be brought into the town and more elaborate architectural styles became possible.

What stone was available for building?

Four different types of stone occur within 15 km of the town but only the red sandstones of the Eden Valley were utilised to any extent. Figure 1 summarises the geology of the Eden Valley and surrounding area.

Carboniferous limestone

Carboniferous limestones outcrop to the west of Penrith in a belt from Caldbeck to Shap, the nearest being in the Redhills RIGS site, adjacent to the A66 trunk road and west of the M6 motorway. Although the limestones were extensively quarried and yielded reasonable freestone for building, it was rarely used in Penrith. However considerable use was made of this stone in villages like Stainton and Greystoke situated on the limestone, including Greystoke Castle built of limestone obtained from quarries on the estate. Where the limestone is affected by iron staining, a delicately coloured rock results which was used in the

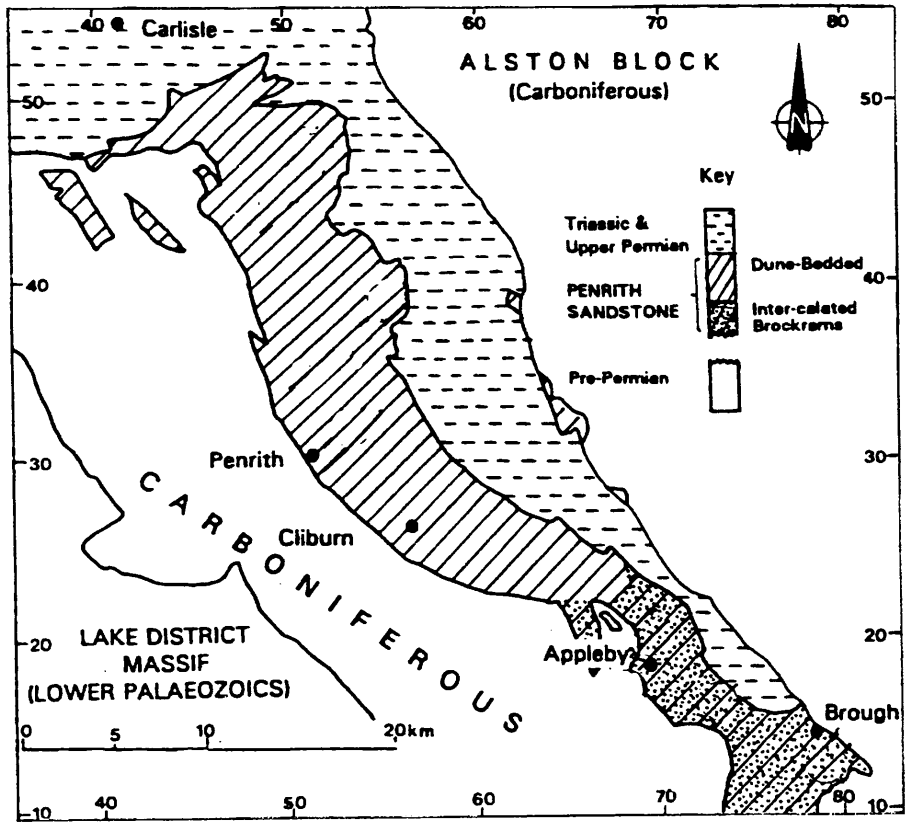


Figure 1 - Rocks of the Eden Valley and surrounding area (adapted from Figure 16.1, Lakeland Rocks and Landscape. Ellerbank Press, with permission of I. Rankin).

Georgian front of Dalemain House at Dacre, judged by Clifton-Taylor (p.96) to one of the most beautiful houses in England.

Lower Carboniferous sandstone

A thick bed of grey, purple-stained, fine-grained massive sandstone between the Tynebottom and the overlying Single Post Limestones was extensively quarried as a major source of building stone for the Greystoke area and other quarries existed near Lamonby. This sandstone was the traditional building stone used in settlements to the west of Penrith, (Arthurton & Wadge, p.129) but there was little evidence of its use in Penrith until improvements in the roads facilitated transport.

Penrith Sandstone

By far the most important source of building stone in Penrith was the red Permian sandstone, known as the Penrith Sandstone. The upper part of the formation where the sand grains are well cemented with secondary silica provided the best and most durable freestone. This sandstone, known to builders as 'Lazonby stone', crops along the western side of the Eden Valley basin, between Armathwaite in the north and Brough in the south (Figure 1). The most striking features of the sandstone are the steeply dipping layers (foreset beds) visible in many outcrops, the remarkable roundness of the sand grains and its red coloration (Cockersole 1990). The sandstone accumulated as wind-blown deposits in the sand dunes of a Sahara-like desert. The characteristics of the Penrith Sandstone are well displayed in the Cowraik Quarry SSSI, a Local Nature Reserve (Grid Ref. NY540308) situated on Beacon Edge east of Penrith (Skipsey & Hewitt 1997).

The numerous old quarries on the heathland between Blaze Fell, near Armathwaite, and Beacon Hill at Penrith provided most of the stone for the houses of the town. The quarries also provided stone for tiling, paving and rough walls while stone from the massive foreset beds were used for pillars, lintels and gateposts. One striking feature is the manner in which it sparkles when the sunlight catches the crystal facets of the secondary silica cement and this feature can be readily seen in the buildings of Penrith on a sunny day. The stone is still worked on a small scale and its principal uses are as facing or decorative stone on modern buildings. It was widely used in this way on the bridges of the M6 motorway and the recent re-furbishment of Penrith town centre used it for the pavements.

In medieval times, sandstone used in walling was generally quite irregular with thick lime mortar bedding, dictated by the availability of stone from shallow hand worked quarries close by. Sometimes they were finished with a rough render but often many coats of lime wash built up to form a sort of render. Later more regular sized, squared blocks were utilised, random pattern at first but by the late eighteenth century were laid in regular courses, with a fine tooled face and much finer joints. The sandstone had a poor tensional strength and when it was used as a lintel, the widths of the openings were restricted unless very deep

and heavy blocks were used. Mullioned windows of the seventeenth century were divided into individual spans of generally no more than 600mm. Later individual openings became wider, windows usually no more than 900mm and doors perhaps 1000mm with deeper lintels, sometimes decorated. But even at these spans, cracking of window lintels frequently happened.

St Bees Sandstone

The St Bees Sandstone with its distinctive chocolate-brown colour is the local representative of the Triassic Sherwood Sandstone and crops along the eastern side of the Eden Valley basin (Figure 1) where it was extensively quarried. Most of the stone was used locally for building and walling. Although less durable than the coarser silicified Penrith Sandstone, its finer texture provided a better finish and it was extensively used as freestone in Penrith. According to 'Ewanian' (1894) when St.Andrews Church was re-built in 1722, each of the Ionic pillars supporting the gallery were formed of single pieces of St Bees Sandstone from the Crowdundle Quarries, near Blencarn.

Rubblestone

Many older buildings are constructed largely of 'rubblestone' i.e. lumps of stone of varying size and often quite irregular. This material is described by Smith (p.240) as 'gathered stone', as it is a mixture of materials that could be collected from nearby surface exposures. Rounded boulders and cobbles of hard volcanic rock carried by glaciers from the Lake District were widespread in earlier days and clearing them to improve meadows and arable land must have taken place over many generations. (Denyer, p.149) and many were incorporated into field boundaries. Penrith Castle provides a striking example of the use of rubblestone, with the outer layers of the massive walls constructed of rough ashlar (squared) blocks of Penrith sandstone and infilled with rounded grey cobbles of volcanic rock. In some earlier buildings, large boulders were used as corner stones and foundations beneath walls of lesser boulders and roughly quarried stone. This usage can be seen where old country walls have been incorporated into later structures, with examples in walls in Drovers Lane, Penrith.

Material for roofs

Thatch was the traditional material for roofs but by the seventeenth century slates gradually came to replace thatch as the common roof covering. Slate is a fine grained metamorphic rock in which the flaky mica particles have been re-aligned under pressure to lie parallel to each other. This property allows the slate to be split or 'riven' into thin sheets and dressed into suitable shapes.

Two of the major formations of the Lake District, the Borrowdale Volcanic Group and the Silurian rocks, both contain workable slates. In the late eighteenth and early nineteenth centuries many Lake District quarries expanded to meet the needs of developing industrial areas. Three standard grades were produced; the best was called 'London' slates, which were the thinnest, smoothest and smallest and which were sold out of the area; next were the

'country' slates and the lowest grade was the 'Tom' slates which were rough, thick and fairly large. Lake District slates are usually laid in diminishing courses with the largest and thickest Tom slates used at the eaves and the smaller country slates used for the smaller courses towards the ridge.

Many of the older Penrith properties around Albert and Queen Streets are roofed with the grey-green slates quarried from the fine tuffs in the Borrowdale Volcanic Series at places like Honister; contrast these roofs with others using Welsh slates, deep blue in colour and very regular in size and shape. It is unlikely that the Welsh slates appeared in the district until after the railway network was established between 1840 and 1880 but thereafter the market was flooded with them and many roofs of Welsh slate can be seen on Victorian buildings. Today roof slates are imported from Spain and even China while manufactured roof tiles are sometimes used when re-roofing older buildings. Clifton-Taylor describes the 'Cumberland Green Roof' as the loveliest roofing slate in Britain!

Thinly bedded sandstone occurs in places within the fossilised sand dunes of the Penrith Sandstone and these were split like slates and used for roof coverings and pavements. Slatequarry Wood near Edenhall is a relic of this practice. When split, these thinly bedded sandstones formed thick, heavy and sturdy roof coverings, looking very appropriate on the sandstone buildings. Stone flags sometimes cover entire roofs but more commonly provide the lower few courses of a slated roof and a good example can be seen on the roof of the Queen Street nursery.

A walk around Penrith

The best way to learn about the buildings of a town is to walk its streets. This short walk looks at both the older vernacular houses and more modern commercial buildings and the route is illustrated in Figure 2. The Penrith Millennium Trail provides more information about the town and copies can be obtained at the Tourist Information Centre.

Start in the car park in front of Penrith railway station (1) where there are three contrasting building styles displayed. In front are the remains of Penrith castle (Figure 3), the earliest building in the town and largely constructed of the local red sandstone (Hugill, 1977). It was commenced in 1399 when a stone curtain wall was added to the original pele tower. Over the next 70 years it was improved, finally becoming a royal fortress for Richard, Duke of Gloucester, as 'Guardian' of the western marches towards Scotland. The outer layers of the massive wall are constructed of rough ashlar blocks of Penrith sandstone and infilled with rounded grey cobbles of volcanic rocks. Behind is the railway station, built in 1846 and constructed principally of the red sandstone with lintels, window frames and corners of contrasting buff sandstone, probably Carboniferous sandstone brought from quarries in Lancashire. On the north side is the Macdonalds restaurant, erected in 2000 in three prefabricated modules. The building has been clad in red Penrith sandstone to enable the building to fit

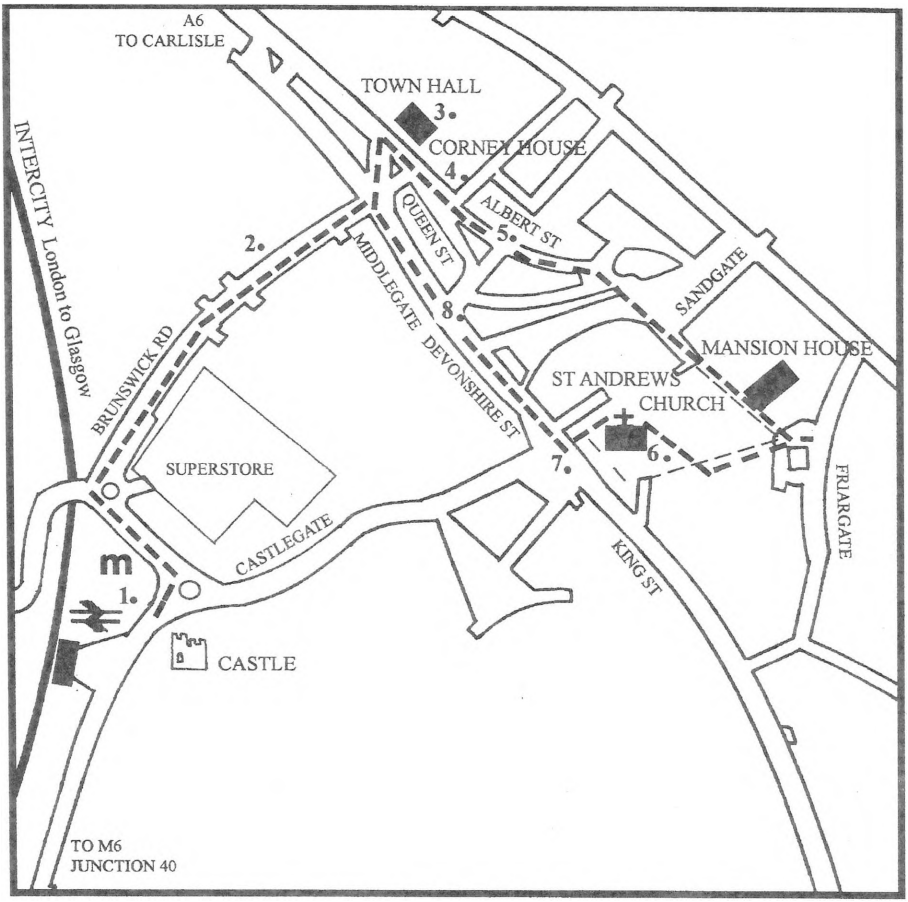


Figure 2 - Street map of Penrith showing locations 1 - 8.



Figure 3 - Penrith Castle (locality 1).

with its historic surroundings, even though the stone used is a very thin veneer (25mm or so) fixed to the prefabricated wall panels!

Now walk round the perimeter of the large Safeway superstore and down Brunswick Road. The superstore occupies the site of the town's old auction mart and some of the buildings remain, including the Agricultural Hotel. The mid-Victorian school and houses of Brunswick Road (2) are all built of Penrith sandstone.

The Town Hall (3) facing you at the foot of the road is the main civic building in the town. It was created in 1906 from two former Adams-style houses originally built in 1791. Considerable controversy occurred during its construction with the then new National Trust and the Society for the Protection of Ancient Buildings unsuccessfully seeking to persuade the Council to retain the facade of the original Adams building. Note the contrasting uses of the red sandstone and cream coloured stone for ornamentation, probably Carboniferous sandstone obtained from Prudholm quarry near Hexham.

Round the corner in Portland Place the ornamental columns at the side door form a feature of the building and are worthy of close examination. They are cut from the Shap granite, easily recognised by the occurrence of numerous large pink felspar crystals (known to geologists as 'phenocrysts') set in a finer white crystalline matrix. There are also several irregular dark masses or inclusions within the granite matrix. These represent pieces of the existing rocks into which the granitic magma was intruded, shattered and caught up in the molten magma.

Turn right along the front of the Town Hall past another large building. This is Corney House (4) a fine Georgian mansion built in 1777 of local red ashlar sandstone with a Lakeland slate roof. Opposite are the Glen Cottage Hotel and Strickland House, early eighteenth century residences constructed of sandstone with painted stucco finish in traditional Cumberland style. Almost next door is the Queen Street Nursery (Figure 4) with a Lakeland slate roof having the lower courses of sandstone flags.

Now walk along Albert Street (5), typical of the local vernacular style in Penrith with late eighteenth and early nineteenth century buildings composed of the local stone with coloured stucco or roughcast finishes. Note in passing that Prince Albert House was once the parish workhouse and that Nos. 30 –32 was once a farmhouse and cottages incorporated into an urban setting.

After Albert Street is the bus station and Sandgate, one of the old market areas. Beyond is the short lane leading to St. Andrews churchyard and church (6) (Figure 5). The earliest remains are the severely eroded pre-Norman crosses and four hogsback grave markers in the churchyard, all composed of Penrith Sandstone. The tower appears to have been built in three stages and



Figure 4 - Queen Street Nursery - an example of the use of sandstone flags for the lower courses of a slated roof

while the date of the earliest stage is unknown, it could be as early as the eleventh century. The church building itself was re-built in 1722 (Pevsner, 1967) in red sandstone but significant weathering and decay has already affected the lower courses of the stonework, illustrating the porosity of the sandstone.

In the churchyard are several gravestones of red sandstone, so severely weathered that the inscriptions have almost gone. In contrast the memorials on gravestones of the Silurian Brathay Flags standing by the church wall are sharp and unweathered. Walk round the churchyard, noting further late eighteenth and early nineteenth century buildings built of Penrith sandstone. The Mansion House (1750) beyond the eastern boundary of the churchyard has rendered sandstone walls with an early twentieth century rear extension in coursed sandstone (Figure 6). Other early eighteenth century sandstone buildings in Friargate in front of the Mansion House illustrate the narrow mullioned windows with sandstone lintels.

From the churchyard, walk through the short lane to the Market Square (7) and Devonshire Street and then to Middlegate (8). These streets contain the main 'prestige' buildings of the town, mostly eighteenth and nineteenth century but with many subsequent alterations. Three banks located here were all built in the early twentieth century as prestige buildings. Barclays bank is built in local stone with elaborate features while the adjacent Nat.West bank built in 1930's was built to a national design using Portland Stone, out of character with its surroundings. Look closely at this stone and see the shell fossils, sliced in preparing the stone blocks. Over the road is the HSBC bank, where buff coloured sandstone is used for elaborate ornamentation. The clock tower in the centre of the square is a notable feature. It was built in 1860 of the pale buff sandstone from Prudholm Quarry, near Hexham in Northumberland, widely used for fine detail work in many of the nineteenth century buildings.

While walking past the George Hotel and through the 'narrows', note the stone used for recent refurbishment of the roadway. The blocks making the carriageway are hard Pennant Sandstone of Carboniferous age from South Wales while the dark kerb setts are diorite imported from China! The pavement is of course the local red sandstone.

The buildings of Middlegate (8) are a mixture of styles and ages, from original seventeenth century buildings to the twentieth century shops. The oldest buildings are the Penrith museum, housed in the sixteenth century Robinson's School, and British Legion building (originally Musgrave Hall) at the north end of the street. The Burtons block was built in 1937 to the company's house style in pale buff sandstone of even in texture, typical of the Carboniferous sandstones that were extensively quarried in the Pennines areas. Every Burtons shop was embellished with a dark polished igneous rock called 'larvikite' with large irridescent felspar crystals from Norway providing the facing below the windows. Greenwoods, over the road, have a similar fascia of larvikite although here it is



Figure 5 - St. Andrews churchyard and church.



Figure 6 - The Mansion House.

of a lighter colour as it is more recent. The Halifax Bank is notable for the colourful polished diorite facing and the fine sandstone entrance showing clear sedimentary structures. An example of a design out of character with its surroundings is seen the in the Argos building. The architect must have assumed that Penrith was a Lake District town and used dark flaggy Silurian sandstone to face the upper part of the building.

This short walk has shown that before the coming of the railways the local red sandstone was virtually the only stone used for building. From the 1850s, improved transportation enabled an increasingly wide variety of stone to be used, initially Carboniferous sandstones allowing more elaborate designs and Welsh slates providing a cheaper roofing material. At the same time, the red Penrith Sandstone was despatched to distant places, such as Bamburgh Castle in Northumberland where Lord Armstrong used this stone when building the west entrance in the early 1900's (Jackson p.107). By the early twentieth century, a wide range of European stone was available, such as Italian marble and the Norwegian larvikite, and now in the twenty-first century materials come from all over the world, like the Chinese kerb stones in the centre of Penrith.

References

ARTHURTON R. S. & WADGE A. J. 1981. Geology of the country around Penrith. Inst. of Geol. Sciences, HMSO. London.

BRUNSKILL R. W. 1978 Vernacular architecture of the Lake Counties, Faber & Faber.

CLIFTON-TAYLOR A. 1972. Pattern of English Buildings, Faber & Faber, London.

COCKERSOLE F. J. 1990. The depositional environments & dune morphology of the Penrith Sandstone. Proc. Cumb. Geol. Soc., Vol.5. Pt.2, 169.

DENYER S. 1991. Traditional buildings & Life in the Lake District, V.Gollancz & National Trust.

FURNESS W. (Owanian) 1894. History of Penrith. (reprint by Bookcase, Carlisle)

HUGILL R. 1977. Castles of Cumberland & Westmorland. F.Graham, Newcastle upon Tyne.

JACKSON D. E. 2001. Building stones of the district around Alnwick, Northumberland, Trans. Nat. Hist. Soc. of Northumbria, Vol.60, Pt.3 101-114.

MILLWARD R. & ROBINSON A. 1983. The Lake District, Methuen.

Penrith Millennium Trail 1999. Penrith Partnership.

PEVSNER N. 1967. Buildings of England: Cumberland & Westmorland, Penguin.

SKIPSEY E. & HEWITT S. 1997. Cowraik Quarry, Penrith, Carlisle Naturalist, , Vol.5, No2, 38-43.

SMITH R. A. & K. 1998. The building stones of Keswick, Proc. Cumb. Geol. Soc. Vol.6, Pt2, 233.

Acknowledgements

This article follows the series of articles on the building stones used in several Cumbrian towns and villages presented in a previous issue of these Proceedings (Proc.Cumb.Geol.Soc, Vol.6, Pt2 1998). The initiative to research and write it came from discussions during a town walk led by Eric Robinson and the author for delegates attending the 3rd U.K.RIGS Conference, held at Newton Rigg College in September 2000, and Dr Robinson's contribution is acknowledged. The assistance of Peter Armstrong of the Penrith Civic Society in providing details and Jean Slee Smith in preparing Figure 2 is also acknowledged.

Eric Skipsey
[redacted]

THE BOWDER STONE, GRANGE-IN-BOROWDALE, CUMBRIA

R. Alan Smith.

The famous Lakeland landmark of the Bowder Stone, in the heart of the Borrowdale Valley, has been a visitor attraction for well over 200 years. Since well before Victorian times, every guide book to the district has included a short entry on this remarkable stone, usually giving little more than its location and basic dimensions, but extolling its attraction as an essential venue on any tourist round. At the present time, thousands of visitors every year take the short stroll along the track from the now extensive car park, ogle at this curiosity, perhaps pose for a photograph beside it, walk round it, climb the ladder to the top and then go on their way. There is no display board to offer any kind of information about the stone and no explanatory guide has ever been written. In spite of this, pictures and representations of the stone continue to appear on souvenir ware, from postcards to tea towels, as well as on calendars and tourism marketing material. From a geological standpoint it has received scant attention.

The object of this paper is to put on record the results of some recent measurements and field observations on the stone and its surrounding area, and offer some ideas as to its likely origin.

Two features make the Bowder Stone special. First its sheer size and bulk. Measuring just over 18m in length and standing 8.18m in vertical height, it is far and away the biggest free-standing lump of rock in the Lake District. Second, and most distinctively, is the way it apparently balances on one corner in an almost gravity defying way. It has been likened most frequently to a stranded ship with its keel turned upward, but more amusingly to *'an enormous lady standing on tiptoe as if to convince us that she is a prima ballerina'* (Bailey 1981), or *'a great lump of rock the size of a house, stranded like a petrified mammoth'* (Lefebure 1964). The description which is perhaps the most apt is the one written by the late Norman Nicholson, the Cumbrian writer and poet, when he said it is *'perched on one corner like a performing elephant on one leg'* (Nicholson 1969).

Whilst the stone was mentioned as a tourist site in the eighteenth century, it was not until the final years of that period that it was turned into a serious tourist attraction by one Joseph Pocklington. Pocklington's works and antics are important and have a direct bearing on this geological and geomorphological investigation. He was a wealthy eccentric who between 1778 and his death in 1817 had a passion for building and 'improving' parts of the Lake District. After building a house on an island in Derwentwater, and a second mansion at Barrow House overlooking the eastern shores of the lake near Ashness, in 1798 he bought the land on which the Bowder Stone stands and 'set to work on the area', almost certainly tidying away much of the small loose debris around the stone, erecting some kind of fence around it and thus defining it as a clear free-standing feature. Additionally he built a small chapel, set up a new druidical stone and erected an ugly cottage (Bowderstone Cottage) where he installed an

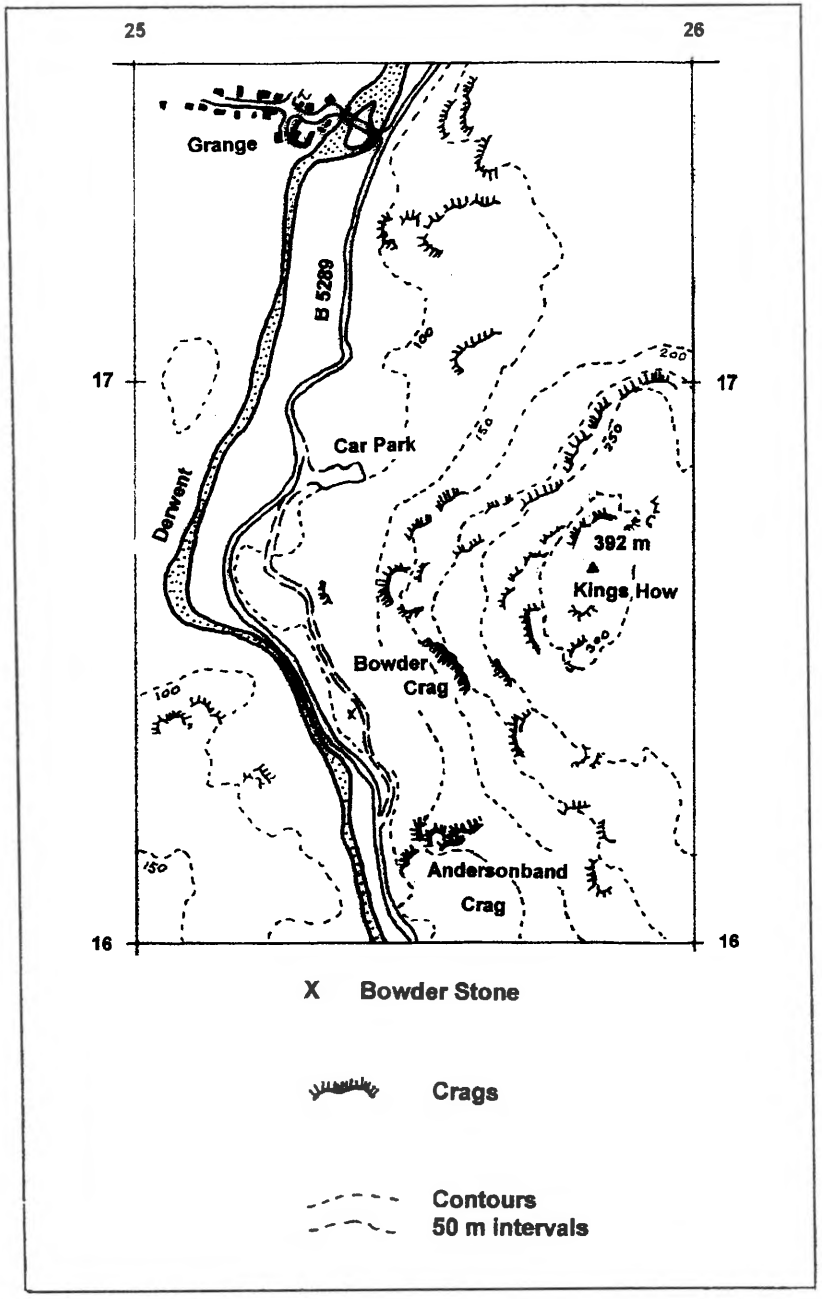


Figure 1 - Location.

elderly lady to show visitors around. It was also Pocklington who first erected a ladder enabling visitors to reach the top of the stone. Particularly relevant to this examination, he measured the stone and made an estimation of its weight. He also seems to have enlarged a hole at the base towards the southern end, in order to allow his lady guide (for a small fee) to shake hands with visitors lying down on the other side of the precariously balanced stone 'to improve their luck'. Throughout Victorian times and well into the Twentieth Century, the ladder, plus an attendant resident at the cottage to show visitors around and provide afternoon teas and sell souvenirs, helped to maintain the stone as a prime tourist venue. The history of tourism to the stone is a story in its own right, beyond the scope of the present paper. Today, apart from the stone itself, all that remains is the ladder to the top (now maintained by the National Trust), the druidical stone and the two Pocklington buildings now modified and serving as climbing club huts.

Location

The stone is situated just over 1km south of the village of Grange (NY 255164) in the section of the valley known as 'The Jaws of Borrowdale'. It lies on a rocky platform at 110m OD. Above it is a steep slope surmounted by Bowder Crag, above which lies the summit of Kings How (392m). Approximately 40m below the stone the River Derwent has cut a rocky defile through the Borrowdale Volcanic Group rocks which underlie the whole area. The rough unsurfaced track by which the stone is reached was the original main road up the Borrowdale valley, the present main road (B5289), being diverted in the Nineteenth Century, to run alongside the river below (Figure 1).

Description and Measurements

The stone is a large piece of dark grey, aphyric andesite lava. Stratigraphically it can be demonstrated to belong to the Grange Crag Member of the Birker Fell Formation close to the base of the Borrowdale Volcanic Group (see later section for explanation). It lies with its long (*a axis*) running almost north-south (bearing 350 degrees to magnetic north) – so for convenience of description, we can refer to its four faces in terms of north, south, east (ladder) and west.

Its dimensions have only been measured once before, by Joseph Pocklington, at the end of the eighteenth century. Ever since, his original dimensions have been quoted, and in fact misquoted, in practically every guide book. For the sake of accuracy, the following details, derived from Pocklington's personal papers (Pocklington 1799), and written in his own hand are copied below.

Measure of Bowtherstone in Borrowdale Cumberland

	F.	*I.*
The Length of the Stone is	*62*	*6*
Perpendicular Height	*36*	*0*
Circumference	*89*	*0*
Contents of Solid Feet	*23,000*	*- 0*
Weight of the above	*1771 Tons 13 Hun.*	

Measure May 15th 1799 by me J. P.

As early as 1831 the above figures had become transposed wrongly in many accounts. The contents were being quoted as 23,090 solid feet and the weight as 1971 tons (but still with the extra 13 cwts.) (Caradus 1831). These higher figures were subsequently adopted by most guide books and other sources from that time on. In many descriptions the weight was rounded up to 'approximately', 'almost', or 'nearly' 2000 tons.

Remeasurement of the stone in November 2001 has enabled these original Pocklington dimensions to be checked and his calculations to be evaluated. Using basic surveying tapes and a clinometer the data obtained has enabled Figures 2 and 3 to be drawn. The level of accuracy obtained is certainly much superior to the data left to us by Pocklington. It is adequate enough for present purposes, but could clearly be done in a much more sophisticated manner if there was a point to it.

The precise weight of the stone is not of particular geological interest and is not unduly germane to the thesis advanced on its origin in the later section. However, it is of enormous popular interest and worth putting on record. Pocklington calculated the 'content of solid feet' as 23,000 - 0. It has to be assumed by this he meant volume in cubic feet. This is the critical measurement and by far and away the most difficult to ascertain. He seems to have used that figure and an assumed specific gravity of slightly more than 2.7 to derive the weight. The remeasured maximum length of the stone (*a axis*) is 18.65m, very close to his 62ft 6ins (NB the *a axis* is not at ground level, it runs from high on the south face down to almost ground level at the north end). Pocklington's measure of 89 feet for the circumference seems to be the girth of the stone measured when a tape is passed through the hole beneath its base. The dimensions of the stone in the sections parallel to the *b and c axes* show a certain amount of variation. Estimates of the cross sectional areas in these planes have had to be made following a series of measurements. Viewed from the southern end the cross-sectional shape is basically rectangular (in fact, quite close to being square) (Figure 4). Most of the stone shows a slightly distorted

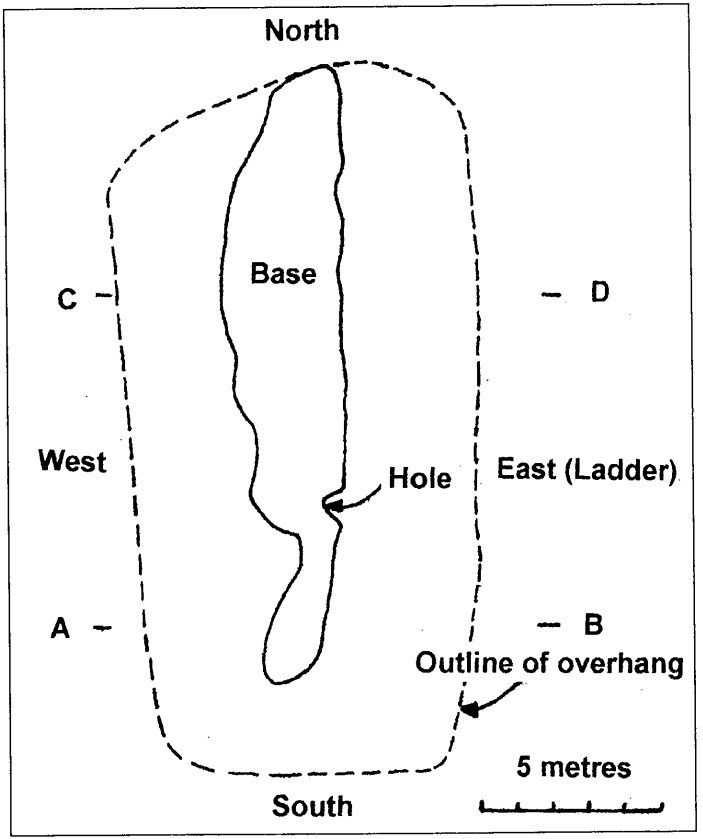


Figure 2 - Plan view

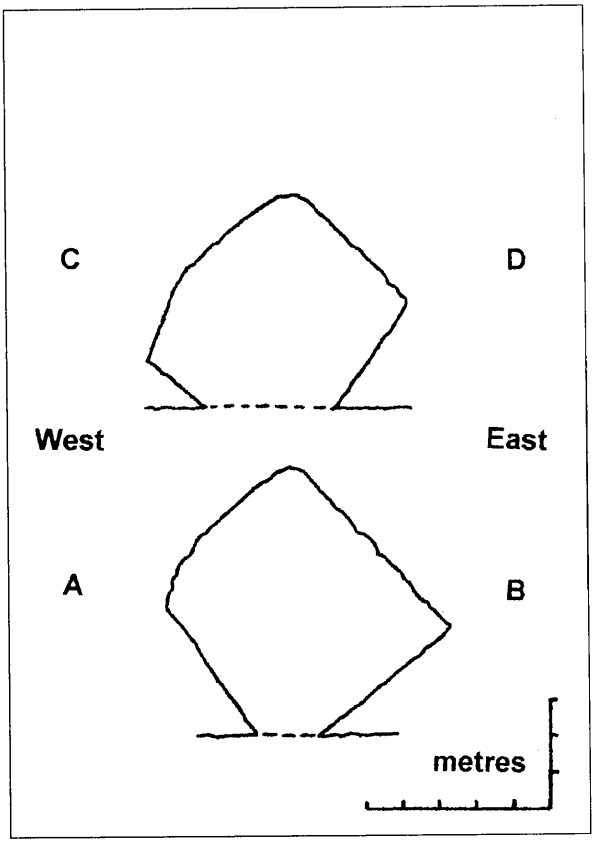


Figure 3 - Cross sections

diamond shape when measured in west-east section (Figure 3). The real difficulty in determining volume and describing shape is at the northern end where a considerable piece of the diamond is missing. There is a quite gentle incline up the northern face (Figure 5). Making reasonable allowances for all these problems regarding shape and hence volume, the recalculated mass is 480.69 cubic metres. Laboratory measurement of samples of the andesite give a specific gravity of 2.65 and thus a calculated total weight of 1273.8 tonnes (1294.18 tons) – i.e. just over 477 tons lighter than Pocklington calculated.

The basic elongated diamond shape of the stone is derived primarily from the joint planes in the andesite. The distinctly planar west and east faces are joint-determined. The stone has its maximum west-east thickness near to the northern end. The base of the rock is at its narrowest at the southern end, this is the end most frequently photographed and the end that emphasises the poised nature of the rock. Most of the northern half of the stone is supported on a base around 3m wide. Projecting the linear undersides of the stone downwards suggests that the 'keel' of the stone is not much more than 1m below the present ground level at the southern end. The *b axis* of the stone appears to run west-east and is approximately 10m. The *c axis* is close to the vertical height of the stone (8.18m). The weight of the stone is fairly symmetrically distributed along a north-south centre line which runs almost directly down the centre of the base. Hence the rock is quite stable in its present position.

Origin

Only two origins can be seriously considered for the stone: either it is a large erratic transported to its present position by ice or it is a piece of rock that has fallen from the crags above. Both origins have been suggested in the popular accounts, but no serious evaluation of the two hypotheses has ever been undertaken. A third possibility lies in a combination of these two ideas – i.e. that it fell from the crags on to ice and was gradually lowered into its present position as the ice melted.

The prime mistake embodied in all the previous descriptions and accounts is that the stone is seen as a single, large, isolated boulder and is not viewed in the context of its surroundings. Once the wider area is looked at there seems little difficulty in very quickly discounting any idea that it is an ice transported erratic and in reaching the conclusive view it has in fact fallen from the crags above.

Erratic hypothesis

There is ample evidence in the Borrowdale Valley of the existence of a major valley glacier in the Late Devensian. Loch Lomond Stadial ice did not reach this part of the valley. The stone itself stands on a glacially scoured and striated platform. Up valley, ice has heavily scoured the nearby spur of Andersonband Crag (NY 855163), and, downstream from the stone, there are some superb *roches moutonnees* features alongside the track to the car park (NY 253166). Above are the glacially steepened trough walls of Bowder Crag

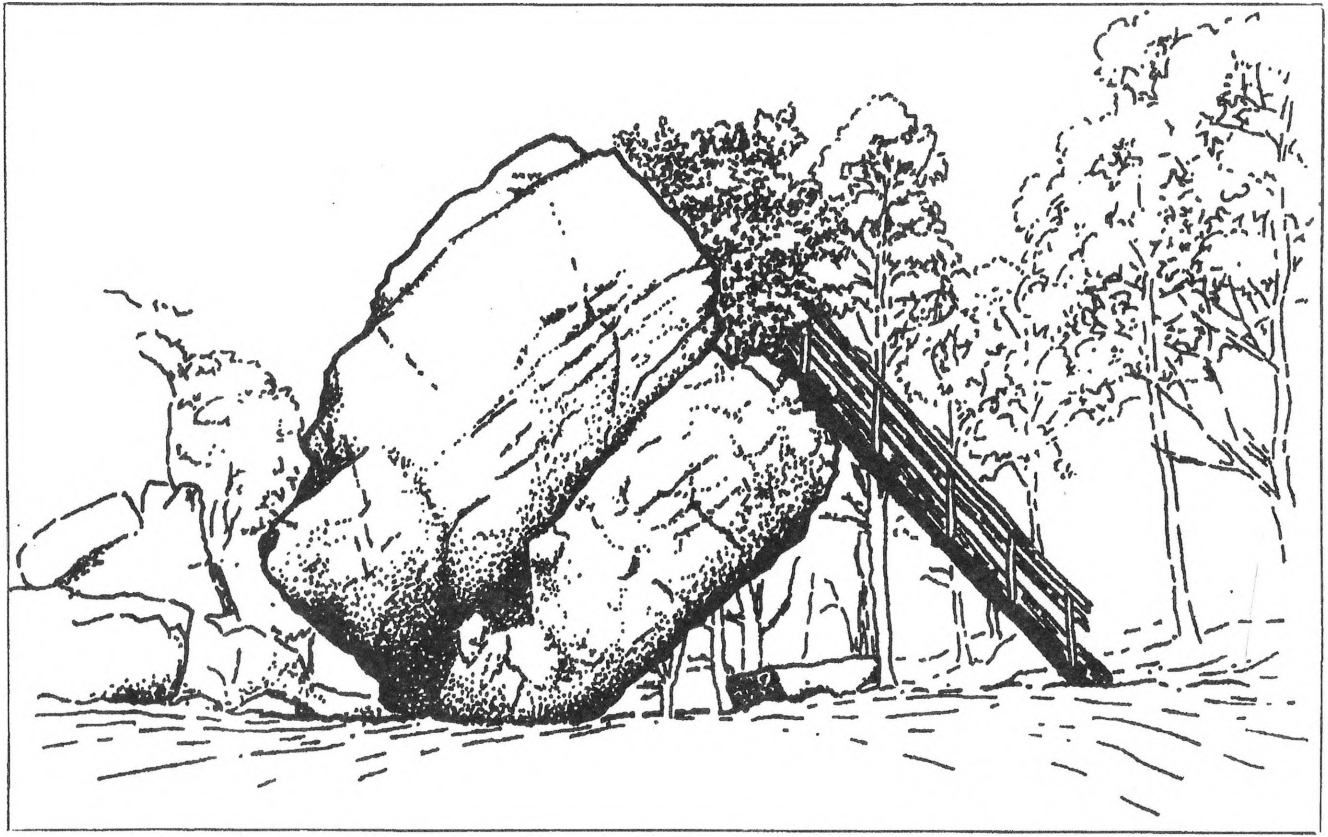


Figure 4 - Southern face.

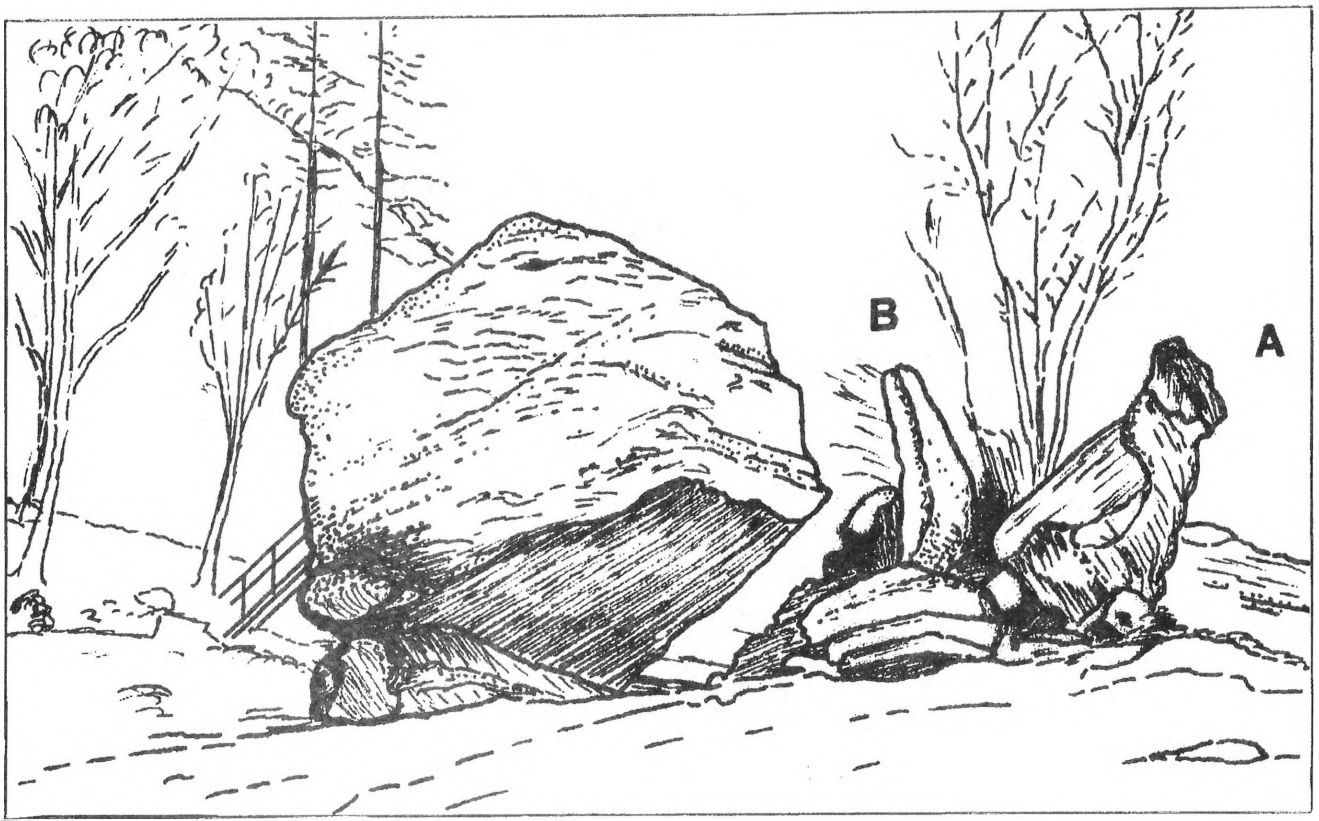


Figure 5 - Northern face.

and the severely ice scoured summit area of Kings How (NY 258167). Clearly, ice could have brought a block of andesite of this size from the upper Borrowdale Valley and stranded it in its present position as an erratic, but it would have had to carry it over, or slightly around, Andersonband Crag and immediately deposited it. Against this hypothesis is the fact that the stone itself shows no signs of glacial striation or rounding. Secondly, a thick, active glacier capable of moving erratics of this size would most likely have been flowing relatively quickly through this constricted Jaws of Borrowdale section of the valley, making it more likely to have carried it through rather than abandon it. Thirdly, this is not a section of the valley where erratics are found. There are many detached boulders, but if there were for example indisputable erratics of known provenance from such sources up-valley as the Blea Crag igneous complex in the Langstrath valley, the case for the existence of downwasting ice and erratic deposition would be strengthened. A totally farcical claim that the stone is an erratic transported by ice from Scotland (Ogbourne 1956) is clearly completely unreasonable.

The most powerful arguments against this hypothesis however, lie in the strength of the evidence for rockfall.

Rockfall hypothesis

If the Bowder Stone is viewed in relationship to the form and nature of the steep slope above it, surmounted by Bowder Crag, it is immediately obvious that here we have a classic example of an unmodified rockfall talus profile - a steep exposed rockwall, vertical in places; a steep, straight upper talus slope; a basal concavity and marked fall sorting of the debris (Figure 6).

The relevant section of the rockwall on Bowder Crag, extends for about 250-300 metres from a point at NY 250166 in a south-easterly direction. It is far from a continuous wall of rock, being broken into a series of prominent buttresses and pinnacles. The section affords some good quality rock climbing. The Fell and Rock Climbing Club of the English Lake District Guide Book to Borrowdale (Kenyon 1999), records 27 individual climbs along this face, varying from the pleasant routes like Bowderstone Pinnacle to modern testpiece climbs on Hells Wall. Many of the rock faces are close to vertical, up to 40 and 50m high and defined by two well-developed sets of near vertical joint planes in the andesite. A series of measurements in the Hells Wall section shows they intersect close to, but never exactly at right angles. On average, a near to north-south set has a bearing of 350 degrees in relation to magnetic north, and a near west-east set has a bearing of 85 degrees. Further south-west along the rockwall the orientation of both sets varies up to 10 degrees, but the angle of intersection remains constant. Hells Wall itself is aligned with the west-east set. Almost parallel to the other joint set, along some of the rockwalls distinctive, narrow (< 1m) belts of cleaved material can be discerned. Generally it is inclined at about 75 degrees to the vertical and within 5-10 degrees of the joint planes. There are many places where slabs are pulling away from the faces of the rock wall, probably more the case on the north-south running faces. The

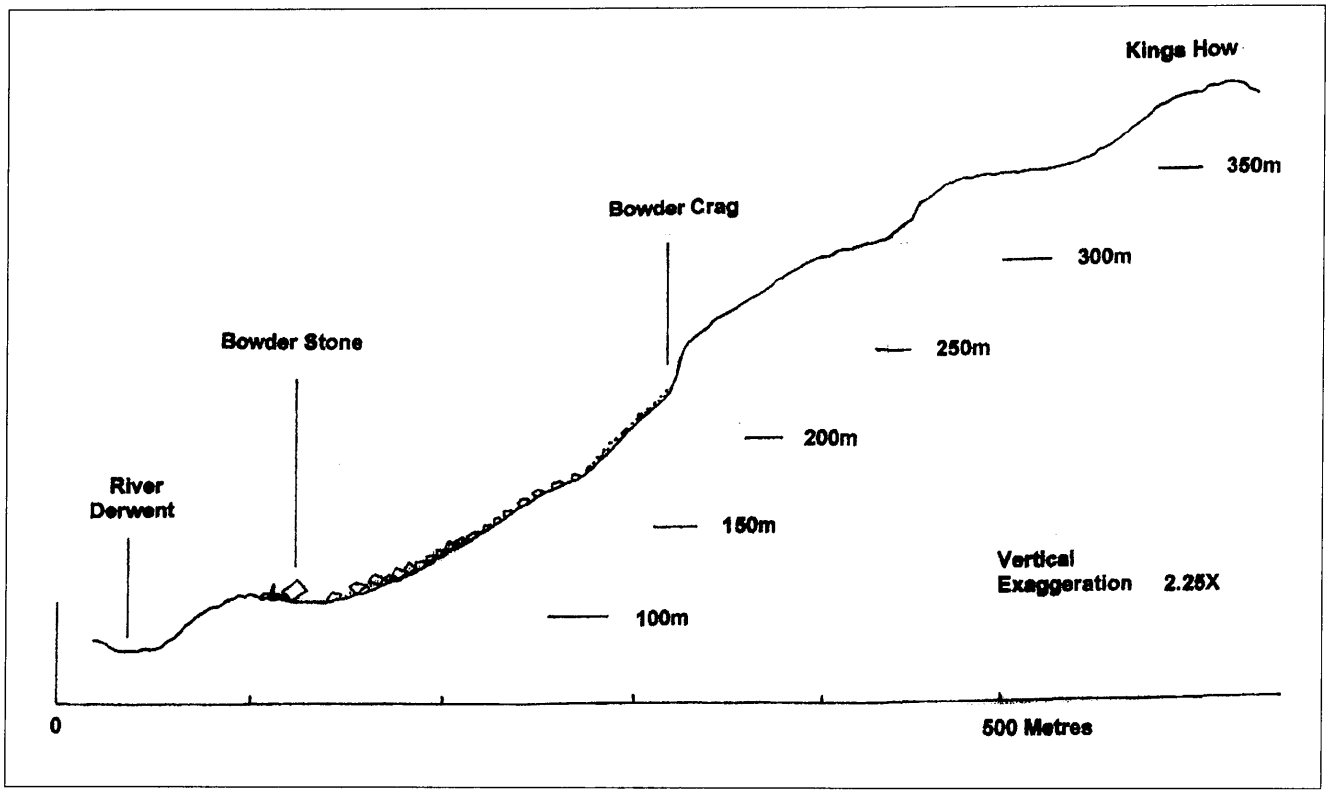


Figure 6 - Slope profile.

rockwall has an irregular line, buttresses and pinnacles are cut by deep clefts and slits, all joint controlled. Rockfall is the dominant process of slope retreat. Further south-westwards the rockwall is progressively less imposing and more broken. The smooth andesite slabs are replaced by beds of cleaved volcaniclastic sandstones. The significant feature of the rockwall is that it sheds clasts that are controlled by the vertical joint pattern – detached blocks show characteristically parallelogram cross sections, defined at their corners by internal angles just below or slightly greater than right angles.

At the foot of the crags the straight talus slope averages 35 degrees, but locally reaches 40 degrees. Clasts on the uppermost parts are generally less than a metre in size, but with a few recently fallen larger slabs. Downslope, however, the talus debris progressively increases in size, with most of the individual pieces measuring over a metre in length. Within this chaotic tangle of boulders, heaped one on top of another in bewildering complexity are some very large pieces indeed – over 10 metres in length. An attempt has been made in Figure 7 to show where the very large ones are lying, but the terrain can only be traversed with extreme difficulty, and it is likely several very large pieces lie partly or totally buried. Mapping of the talus apron however shows it to be sharply defined on either side. At the foot of the apron large boulders lie scattered and free standing. Amongst these is the Bowder Stone itself, which demonstrates the success of the largest blocks in overcoming frictional losses as they travel downslope. Material is not being added to the lower half of the apron at present. Towards the base, where the profile is distinctly concave, the blocks are heavily moss covered or encrusted with lichens. Around three quarters of the talus apron is wooded with oak, birch, holly, and yew trees struggling to survive in the cracks between the blocks. Given the configuration of the talus apron, the size of the debris, the distribution of the largest blocks and the general 'maturity' of the material, it seems likely that most of this material (including the Bowder Stone) was derived from a single and sudden slope failure from Bowder Crag.

The Bowder Stone itself successfully travelled to the foot of the slope, but as it met slightly rising ground, its progress was checked. It is likely that other blocks were close to it and a few possibly ahead of it. As it crashed on to the rising platform where it now stands it smashed against this rocky protuberance and tangled with some of the blocks in front of it. This not only seems to have been sufficient to stop the forward motion, but also to impact with such force as to cause material to break off the stone, including two very large flat slabs of rock which spalled off and came to rest as erect stones on the western (downslope side) (Figure 5A and B). It seems possible that this forward motion having been checked and substantial pieces discarded, the remaining stone gently settled backwards and, because of its symmetrically disposed weight, came to rest on its corner. In front of the stone (i.e. on the west side) today there remains a group (probably around 30) of substantial fragments. The area is difficult to interpret. Some of the material is *in situ* bedrock that helped to check the forward motion of the stone. Others are fragments that came down at the same time as the main stone. However, it is impossible to tell which of the

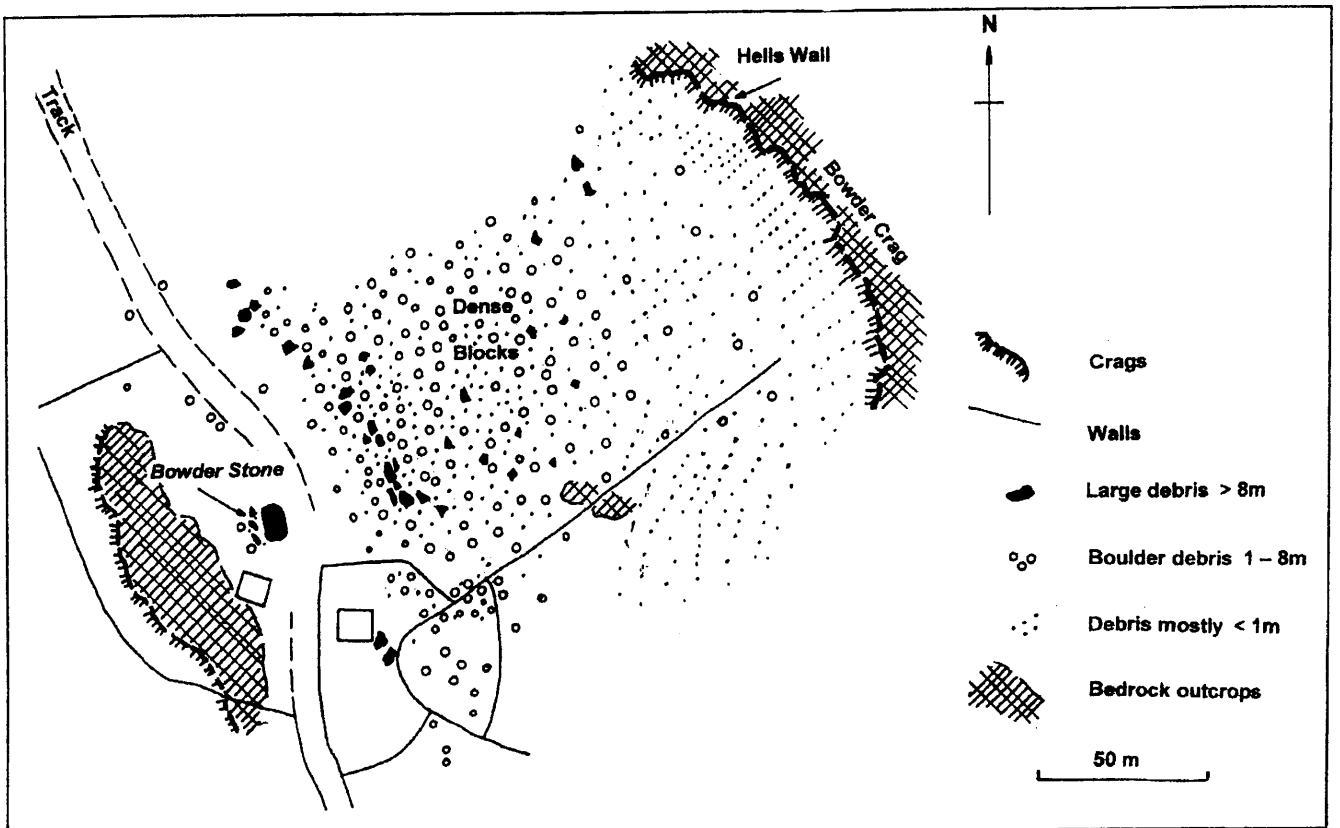


Figure 7 - Rockfall talus.

boulders are actually in their original position - the very large ones undoubtedly are in place, but some of the movable ones may have been 'tidied' by Pocklington and his men at the end of the Eighteenth Century to 'improve' the view of the stone and emphasise its poised nature. The two largest erect pieces (Figure 5A and B), seem not to have been moved, their size would certainly have mitigated against this.

The reasons therefore for concluding the stone resulted from a rockfall from Bowder Crag are:

- Hand specimens of the andesite from the stone and from exposures on the Hells Wall section of Bowder Crag (Grange Crag Member) are identical.
- The basic 'diamond' cross-sectional shape of the stone mirrors exactly the vertical joint pattern seen in the rocks of Bowder Crag. This is very obvious as you stand on top of the stone, both the eastern (ladder) and western faces slope away at between 40 and 45 degrees – defining the two joint planes. The overhanging undersides are similarly defined. The stone is clearly lying on its side (*on the a axis*). It would have been too much to expect a vertical piece of cliff face (over 18 m high) to have remained in a vertical position having travelled roughly 250m downslope.
- One of the large erect stones (Figure 5A) which stands in the group of boulders on the western side of the stone shows a belt of cleavage, aligned close to the joint planes on its broken northern end, identical to the belts of cleavage seen on the western facing slabs of Hells Wall.
- At the northern end of the stone the keel is actually broken. Two large wedges of rock at is base have fractured from the mass of the stone, but have remained in position. These fragments may incidentally help to support the stone, the base of one of them (on the western side) is not visible and may be anchoring the main mass at depth. Fracturing would be understandable in a rockfall situation – much more likely than if the stone had been an erratic lowered into position by ice, when fractured sections would most probably have become detached.
- The position of the stone at the toe of the talus spread is exactly where it would be expected to be in a rockfall event of this magnitude.

Age

Finally one major question remains unresolved – when did such a large rock fall take place? In reality we have no method of ascertaining this with any certainty. There is no evidence to suggest it came down in historic times. A major rockfall of this size occurring in the last few centuries, would have been recorded in some way or other. The maturity of the talus deposit however, supports a thesis that it is a relic deposit. In general, the majority of studies of talus slopes in upland Britain infer they were produced under a much more severe climate regime than that of the present. Ballantyne and Harris (1994) in their revue of work on relic taluses in Wales, Northern England and Scotland, conclude that formation during the Late Devensian Lateglacial is the most likely.

Retreat of the Late Devensian ice exposed a glacially steepened slope and potentially unstable rockwalls. The severe periglacial climate that persisted during the early stages of the ice withdrawal and during the Loch Lomond Stadial (when ice may have been only just over 2km away at the Rosthwaite Moraines), (McDougall 2001), resulted in widespread shattering of exposed rock surfaces. The lower talus apron and the debris around and immediately above the stone are mature and stable and have all the characteristics of a relic feature.

References

BAILEY, B. J., 1981. Lakeland Walks and Legends, Mayflower Books, p 82.

BALLANTYNE, C. K. and HARRIS, C. 1994. The Periglaciation of Great Britain. Cambridge Univ. Press, Chapter 12.

CARADUS, M. 1831. Advertisement for the Bowder Stone, Printed by Thomas Bailey, Keswick. Keswick Museum exhibit No. 44.

KENYON, R. J., 1999. Borrowdale, Climbing Guides to the English Lake District, Fell and Rock Climbing Club of the English Lake District, pp 139-144.

LEFEBURE, M., 1864. The English Lake District, Robert Hale, London, p 30.

McDOUGALL, D. A., 2001. The Geomorphological impact of Loch Lomond (Younger Dryas) Stadial plateau icefields in the central Lake District, northwest England. Journ. Quaternary Science, Vol. 16(6) pp 531-543.

NICHOLSON, N., 1969. Greater Lakeland, Robert Hale, London, p 30.

OGBOURNE, H. A. L., 1956. Carried by Ice, Cumbria Vol. 6, p 156. (Refuted by BOUGHTON, E. G., 1956. Cumbria Vol. 6, p 211).

POCKLINGTON, J., 1799. Joseph Pocklington Papers, Cumbria Record Office, Carlisle, D.Sten Pocklington No. 11.

Acknowledgements

I would like to thank Ray Trickey for assistance with the measurement and computation of the stone, and also the many visitors who quite voluntarily became involved with tape holding and asking interesting questions whilst the field work was in progress. Ann Kelley has assisted with the laboratory determination of the SG of the rock samples. Thanks are also due to the many local people who responded to an appeal in *The Keswick Reminder* for historical information on the stone. Much of this has not been used here, although it has helped in understanding the site. There is much local and visitor interest in the stone, it is hoped this geological interpretation will enhance peoples enjoyment of the area.

Dr. R.A. Smith
[redacted]

ON THE GENESIS OF THE SHEAR-ZONE-HOSTED GOLD MINERALIZATION IN SOUTH EASTERN DESERT, EGYPT

Dr William Edward Gordon Taylor & Dr Yahia Abbas El Kazzaz

Summary

The discovery, extraction and exploitation of Egyptian gold can be traced to the Pharaonic times. Nearly a hundred gold occurrences from the Eastern Desert are recognized and almost all of them have been previously attributed to an epithermal (*s.s.*) origin. However an epithermal model does not satisfactorily explain the origin of the gold-bearing quartz veins of central Wadi Allaqi, which were developed in a volcano-sedimentary sequence within a back-arc tectonic provenance.

Remote-sensed images and field observation show that the mineralized rocks of central Wadi Allaqi were restricted to the ubiquitous shear-zones, which were hosted in complex, regionally metamorphosed terranes. Relatively thin (a few centimetres to a metre) mineralized quartz veins, which occur along the shear-zones possess distinct but localised alteration zones, up to 5m in width, within the volcaniclastic country rocks. The spatial and temporal structural relationships indicate that the mineralized veins have developed as part of a brittle-ductile shear sequence in low-grade regional metamorphic conditions which was broadly synchronous with the earliest D1 deformation event (El Kazzaz & Taylor 2002; Taylor *et al.* 1993) of the Pan-African orogeny in central Wadi Allaqi. A further two distinct mineralization events are recognized subsequent to the earliest main event.

Investigations of the petrography, fluid inclusions and oxygen and hydrogen stable isotopes tend to support the preferred metamorphic provenance for the auriferous fluids.

Introduction

From about 2500 BC, the ancient Egyptians used gold for sculptures, jewellery, decoration of buildings, and embellishment of sarcophaguses (Hussein 1990). Although ancient wall paintings indicate that some of the gold may have come from what is now Sudan, the vast majority of the gold came from mines in the Eastern Desert. Indeed the oldest geological map known is of a gold mine in the northern Eastern Desert of Egypt and is dated at between 1300 and 1205 BC. The almost complete papyrus map is now housed in the Turin Museum and shows a variety of workings and geological features in amazing detail. Some 95 gold occurrences are known in the region (Figure 1) and most have been mined.

Reliable details of gold production only exist for the present century and show extremely variable recovery rates with four main peaks in 1905, 1915, 1940, and 1954. The maximum annual production was achieved in 1954 was over 530 kg of gold (Taylor 1997).

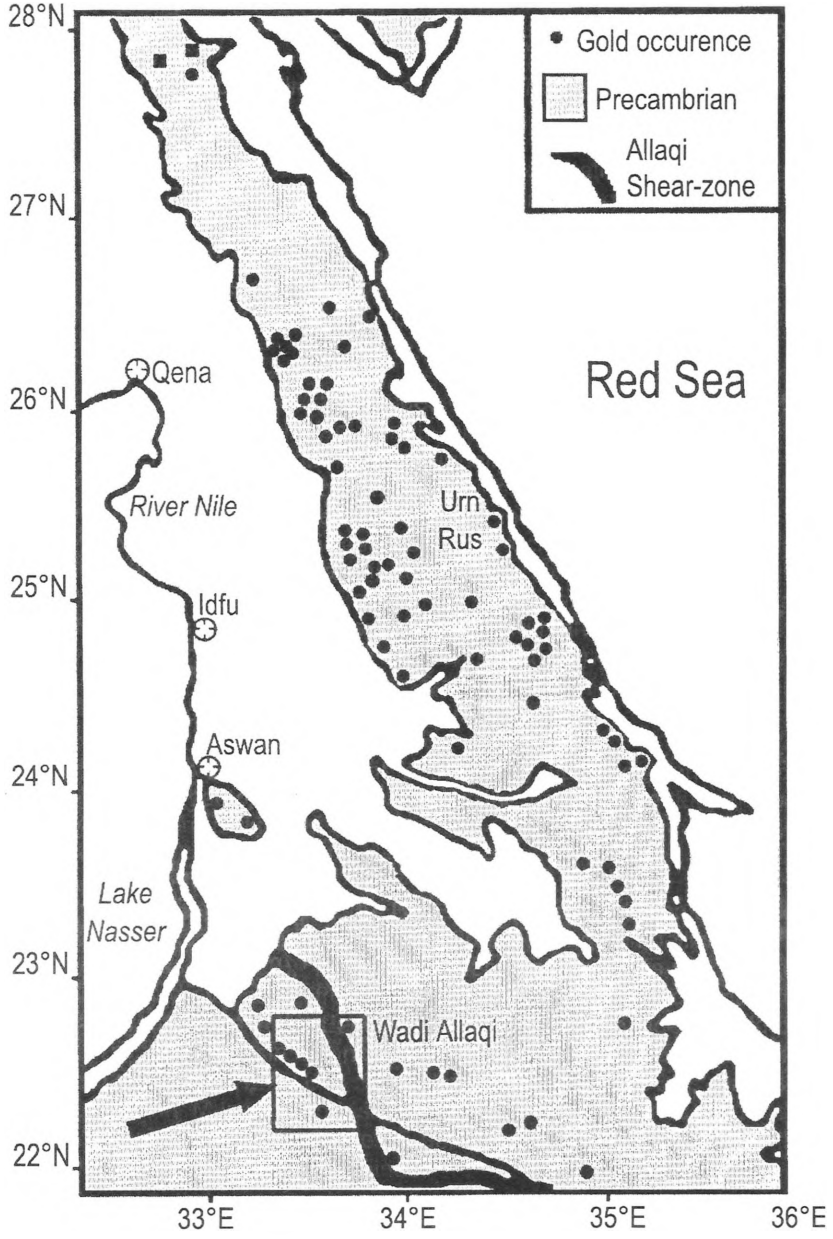


Figure 1 - Gold occurences in the Eastern Desert of Egypt; arrow indicates area under investigation (box); unshaded areas are Phanerozoic rocks.

The genesis of the gold deposits has been previously ascribed to an epithermal process developed in association with Andean-type calc-alkaline felsic volcanics (Hussein 1990). This article sets out preliminary data on the gold deposits of central Wadi Allaqi that does not support that interpretation and suggests an origin closely associated with the tectonic and metamorphic events of the Pan-African Orogeny (950-550 Ma; Kennedy 1964; Shackleton 1986).

Structural control of the ore bodies in central Wadi Allaqi

The most prominent structural feature close to Wadi Allaqi is the *Allaqi Shear-zone* which runs within the Proterozoic rocks from near the Red Sea to Lake Nasser (Figure 1). Associated with the shear-zone are numerous subsidiary, splay shear zones forming complex duplex structures. These structures have been formed in the earliest deformation phase of the Pan-African Orogeny (D1; El Kazzaz & Taylor 2002) during which the rocks were metamorphosed to greenschist facies assemblages (about 2-3 kilobars pressure and 260-300°C temperature; Barker 1990 p.149). Subsequently the rocks were further deformed and four other phases have been recognised (D2, D3, D4 & D5; Taylor *et al.* 1993; El Kazzaz & Taylor 2002) demonstrating a typical polyphase orogenesis.

The gold is almost entirely found within sigmoidal quartz veins, which are hosted by a complex series of Neoproterozoic andesitic to basaltic volcano-sedimentary lithological structurally bounded sequences that include stromatolitic limestones, rudites and rare lava flows. The sequences are intruded by syn-tectonic granitic plutons of various ages and in one pluton (Atshani Pluton) gold-bearing quartz veins, hosted by volcaniclastic rocks, occur as enclaves. It has been demonstrated that the sequences are similar to those found in a back-arc basin tectonic environment (El Kazzaz 1995). The quartz veins vary in thickness from a few centimetres to over a metre, almost exclusively contained within the D1 shear-zones and are deformed by structures of the later phases. The mineralized quartz veins possess distinct but localised alteration zones, up to 5m in width, within the volcaniclastic country rocks. Although rare gold grains have been found in the alteration zones, a large proportion of the gold is restricted to the quartz veins.

Because of the widespread intense deformation, intermediate stages in the development of the quartz veins are rarely observed. It is probable that the veins started to form in tension gashes and were subsequently rotated and dilated sinisterly with an increase in shear strain (Figure 2). Thus the veins can be demonstrated as part of a brittle-ductile shear sequence with the foliation formed in D1 being sub-parallel to the shear walls. Most commonly, the grains of gold are found near the bends of the sigmoidal quartz veins where the stress system would be more amenable to mineral deposition.

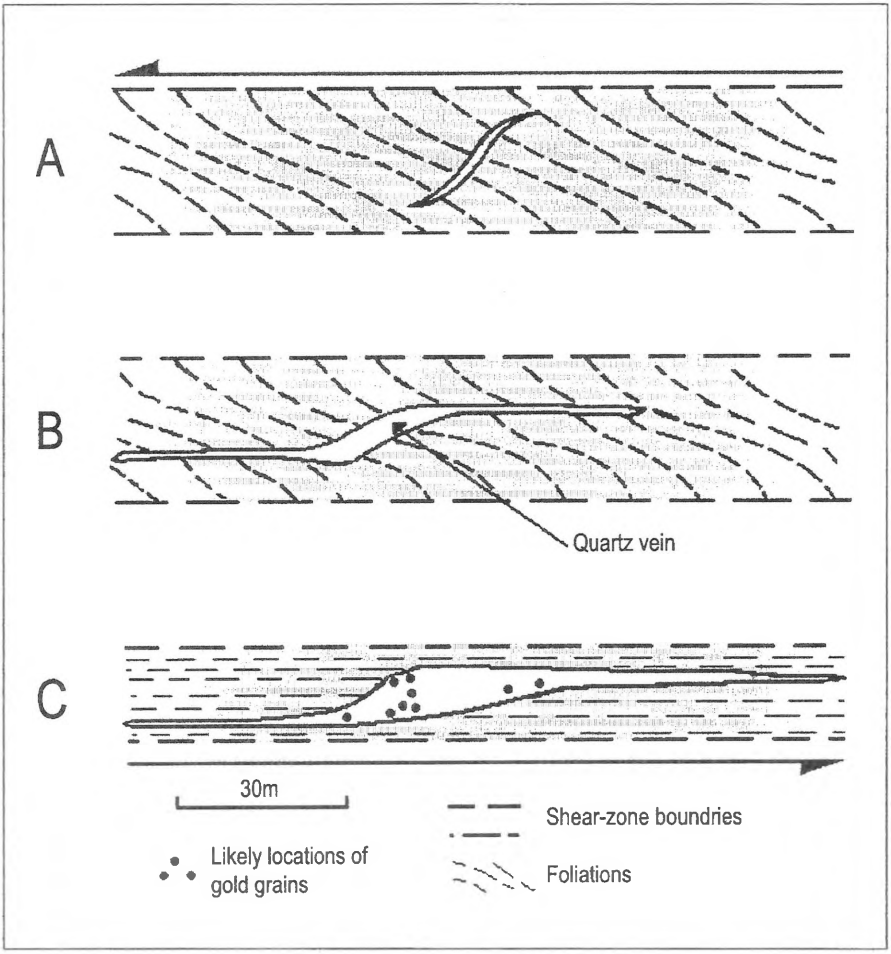


Figure 2 - Progressive development of a gold-bearing quartz vein; note increase in strain from (a) to (c) and the rotation of the foliation within the shear zone. The horizontal arrows to the top and bottom of the diagram indicate the sinistral sense of shear.

Mineralization Paragenesis

A paragenetic history has been deduced for the quartz veins with respect to the regional deformation history using a combination of field and microscopiccriteria (Figure 3; El Kazzaz 1995). The main features of the history are (a) the early deposition of gold (syn-D1) associated with greenschist facies minerals and (b) the late residual/diagenetic alterations that have led to the formation of some diagnostic secondary minerals.

In the *early mineralization event* individual gold grains occur but are rarely greater than 5μm in diameter. Generally these individual grains occur as one in every three microscopic slides! Strained quartz is the predominant gangue mineral often associated with chlorite, occasionally with biotite, and sometimes included within pyrite. The phyllosilicate minerals have unexpectedly high amounts of copper, chromium, iron, lead, nickel and zinc and are associated with rare iron- and calcium-rich arsenate minerals. ICP-MS chemical analyses revealed the presence of some unusual mercury compounds that may be associated with these latter minerals, but individual mercury minerals have not been identified. Minor amounts of ankerite and calcite have been observed but it is not certain whether they formed at this or the later event. In the relatively narrow wall-rock alteration zones, plagioclase is changed to epidote and sericite, disseminated fine-grained calcite is found parallel to D1 foliations, and chlorite occurs as a product of the various reactions.

The *later mineralization event* is characterised by the growth of euhedral pyrite, which cuts D1 structures and shows evidence of brittle deformation.

The *residual/diagenetic event* is demonstrated by alteration of pyrite to goethite and the formation of minor amounts of celestine, xenotime and monazite. The latter are diagnostic of weathering or diagenetic conditions

Geochemical investigations

Using ICP-MS techniques it has been shown that the concentration of gold, in the veins that are presently exposed, is rarely greater than 7g/t and so only in a few locations are the deposits of commercial value.

The fluid inclusions and stable isotopes of oxygen and hydrogen for the quartz veins have been investigated to throw some light on the nature of the ore-forming fluids and their conditions of formation. It must be emphasised that this was very much a preliminary study and that a detailed investigation would be required to provide a more definitive identification of the sources of the respective elements.

Fluid inclusions occur in the quartz and calcite of both the veins and the wall rocks but this preliminary study concentrated upon the abundant primary types in the quartz of the veins. The external shapes of the primary inclusions show a great variety. Oblate, cylindrical, negative cubic and irregular forms are common and most occur isolated. Secondary inclusions are generally aligned along

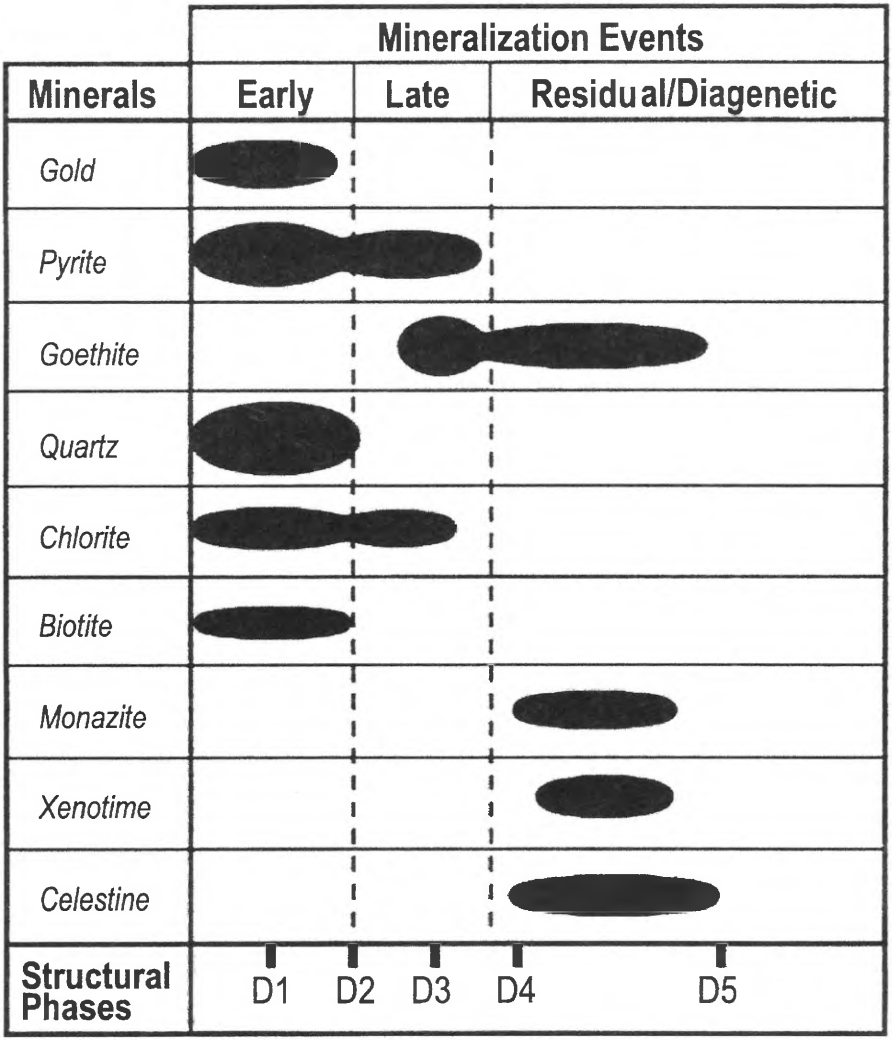


Figure 3 - The paragenetic history for the central Wadi Allaqi shear-zone-hosted gold deposits related to the deformation phases.

conjugate fractures associated with D4 structures. All types of inclusions are relatively small (diameters <15μm) but the secondary inclusions are particularly minute.

Using the criteria of Roedder (1984), and on the basis of petrography and fill types, five main types of primary inclusions have been distinguished (Figure 4). Subdivision of types 1, 2 and 3 were based mainly on the proportion of liquid and vapour phases. Type 4 inclusions are always associated with chlorite, which is a syn-D1 formed mineral. Type 5 is a more complex type of inclusion with three phases.

Some limited microthermometric measurements were made. The data for homogenization temperatures (T_h; Figure 5) indicate two main concentrations, *viz.*, for types 2 and 3 about an average of 100°C and for type 4 about an average of 200°C. Taking into account pressure estimates of about 2 kilobars, this would yield tentative fluid trapping temperatures [T_t] of approximately 320°C for type 4 inclusions (Shepherd *et al.* 1985). Freezing data for type 4 inclusions indicate that the salinity of the fluid is about 25 weight % equivalent NaCl. Estimating the T_t for other inclusions was not attempted because of the lack of precision.

The preliminary analyses for stable isotopes of hydrogen and oxygen on samples of vein quartz yielded some interesting and unusual results, which require further detailed investigation. Nevertheless, two samples did give more reliable results for both $\delta^{18}O$ and δD and plot just outside the 'metamorphic water' field (Figure 6a). The range of $\delta^{18}O$ values (Figure 6b) tend to lie close to that found in the 'metamorphic water' field.

Although this preliminary investigation raises more questions than it answers, since there is an indication that a complex mixture of fluids is highly likely, on balance the original source of the ore-forming fluids was probably derived from metamorphic water during the formation of the D1 shear-zones.

Summary of the gold deposits

The main features of the quartz-vein gold deposits of central Wadi Allaqi may be summarised as follows.

(a) *Tectonostratigraphical setting*: quartz-veins restricted to ubiquitous D1 shear-zones and, within the oldest pluton (Atshani Granite; El Kazzaz 2002), preserved in the D1 shear-zones of volcaniclastic rock enclaves.

(b) *Regional depositional environment*: the veins were formed along fractures in brittle-ductile shear-zones, the mineralizing fluids were released during deformation and metamorphism

(c) *Age range*: the host rocks of the veins are Neoproterozoic and mineralization commenced during the earliest deformation phase (D1) of the Pan-African orogeny.

Type	Phases Present	Proportion of Phases	Forms (not to scale)
1	Vapour (V) -rich two phase	V = 80 % L = 20%	
2	Liquid (L) -rich two phases	V = 70 % L = 30%	
3	Liquid and vapour (L≈V)	V = 60 - 50 % L = 40 - 50%	
4	Liquid - rich and vapour + chlorite	V = 70 % L = 30%	
5	Immiscible aqueous liquid, two vapours	V = 75 % L = 25%	

Figure 4 - Primary fluid inclusion types from the quartz gangue of the gold deposits; bar in type 5 form diagram is 10μm.

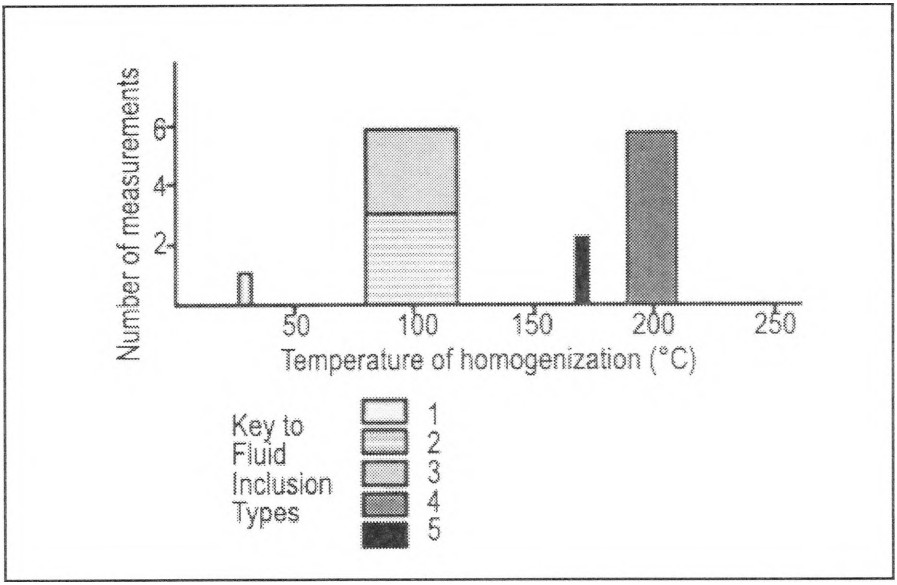


Figure 5 - T_h data for the primary fluid inclusions from both barren and gold-bearing quartz veins; width of each column indicates uncertainty of the data.

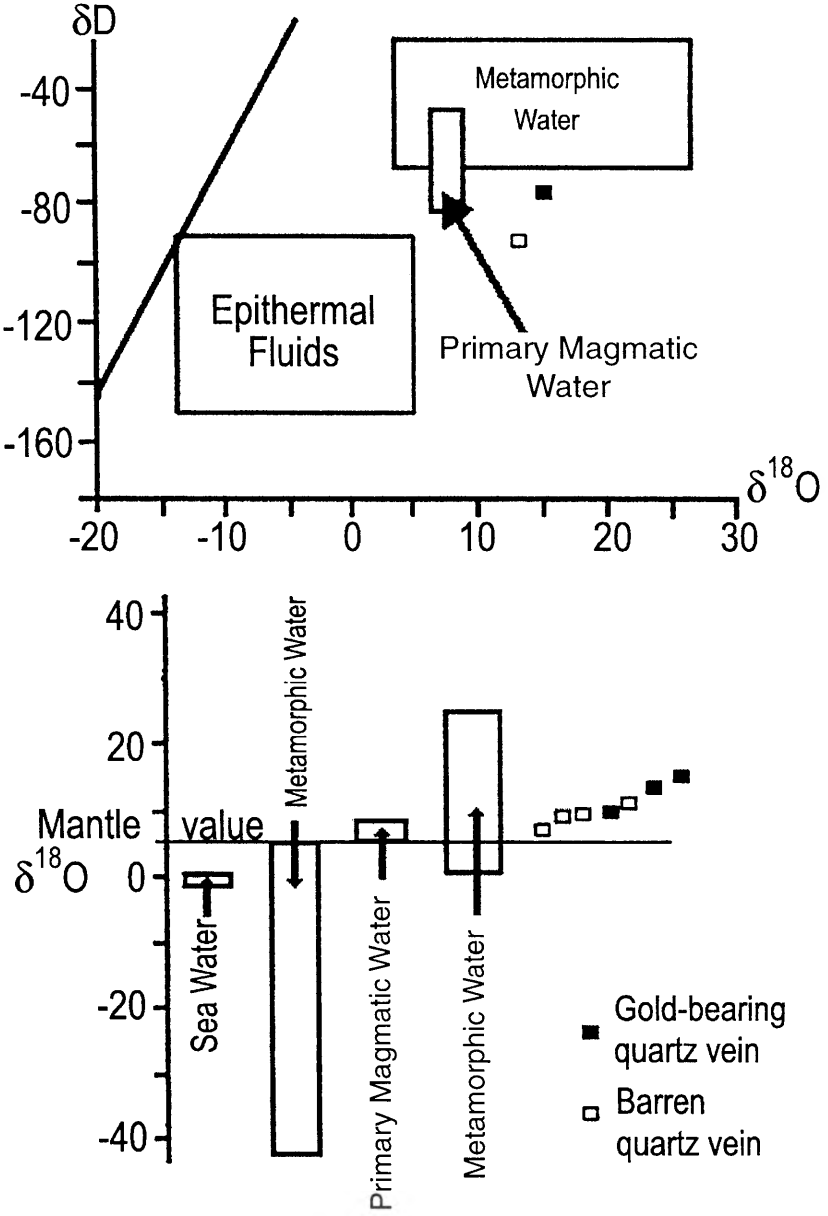


Figure 6 - (a) Plots of δD against $\delta^{18}O$ for stable isotopes from the central Wadi Allaqi; the straight line represents values for present-day meteoric waters. (b) Measurements of $\delta^{18}O$ for gold-bearing and barren quartz veins in central Wadi Allaqi in comparison with the range of values found in various naturally-occurring waters

(d) *Host rocks*: exclusively volcaniclastic rocks.

(e) *Associated rocks*: granitic intrusions associated in space but not in time.

(f) *Ore mineralogy*: pyrite, native gold; secondary alteration to goethite and other diagenetic minerals.

(g) *Gangue minerals*: quartz, chlorite, sericite.

(h) *Structure*: sigmoidal-shaped, gold-bearing quartz veins hosted within shear-zones; the quartz in the veins shows varying intensities of strain and frequently stained with iron oxide; no open-space structures.

(i) *Isotopic signatures*: very complex; preliminary data for ^{18}O stable isotope gives a metamorphic water range and plots combining data for hydrogen (δD) and oxygen ($\delta^{18}O$) occur in an intermediate position between metamorphic and magmatic water.

(j) *Fluid inclusions*: very complex; most fluids are rich in varying amounts of CO_2 and the T_h ranges from 29-165°C. Probably the initial fluids were metamorphic in origin since inclusions associated with chlorite gave T_h ranges from 180-220°C. The salinity of the fluid in the latter inclusions is about 25 weight % equivalent NaCl.

Discussion and Conclusions

The genesis of the Egyptian Pan-African gold mineralization has been discussed by many geologists (*e.g.*, Hussein 1990), all of whom favoured an epigenetic hydrothermal model with granitic intrusions providing the heat source. The information given above indicates that this is an oversimplification and at least some gold deposits in the Eastern Desert do not fit into that model. Harraz & El Dahhar (1993) have obtained T_h values in the range of 250-300°C for fluid inclusions from gold-bearing quartz veins of the Um Rus gold mine of the central Eastern Desert (Figure 1) and have questioned previous interpretations for the genesis of the deposits.

Mesozoic and Cenozoic epithermal geothermal systems in volcanic terrains (Henley 1991) are characterised by acidic to intermediate volcanic wall rocks, intense and pervasive alteration haloes, and widespread presence of hydrothermal breccia. The wall rocks of most epithermal deposits are unmetamorphosed, although Henley (1991) has suggested that metamorphism and deformation of deposits in more ancient volcaniclastic rocks could have occurred afterwards. Most epithermal gold deposits have formed from solutions in the range of 0.5 - 5 weight % NaCl. None of the criteria indicated above fit the central Wadi Allaqi gold deposits, which are restricted to relatively narrow, widespread shear-zones formed during the D1 deformation phase close to the acme of greenschist facies regional metamorphism. Moreover, the typical pre-tectonic mineralization in a back-arc tectonic setting is polymetallic or kuroko-

type massive base-metal deposits that would occur concentrated in specific locations (*e.g.*, the Okinawa Trough, Sakai *et al.* 1990).

In conclusion, a metamorphic rather than epithermal origin is favoured for the formation of the gold-bearing veins because the:

(a) host rocks are affected by low-grade greenschist facies metamorphism and strong, complex deformation and are of Neoproterozoic volcaniclastic types in which epithermal-type mineralization is very rare;

(b) widespread vein system predates the intrusion of the Atshani Granite, which was emplaced as a stoped pluton into relatively cold country rocks and does not form mineralized haloes;

(c) petrographical data indicates that the gold is associated with complex phyllosilicates, which were formed during an earlier metamorphic event coeval with the D1 deformation;

(d) preliminary data from fluid inclusion and oxygen and hydrogen stable isotope investigations indicate that the trapped fluids have a metamorphic affinity;

(e) composition of the trapped fluids is very complex and some are rich in CO_2, which is typical of metamorphic reactions in volcaniclastic rocks.

This interpretation is advanced with some caution because of the overall complexity of the duration and nature of the probable fluids that formed the gold mineralization, and their relationship to the associated tectonism.

References

BARKER, A. J., 1990. Introduction to metamorphic textures and microstructures, Glasgow: Blackie & Sons Limited.

EL KAZZAZ, Y. A. H. A., 1995. Tectonics and mineralization of Wadi Allaqi, south Eastern Desert, Egypt, Ph.D. thesis, University of Luton.

EL KAZZAZ & TAYLOR, W. E. G., 2002. Tectonic evolution of the Allaqi shear zone and implications for the Pan-African terrane amalgamation in the south Eastern Desert, Egypt, Journal of African Earth Sciences, 33, 177-197.

HARRAZ, H. Z. & EL DAHHAR, A M., 1993. Nature and composition of gold forming fluid inclusions in vein materials, Journal of African & Middle East Earth Sciences, 17, 341-353.

HENLEY, R.W., 1991. Epithermal gold deposits in volcanic terranes, in: Foster, R. P. (Ed) Gold Metallogeny and Exploration, Glasgow: Blackie & Sons, 133-164.

HUSSEIN, A. A. A., 1990. Mineral Deposits, in: Said R. (Ed), The Geology of Egypt, Amsterdam: A. A. Balkema, 511-566.

KENNEDY, W. Q., 1964. The structural differentiation of Africa in the Pan-African tectonic episode, Annual Report 8, Research Institute of African Geology, University of Leeds, 197-225.

ROEDDER, E., 1984. Fluid Inclusions, Reviews in Mineralogy 12, Washington, D.C.: Mineralogical Society of America.

SAKAI, H., GAMO, T., KIM, S. E., TSUTSUMI, M., TANAKA, T., ISHIBASHI, J., WAKITA, H., YAMANO, M. & OOMORI, T, 1990. Venting of carbon dioxide-rich fluid and hydrate formation in mid-Okinawa Trough back-arc basin Science, 248, 1093-1096.

SHACKLETON, R. M., 1986. Precambrian collision tectonics, in: Coward, M. P. & Ries, A. C. (Eds), Collision Tectonics, London, Geological Society, Special Publication, 329-349.

SHEPHERD, T.J., RANKIN, A. H., & ALDERTON, D. H. M., 1985. A practical guide to fluid inclusion studies, Glasgow, Blackie & Sons.

TAYLOR, W. E. G., 1997. A review of Egyptian gold deposits, Newsletter of the International Liaison Group on Gold Mineralization, 24, 60-61.

TAYLOR, W. E. G., EL KAZZAZ, Y. A. H. A., & RASHWAN, A. A., 1993. An outline of the tectonic framework for the Pan-African orogeny in the vicinity of the Wadi Um Relan area, south Eastern Desert, Egypt, in Thorweihe, U. & Schandelmeier, H. (Eds.), Geoscientific Research in Northeast Africa, Rotterdam: A. A. Balkema, 31-34.

Acknowledgements

Awards from the British Council, NERC financially supported this investigation [ICP/31/1192], the Egyptian Geological Survey & Mining Authority, and a University of Luton research studentship to Dr. El Kazzaz. The following provided considerable material assistance for this particular investigation, and are gratefully acknowledged: Dr. A. E. Fallick, Dr. A. A. Hussein, Dr. K. Jarvis, Dr. A. Kearsley, and Professor A. Rankin.

William Edward Gordon Taylor
[redacted]

Yahia Abbas El Kazzaz
[redacted]

(Both formerly of the Lithospheric Stress Research Group, University of Luton)

THE SOLWAY REGION IN THE LATE PLEISTOCENE

Dr Richard Clark

Introduction

The Solway Firth axis joins and integrates its Scottish and Cumbrian sides which have shared environmental history and acted as one unit during the later part of the Pleistocene. At one time north Cumbria and the Scottish side contributed largely to a movement of ice from the Irish Sea catchment (ISC) into the North Sea catchment (NSC). At another time, both parts contributed to a great outflow of ice westward into the north part of the Irish Sea basin (ISB). There was also a lesser later movement of ice across the region. The two parts share unresolved problems of what happened and when. Beyond the variation imposed by differences in lithology, structure and disposition of major relief features there is a unity of landscape style that tells of a largely common formation. Neither part can be fully understood in isolation yet they have usually been dealt with separately. The sheer size of the region and how its ice influenced and was influenced by circumstances from the Scottish Highlands and Firth of Clyde in the north-west to the North Sea coastlands in the east are also important. Although there have been several recent reviews of glaciation north and south of the Solway (Mitchell and Clark 1994, Clark and Smith 1998, Tipping 1999) there are already new perspectives to consider.

The south limit extends from St Bees Head across the northern Lake District (LD), to the head of the Eden valley and Stainmore. The north limit extends east from Wigtown Bay to include the northern catchment of Solway Firth as far as Liddesdale and the Irthing valley. The region is about 100km east-west and 100km north-south. An area of this size and diversity is inevitably complex.

The first part of this review considers the extent and effect of ice transfer from the Solway region east across the North Pennines. The end of that movement and its associated landforms especially near the west-east crossings are also reassessed. The second part largely deals with a later broad convergence of ice into the Solway Firth area from hills to north and south. The significance of some meltwater discharge systems and the nature of an even later Scottish Readvance of ice are then discussed. The potential implications of fresh appraisal of Solway glaciation for its relationships in both place and time with adjacent areas are also considered.

PART ONE

The ice goes east

1. The context

In one of the more readable and dynamic accounts of this Late Pleistocene glacial period, Wright (1936, 63), dealing with accumulation of ice from the north, said *'the congestion in the Irish Sea Basin had a remarkable effect on the*

glaciers developed in the Lake District, and in that part of the Southern Uplands immediately north of the Solway Firth. This ice, finding its escape to the west barred, turned eastwards into the Vale of Eden, which it soon filled to overflowing, and then poured over the lower passes of the Pennines into the head-waters of the Tyne and Tees. There it swept down the valleys of these rivers to join the great glacier, which issuing from the valleys of the Forth and Tweed, crept south along the coast of England. Thus again we find the Western ice relieving itself by sending glaciers to the east .....'.

Any such barrier to movement of Solway ice west had to divert it elsewhere and also to exclude Highland-Clyde ice. To separate, divert, exclude, its surface had to be high enough to form a culmination or ice-shed. Reports (Dixon et al 1926) of Ennerdale intrusive rocks in north Cumbria and general lack of report of Ailsa Craig erratics east of Wigtown Bay suggest where a divide may have been, perhaps extending south from the Cairnsmore of Fleet area.

In the Solway area the eastward salient of this Late Devensian Maximum or 'main glaciation' ice (29000 - 22000ka BP) into NSC extended for about 90km from the head of North Tyne valley to the southern side of Stainmore where it met the ice from round the head of Swaledale (Figure 1). This stretch was broken only by the higher parts of the North Pennine scarp. The ice bed (not its surface) at the crossing was well over 600m OD which allows a conservative estimate of ice thickness of 450m in the Tyne Gap and 250m over central Stainmore. Ice surfaces in the distant source areas would have been significantly higher than where the ice crossed the Pennines.

Easily recognisable rocks have been used from the time the glacial hypothesis was formulated and accepted to trace the movements of the ice that carried them (Avebury 1906, Raistrick 1931, Lunn 1995). The Shap Granite from south of Solway and the Criffel-Dalbeattie granite suite rocks from north of the Solway are among these distinctive rock types. A general picture emerged before the mid-20th century. It was deduced that ice had moved east from Galloway, crossing the Dalbeattie and Criffel granite outcrops, pressing north into Esk and other valleys near Langholm (Lumsden et al 1967), moving up Liddesdale and east across Bewcastle Fells into the North Tyne catchment. Erratics from Dumfries and Galloway have been traced in the Eden valley and over Stainmore where they are accompanied by Shap erratics carried by ice from the eastern LD. Apparently that southern branch of Scottish ice movement was overwhelmed by increased ice flow from the northern LD, from which erratics are found north of Gilsland in the Tyne Gap and as far north as Wark in the North Tyne valley.

2. Stainmore and Teesdale

Indicators of flow direction (Figure 4) suggest ice converged from north-west, from Shap Fell to the west and from the Howgill Fells to the south-west to pass east over Stainmore on a 14km front south from Mickle Fell. East of Mickle

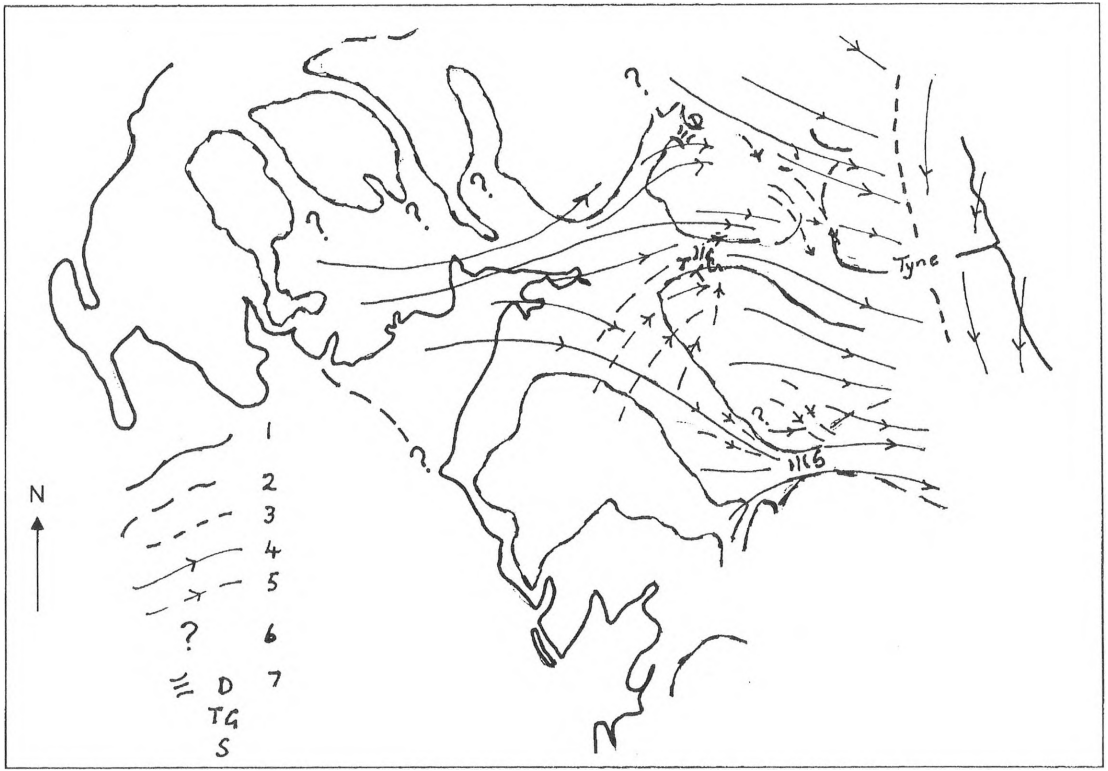


Figure 1 - Ice movements during 'Late Devensian Maximum' glaciation.
Key: 1 edge of upland; 2 possible location of ice crest separating ice flows; 3 western limit of ice from Forth-Tweed area; 4 ice movements; 5 locally later ice movements; 6 location of uncertainty; 7 sills - Deadwater, Tyne Gap, Stainmore.

Fell, Stainmore ice merged with upper Teesdale ice. Landforms and drift suggest that ice surface there, at its maximum thickness, sloped east. When meltwater flow became sufficient and well organised, channels were cut leading into the Wear catchment at altitudes up to 450m OD, with ice crossing into the southern part of the Weardale catchment. South from its contact there with ice from upper Weardale to contact with Swaledale ice (Wells 1957) the combined Tees-Stainmore ice was about 22km wide. In the axis of the Tees valley near Barnard Castle ice thickness could have been over 360m.

In later stages of its passage east ice drumlinised drift across the width of Stainmore as the combined ice flows did in the Tees valley east of Barnard Castle. Parallel moulding of drift and rockhead, and control of meltwater flow direction occurred on the ice flanks. On the Eden valley side of Stainmore converging drumlin alignments reveal ice paths and show that some drift-moulding took place on the icebed rising to the Stainmore crest.

In upper Teesdale ice-moulded landforms, including drumlins, occur over much of the ground notably along the south-east trending Harwood Beck-Tees axis converging with Stainmore drumlins near Middleton in Teesdale. Such landforms occur up to about 650m OD and alignments show convergence of ice from west and north of Cow Green reservoir. Indications (on satellite images) of ice moulding between Knock Fell, Meldon Hill and upper Maize Beck prompt the question of whether all the ice was generated on the high plateau west of Meldon Hill without supplement by Solway ice crossing the Pennine crest at 700 - 600m OD (Mitchell and Clark 1994).

East of Barnard Castle drift landforms are more subdued and ice flow indicators less prominent. The valley is flanked by deep longitudinal meltwater discharge channels at the foot of each valley side. The crest to Swaledale is crossed by channels at 380m OD near Sleightholme and 400m OD further east. Where the southern flank of the ice flow turned SE towards Richmond, diverting Swaledale ice, its surface would have been no lower. There seem to have been little obstacle to Tees-Solway ice flow into the Vale of York given the height of rockhead north of Northallerton and ice surface altitudes at the north end of the vale.

3. The Tyne area

The main eastward movement of Solway ice was by way of the Tyne catchment. The path was about 45km wide, more than half of that over high ground north of Cross Fell and thence across the valleys leading north to the Tyne corridor. Beyond the constraining effect of the North Pennines, east of West Allendale, the ice spread, as shown by erratic content in drift deposits, to cover the Derwent catchment and to cross the lower Wear valley (Lunn 1995). Its margin is quite closely followed by that of the highest associated meltwater channels, South Tynedale to West Allendale (c. 450m), West to East Allendale (c. 520m), east from East Allendale (c. 450m), Devil's Water catchment to Derwent (c. 360m). A suite of lower channels further to north and east shows

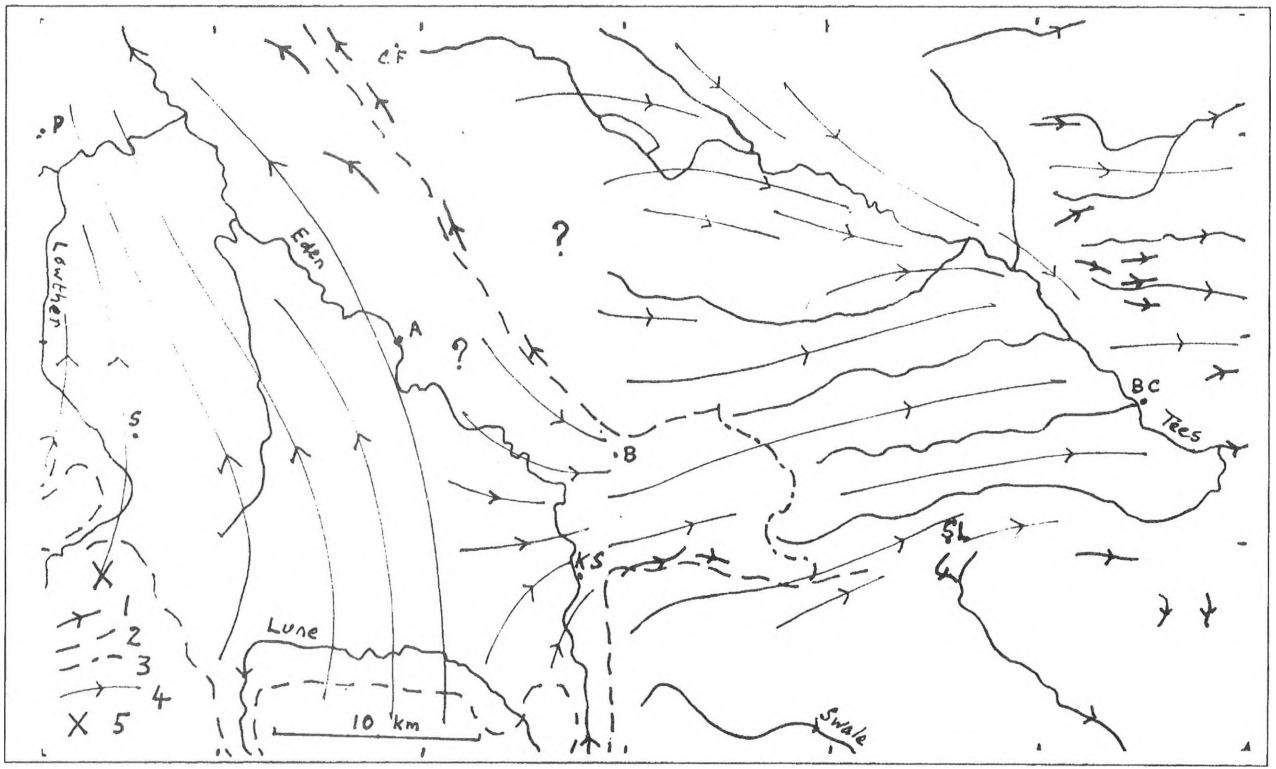


Figure 2 - Upper Tees and upper Eden areas: selected landscape elements. Key: 1 meltwater routes (locally schematic); 2 foot of Pennine scarp; 3 crest of Stainmore sill; 4 ice movements (not all contemporary); 5 location of Shap Granite outcrop; A Appleby; B Brough; BC Barnard Castle; CF Cross Fell; KS Kirkby Stephen; P Penrith; S Shap; SL Sleightholme.

how meltwater moved at successively lower levels above the Tyne valley floor and to the Wear valley.

Ice in and east of the Tyne Gap (Figure 5) moved in 'drumlin mode' at some stage and, as at Stainmore, the feeding ice to the west moved similarly. It is also evident that, at least for the lowest part of the Tyne Gap, drumlin mode was succeeded by ice stagnation but continued input of water beneath and beyond the ice cover. The Tyne axis carries almost continuous sand-gravel deposits (Lunn 1995). It is important to clarify whether any of these, as west of Hexham, were ice-moulded in later ice movement. In places, as near Whitley Chapel, kame deposits occupy what may be thought of as sediment sumps or traps (Clark 1970). West of Newcastle at Greenside (150m OD) where ridge-crest kame deposits show meltwater moved well above the floor of the Tyne valley somehow constrained from access to valley floor.

For almost 20km of its width the Tyne Gap is lower than Stainmore and it faces the main Solway input axis: impressive as is the evidence of the effects of ice moving across Stainmore, the eastward input of ice and water by the Tyne Gap was of greater magnitude. The access of Solway ice to the North Tyne valley, though some 20km wide, was restricted by high ground with a low pass only at Deadwater. Even so western ice was influential. Ice generated on high ground north of the R. North Tyne moved parallel with the valley and along the R. Tarset valley where there are ice-moulded features and drumlins in the lower part near Greenhaugh alongside those in the North Tyne valley. On the high ground east of the lower Tarset valley and east of lower Redesdale and North Tynedale, depositional and erosional landforms tell of eastward ice movement in continuation of the direction on the high ground of the Wark Forest area where the grain of combined erosion and drift moulding is impressive. Similar features near the valley floor may tell of a subsequent later, more confined ice movement south-east to the main Tyne valley near Hexham.

The end of eastward ice flow

1. The context

There is some evidence that before eastward movement of ice, ISC-NSC, ceased there was a reduction in volume of ice transferred. In the Tyne valley near Hexham there is the turn of ice-flow lines in the North Tyne valley to the South Tyne valley at levels below the interfluves that carry the west-east alignment. That shows ice no longer moved broadly east from Rede - North Tyne valleys to Wansbeck and Blyth valleys north of Newcastle. Similarly, alignments in the Tees valley above Barnard Castle imply a more restricted discharge than when ice extended to the crest with Weardale and sent meltwater to the Hamsterley Forest-Bedburn area. In the vicinity of the sills between ISC and NSC, differences in alignment of ice flow indicators may imply similar change. On the north flank of Stainmore high in the Warcop Fell-Helbeck Fell area alignments run almost west-east. To the west at the foot of the Pennine scarp they run north-west to south-east towards Brough and the centre of the

Stainmore sill. On the north flank of the Tyne Gap there is a comparable difference: there is a west-east grain on the Spadeadam plateau but on lower ground near Bewcastle and Askerton a north-west to south-east grain towards the lower part of Tyne Gap. In the S. Tyne valley south of Haltwhistle there is a south-north alignment across the more widespread grain. As is frequently the case, more than one circumstance might explain the evidence. One possibility is that transfer of ice to more rapid drumlin mode flow meant a smaller ice stream could discharge ice input. A second is that more than one phase of ice input and discharge is represented, that is, that the story is more complex than has generally been assumed.

That ISC - NSC ice moved in drumlin-mode is well evidenced west of, on, and east of the sills so that accelerated discharge seems likely to have occurred there but the moulding of drift more widely, as in the extensive Wark Forest area, shows fairly rapid flow (assuming that such is associated with drumlin formation) was not always restricted to the lowest parts of the sills.

It is likely that the last places where ice moved east were the sills, movement having ended earlier over the higher ground. Some indication of this is seen near the Tyne Gap and Stainmore. There could not have been no ice over the sills when movement ceased nor was ice there necessarily thin at that time. Ice surface slope must be sufficient to sustain flow. Lessening of that slope to some local critical limit ends flow. At very moment of cessation, which is unlikely to have been simultaneous among the sills, ice on the west side could not have been lower than the sill altitude. Thus, just west of Stainmore at that time ice surface altitude would have been in excess of 500m OD plus Stainmore ice thickness. That gives an ice thickness on the west in unknown excess of 360m. At the head of Liddesdale when ice last moved into the North Tyne valley from the west the ice surface would have been much the same, the ice thickness somewhat greater. In the Tyne Gap the ice surface may have been a little lower at cessation but the ice thickness to the west, near Brampton, would have been of the same order. The point is that at cessation there was still a lot of ice on the west side of the sills. It is quite likely that drumlin mode ice flow led to ice stagnation for as drumlin mode flow has been associated with rapid ice discharge it may have led to reduced ice thicknesses and surface gradients so contributing to loss of mobility.

Very little is known about what happened to the residual ice west of the sills. Also, there are very few extensive landforms west of the sills which tell of the great eastward transfer of ice. Because there are landform indicators of ice and water convergence from north and south, Deadwater and Stainmore, towards the Tyne Gap, because the Gap is the lowest sill and faced west into the centre of the main ice flow it has been assumed that it was the last of the sills to be crossed by that ice. The assumption requires some examination because the landform evidence, from the head of Liddlesdale near Deadwater, past the Tyne Gap, to Stainmore, is complex, partly ambiguous and partly undeciphered. It

raises the question of whether more than one episode of glaciation has been involved.

2. The Tyne Gap and Brampton Moraine

In the vicinity of Gilsland (Figure 3) the width of the Tyne Gap below about 300m OD is 15km. The two most significant landforms are the Gilsland-Haltwhistle valley and the Brampton Moraine. The valley opens to the Irthing valley near Gilsland at its west end and to the South Tyne at its east end near Haltwhistle. It has been cut across the intervening ridge, possibly by ice erosion (Bouledroua et al 1988). Its present significance is as lowest route for meltwater discharge to the east. Kame mounds rising above general aggradation level show some water was fed in from ice above the present valley floor. Sand-gravel infill over glacial till shows aggradation during the later stages of meltwater movement. The last flows through the valley were at about 135 - 140m OD. West of Gilsland, the Midgeholme Moss col and upper part of Mill Beck valley to its West can be seen as a feeder route for meltwater to the Gilsland-Haltwhistle valley. Also west of Gilsland, the incised Irthing valley may have functioned for several km as a route for meltwater moving east to Gilsland and beyond, though not to the whole of its present depth of incision.

The Brampton Moraine is a major sand and gravel accumulation. Its surface is a complex of eskers, kame ridges and mounds, large and small kettle holes, and flats where sediment accumulated to various levels. It lies along the foot of the Pennine scarp and extends into the scarpfoot lowland to the west. The main part of the moraine extends from Naworth near the R. Irthing south for some 15km to Hornsby near the R. Eden. At the scarpfoot its upper margin is about 200m OD and its lower margin, near Hayton and Heads Nook, is at about 60m OD. The R. Gelt, which has a substantial catchment within the Pennines, has made the only significant incision across the moraine. Otherwise it remains largely as it was built.

Trotter (1929) thought the moraine accumulated in and near lakes impounded between the Pennine high ground and the west-retreating margin of the ISC - NSC ice as it lay across the Tyne Gap and along the Pennine Scarp. As the ice thinned the moraine extended westward being built up to successively lower levels. The lowest lake outlet to the east was through the Gilsland-Haltwhistle valley and the lake level was held at about 135-140m OD until thinning of ice allowed drainage west, presumably under the remaining ice. Several levels on the moraine are lower than, thus younger than, the part that was built during escape of water to the Tyne valley. Huddart (1981) agreed with the essential points of this interpretation. He thought that a lake with falling surface level continued in existence after formation of the main moraine but still impounded by thinning and *'retreating Main Glaciation ice which ..... maintained an active frontal margin'* (Huddart 1981, 102). 'Active' implies the ice there *'unlike the marginal zones of this ice sheet'* still had some forward motion even though its frontal position was retreating, a quite normal occurrence. The lake levels recognised by Huddart were 67-30m OD. Huddart considered the

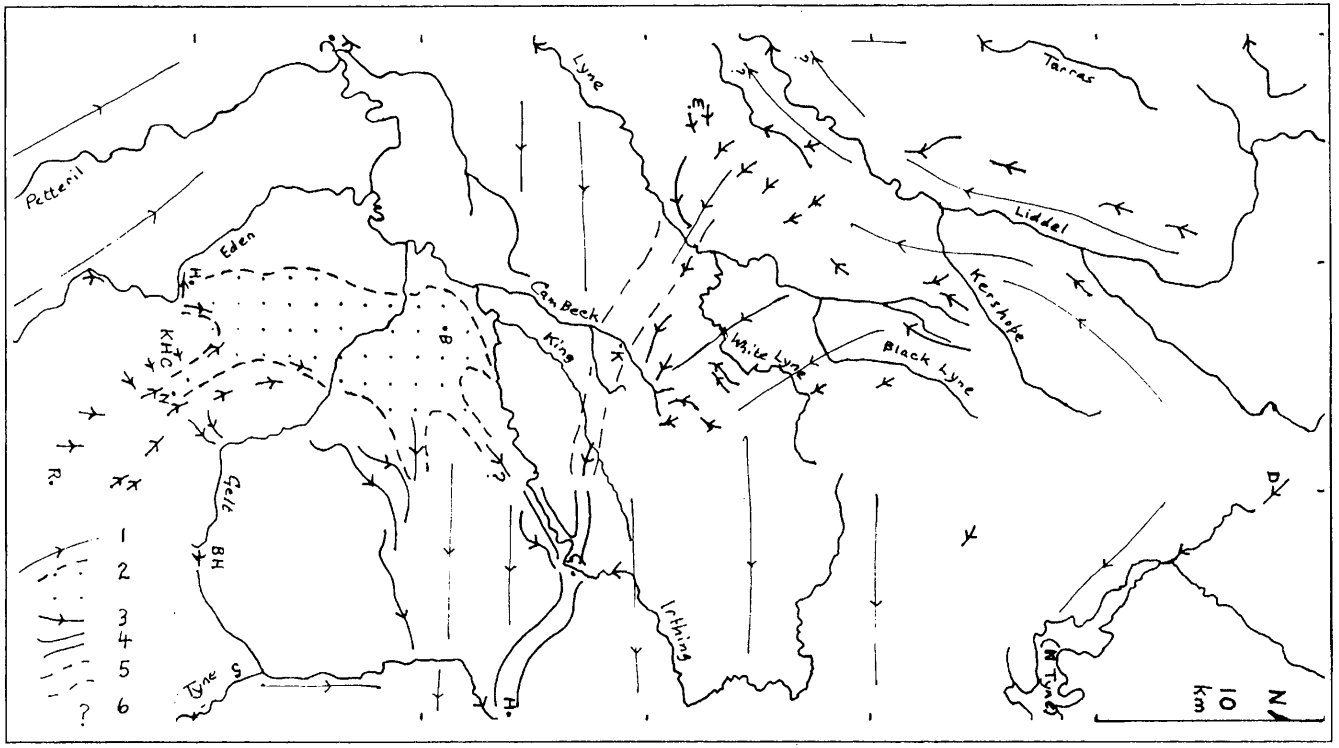


Figure 3 - The Tyne Gap-Brampton Moraine area. Key: 1 ice movements; 2 Brampton Moraine; 3 meltwater routes (locally schematic); 4 Gilsland- Haltwhistle valley; 5 Kame tract; 6 problematic ice direction noted in text; B Brampton; BH Butt Hill channel; C Carlisle; D Deadwater; E Easton; G Gilsland; H Haltwhistle; K Kirkcambeck; KHC King Harry's Common; N Newbiggin; R Renwick.

Wampool channel west of Dalston was the only possible outlet for the lakes: this channel is discussed later.

3. The area north-west of the Tyne Gap

This area includes Liddesdale and the area drained by the R. Lyne and its two main tributaries, the Black and the White Lyne. On its southern fringe are parts of the Irthing catchment. In upper Liddesdale and its tributary valleys alignments of ice-moulding converge southward across earlier ISC-NSL paths. Also there are valleyside meltwater channels that led water southward. South of Kershope Burn, a major tributary to Liddel Water from the east, north-south aligned drumlins and meltwater channels extend into the Lyne catchment where the alignment turns to north-west to south-east. Some channels have humped long profiles indicating sub-glacial erosion by water moving under hydrostatic pressure. There are also some short eskers. Further south, the crest between Liddesdale and Lyne catchment is crossed by meltwater channels. Water moved south-east across the crest and beyond in a tract of channels and discontinuous kame mounds by Stapleton and Kirkcambeck to the Midgeholme col and thus to the Gilsland-Haltwhistle valley. This suggests that thicker ice over lower ground in the south of the area still inhibited drainage to the Solway. Kame mounds at Easton, north-east of Longtown, were built to a height that suggests their construction was at about the time when the Gilsland-Haltwhistle route was abandoned. Also, channels across the Liddesdale-Lyne crest were succeeded by downvalley channels along the east side of Liddesdale. These lead to the R. Esk near Longtown. When this change in direction of water escape occurred water from the upper Lyne and Cam Beck catchments, previously diverted east, could move to lower levels between Brampton and Carlisle, as could water from the upper part of R. Irthing.

This evidence shows that in an area where ice had moved east and north-east to North Tyne and South Tyne valleys there has been a later ice movement from Liddesdale across the Lyne valleys towards the Tyne Gap. Whether the latter movement of ice was part of the decline of the main ISC-NSC ice sheet or a separate episode of glaciation is not yet determined.

4. The Eden valley between Stainmore and the Brampton Moraine

Between Brough and Kirkby Stephen on the west side of the Stainmore sill (Figure 4) the floor of the Eden valley is a drumlin tract. Drumlin alignments converge from north-west, west and south-west. Convergence is such that alignments occupying a zone about 20km north-south near Appleby take half that space at the west foot of Stainmore. The contribution from the north-west has been ascribed to ice from Scotland: it contains clasts from Scotland but also others of LD origin. The west-east drumlins hold local and LD clasts: they mark the route by which Shap granite erratics reached the east of England. Drumlins further south were formed under ice from the northern Howgill Fells. There is evidence round Kirkby Stephen that the directions of ice movement from the

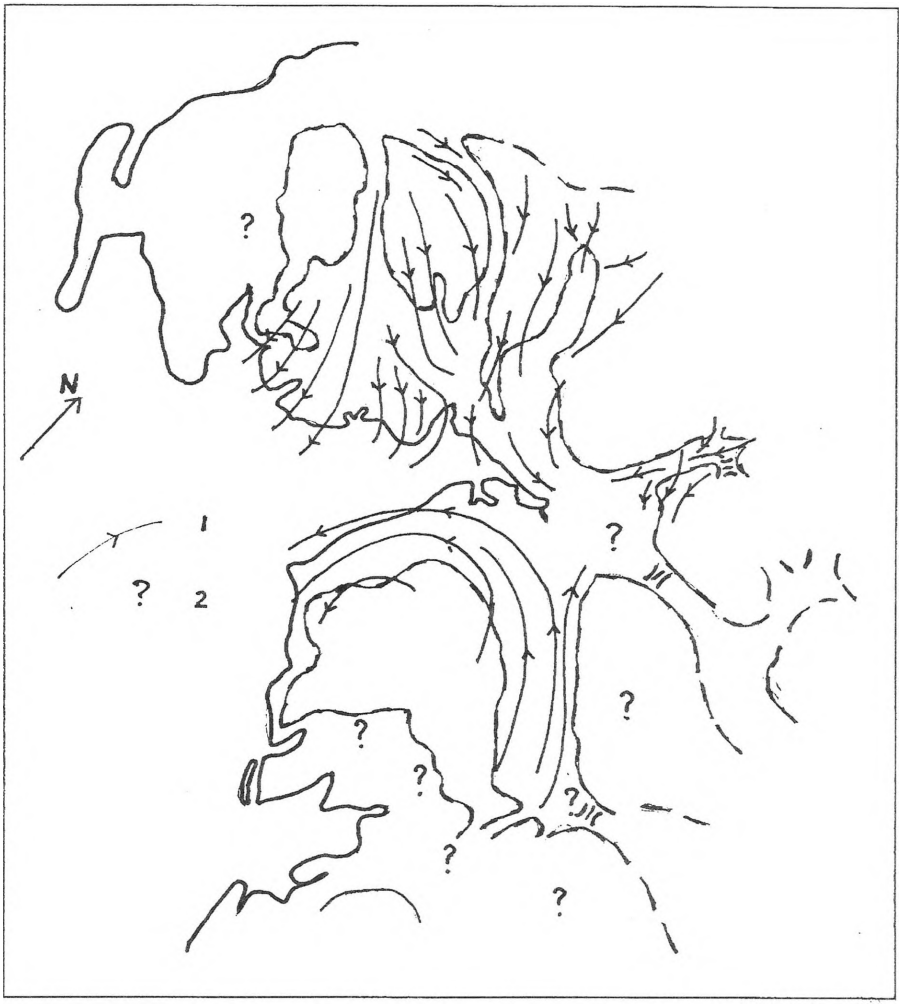


Figure 4 - Ice movements at time of 'broad flow'.
Key: 1 ice movements; 2 locations of uncertainty

Howgills varied in the course of ISC-NSC ice movement across Stainmore. A similar shift in ice movement has been proposed to account for modifications of drumlin shapes near Brough. Riley considered that these changes implied that 'when the superimposed drumlins were in process of formation the Scottish ice was relatively more important than the confluent LD and Howgill Fells ice streams, and deflected these streams' (Riley 1987, 330).

That conclusion is important: it implies that Scottish ice was still moving to Stainmore in a relatively late stage of the ISC-NSC ice transfer. That conflicts with evidence for north-east movement of LD ice across the Eden valley over hills north of Cross Fell and through the Tyne Gap. If the incompatibility is to be resolved by LD ice having reworked the deposits of earlier Scottish ice, that would need LD ice to have filled the Eden valley some moving south-east towards Stainmore. If contemporary with the north-east movement of LD ice, that would have required an ice divide across the Eden valley separating divergent movements of LD ice.

The convergent drumlin alignments near Brough and Kirkby Stephen form part of another puzzle. West of line that runs a little east of south from Appleby to the upper Lune valley drumlins are aligned almost south-north truncating the convergent alignment. Until recently that conjunction of ice movement indicators was explained by proposition of:

(i) movements within the ice cover of a sort never observed in existing ice masses, as *'distribution [of Shap granite erratics] suggests that the basal ice and the upper layers often moved in different directions'* (King 1976, 114);

(ii) a north-south ice divide along the Appleby Line (Hollingworth 1931) which could not have led to the drumlin alignments if was intended to explain. Moreover as it would have separated outcrop of Shap granite from its route east by Stainmore it could not have operated over the whole relevant period so a mechanism for either early formation of ice divide and subsequent breakdown or late formation would have been needed.

Letzer (1981) recognized that modification of 'convergence' drumlins along the Appleby Line showed that north-moving ice had imprinted a second alignment on drumlins initially formed by east-moving ice. East of the Appleby Line that overprinting was not evident and west of it the convergence drumlins were wholly obscured. Thus the alignments are not contemporary and the need for improbable ice motions and a local ice divide disappears. Riley, nee Letzer, (1987) considered that the north-moving ice from the Howgill Fells which had imprinted its drumlins across terrain earlier occupied by LD and Scottish (as she thought) ice moving to Stainmore demonstrated the end of movement across Stainmore but considered that it belonged to the same episode of glaciation: *'these features simply reflect the deglacial part of a single glacial episode'* (Riley 1987, 331).

Having resolved one paradox Riley presented another. How could it have been that in a deglacial environment the Howgill Fells, small, neither very high nor with very high precipitation, generated a north-going ice flow that overrode or replaced ice from the more extensive, higher, wetter eastern LD fells? And how was it that the Howgill ice that moved north was not effective in obliterating convergence drumlins east of the Appleby Line? The second question involves the capability of ice to re-form its bed. It is unlikely that the area round Kirkby Stephen and Brough was not occupied by ice from the Howgills and from other adjacent hills when Howgill ice was moving north on the other side of the Appleby Line. It may have been that the ice there did not transform to rapid-flow mode capable of altering the older drumlins. There is another uncertainty. Near Appleby it is not easy to discriminate between drumlins associated with northern contribution to convergence of ice towards Stainmore and those related to Howgill ice moving north. Also, along and at the foot of the Pennine scarp east of Appleby there are channels that led meltwater to the north-west contrary to movement of 'convergence ice'. They imply a north-west downslope of ice surface in that part of the area east of the Appleby Line, that is, contrary to the previous ice slope direction towards Stainmore. Burgess and Holliday (1979) noted that some of the channels have humped long profiles indicative of water flowing under hydrostatic head.

Howgill ice approached the Pennine scarp north of Appleby. From about Murton at the scarp foot north for 25km to Renwick the scarp carries meltwater channels that led water north-west. The upper limit of smallest channels is about 500m OD but most are below about 430m OD. An ice edge that shrank from an upper limit of some 500m OD and an ice surface sloping down to the north are implied. West of the path of ice that moved north from the Howgills, moulded drift (including drumlins) and erosional grain on rockhead tell of ice movement from Birkbeck, Shap, and Haweswater fells northward to the Penrith area. On the edge of the LD fells erosional evidence extends up to about 500m OD. Ice from the Howgills was part of a broad flow which, from the eastern LD fells to Pennine scarp, was over 20km wide south of Penrith. This broad flow of ice, joined by ice from the Ullswater and Thirlmere fells, moved in parallel paths that curved round the northern edge of the Skiddaw Fells towards the ISB rather than towards the east.

Some Howgill ice entered the Petteril valley near Penrith, some crossed obliquely the Penrith Sandstone escarpment north of Penrith, and some moved north down the Eden Valley. North of Melmerby, the broad Eden valley between Pennines and sandstone escarpment rises markedly to King Harry's Common and the R. Eden is confined to a narrow gorge by which it breaks through the closure of the valley. This setting, very different from the open terrain west of the Penrith Sandstone escarpment, seems to have facilitated stagnation of the eastern portion of the broad flow and the accumulation of very large quantities of water-sorted sediment. Arthurton and Wadge (1981) described many esker-

kame-channel complexes in the Petteril and Eden valleys north of Penrith, water movement controlled first by ice cover and then by form of land surfaces.

The zone of scarpfoot and scarpface meltwater channels extends north of Renwick beyond the closure of the Eden valley. Col channels led water to the upper Gelt valley and beyond to the S. Tyne valley. Other than by the Butt Hill channel, 460 - 450m OD which may be part of this set, meltwater reached the South Tyne valley north of Lambley 55km north of Murton. Again excluding Butt Hill, the highest scarp channel turns into the Tyne Gap at about 340m OD and reaches the South Tyne at about 170m OD. Lower channels led along the scarp, by Newbiggin, to the upper margin of the Brampton Moraine and so by eskers and channels to the S. Tyne.

Sand-gravel mounds around Newbiggin are contiguous with those in the Brampton Moraine, the channels are decreasingly incised towards the moraine and merge with moraine flats. Meltwater from the south by Newbiggin probably contributed sediment to build the higher parts of the Brampton Moraine. Water would have escaped by way of the Tyne Gap, some by the Gilsland-Haltwhistle valley. When that valley ceased to discharge meltwater and water levels fell in the Eden valley, the Newbiggin route was abandoned. Water moved though the Eden gorge to a channel (120 - 130m OD) leading north by Hornsby. That water could have carried sediment to the lower parts of the moraine. Later water moved at present river level (about 40m OD) and, as shown by valley floor eskers, still in the presence of ice.

There is strong evidence to associate some part of the building of the Brampton Moraine and discharge of meltwater by the Tyne Gap with movements of ice from both north-west and south towards the Tyne Gap. From their matching contexts it is possible the two ice movements were contemporary. It was Riley's (1987) opinion that they occurred in the closing stage of the ISC - NSC ice transfer after cessation of ice movement east across Stainmore. Against that must be set the magnitude of the related ice movement. The broad flow of ice some 20km wide across the Eden valley and reaching to over 500m OD on the eastside of the LD was joined by more ice from the LD. Was this a new glacial episode? If so, it implies that the Brampton Moraine was not built wholly (or at all?) in the main ISC - NSC episode and that the Tyne Gap was crossed by meltwater and reached, or more than just reached, by ice after that part of the glaciation.

The occurrence of Shap granite among erratics in the Haltwhistle area (Johnson 1952) required ice movement from a source of granite clasts (outcrop or drift already holding clasts) to the Tyne Gap. Unless that was by LD ice before Scottish ice moved south to Stainmore, only a post-Stainmore ice movement seems possible. That would be either an immediate post-Stainmore ice flow (if such there was) or as part of the later broad flow movement. Granite emplacement would be before completion of the Brampton Moraine for the moraine surface seems unmodified by passage of ice.

PART TWO

What Next? Readvance?

Evidence of fluctuations in ice sheet margins and of more extensive readvance had been reported from north and west Cumbria by Geological Survey staff in the early and middle parts of the 20th Century (Smith 1912, 1932, Trotter 1929). Trotter believed that readvance ice had extended over much of lowland north Cumbria. These movements involved ice spreading inland from the west or north-west. Any such spread would have obscured or modified drainage patterns initiated by a previous ice cover. The first major systematic scrutiny of claims for readvance (Huddart, 1977, 1981, 1991, 1994) confirmed limited ice advances onto coastlands, Carlisle to Low Furness. Even so, scepticism about readvances persisted. Investigations for NIREX into suitability of a site near Sellafield for storage of nuclear waste required detailed examination of onshore and offshore Quaternary deposits (references in Clark and Smith 1998 and Merritt and Auton 2000). Merritt and Auton (2000) outlined and discussed the Quaternary depositional history of the Sellafield area. A complex extensive post-main glaciation ice advance into the Gosforth area and a later more limited Scottish Readvance across the present coastline were identified. This latter was tentatively correlated with an Irish Killard Point Stadial for which a date of about 14ka BP has been suggested.

The Gosforth event (GOS) is of particular interest. Merritt and Auton concluded that the main ice cover experienced *'a significant glacial retreat'*, possibly between about 22 and 18 ka BP. While the margin of a shrunken ISB ice mass remained close to the coast of west Cumbria much of the bed of the northern Irish Sea probably lost its ice cover. *'There followed a major expansion of ice….. the 'Gosforth Oscillation'. The Irish Sea ice stream became re-established and affected most of the Sellafield district…. below an elevation of about 100m OD…. Most of the drumlins in the region probably formed during this event, but its exact timing is unknown….. However,….. the Gosforth Oscillation may correlate with the Dimlington Advance in eastern Yorkshire (after 18.5 ka BP) and the Belderg Readvance in Ireland (at about 17 ka BP)'* (Merritt and Auton 2000, 150). Other than the GOS, or the broad flow episodes, which may be identical, there appears to be no Solway equivalent of the Dimlington Advance. Their graphic representation of the Gosforth Oscillation (Merritt and Auton 2000, 142, Fig. 8, Stage 7a) shows ice moving west of south across the low ground west of Murton Fell (West Cumbria), receiving Ennerdale ice and turning to move east of south broadly parallel to the coastline south of St Bees Head. Ice cover extended west of the present coastline with concentric flow paths. Their interpretation of the GOS interval and its ice cover is important. It infers a new episode of ice generation and discharge after the main glaciation. It also implies a relationship with north and east Cumbria where there is evidence for an anticlockwise broadflow of ice along concentric paths to West Cumbria.

The Cumbrian side of the Solway Firth

The term 'broad flow' is here used for the whole anticlockwise flow of ice across north Cumbria. On its west side, Howgill ice was accompanied by ice from the Birkbeck Fells, Shap Fells, Haweswater, Ullswater and Thirlmere areas in turn. The resultant mass pivoted round the Skiddaw upland, some to cross obliquely the coastline south of Silloth to pick up Derwent and Cocker valley ice before passing Murton Fell and the foot of Ennerdale. The ice paths crossed those implied by drift and landforms associated with the main glaciation. The newer ice paths are indicated by erosional grain on bedrock, mainly in upland areas on the inner flank of the flow but also on lower ground, by drumlins and other drift alignments. Erosion of rockhead occurs to over 500m OD on the northern edge of the Lake District. Parallel ice paths imply a fairly uniform ice surface altitude across the ice flow. Thus considerable ice thicknesses over the Solway lowland are indicated. It is curious that, while in drumlin mode flow, its outermost path in the Carlisle area remained concentric, with no obvious spread north to the Solway Firth. The constraint restricting ice to its arcuate path was, presumably, applied from the north.

For present purpose we need to indicate only the major characteristics of the terrain crossed by the broad flow. West of the Appleby Line, in the Crosby Ravensworth area there is a northward transition from the high country of bare limestone scars to partial drumlinising of drift on dip slopes to more fully developed drumlins on lower ground round King's Meaburn. Erosional grain on the limestone follows the limestone round from north of the upper Lune valley to west of Cockermouth. The turns in ice paths correspond to the changes in strike. In some cases rockhead erosion by ice seems to have shaped whole hills as Hay (1944) noted. The hills in Mell Fell Conglomerate, from Pooley Bridge to Great Mell Fell, Setmurthy Common near Cockermouth and the Dean Moor upland inland from Whitehaven are cases in point. This is a grain peculiar to the turn of broad flow ice. Penrith Sandstone hills north from Whinfell (south-east of Penrith) northwards have been shaped in both plan and profile.

In the lowland drumlin country there are contrasts such as between the smooth terrain with almost imperceptible grain south of Carlisle and the highly attenuated drumlins as round Wiggonby south-west of Carlisle and from Wigton to Maryport. These latter may be a response in drift to relatively rapid basal ice movement, perhaps over wet weak sediment.

Curiously, and perhaps because of their considerable Scottish content, Dixon et al (1926) considered that drumlins south of Silloth were made by Scottish ice, which, judging by drumlin alignment, moved from the south-west rather than that they were part of the north Cumbria broad flow suite. That led to postulation of a rather unlikely direction of ice movement from Scotland into Cumbria.

Drumlin fields in the Solway area are numerous and extensive. Most seem to be associated with broad flow ice or its Scottish equivalent. In the NSC where Solway ice augmented Tees and Tyne ice most have been ascribed to main glaciation ice. Drumlins have been successfully used as indicators of ice movement directions on the assumption that they are streamlined by moving ice. Degree of drumlin attenuation has been used to infer relative rates of ice movement. The more familiar explanation of drumlin formation has been challenged. It proposed that interaction between moving ice, the debris incorporated in its base, and the bed over which the ice moved led in suitable circumstances to erosion of bed, or deposition of debris, in drumlin form. Ice did the work. A more recent proposition is that the work was done by large volumes of water in fast, turbulent flow between ice and bed. Drumlins would be formed by fluvial erosion of bed or as infills by sediment, as flow water declined, of cavities eroded in the ice base during preceding turbulent flow. Despite field, experimental and theoretical support for such processes, evidence for sources, accumulation and storage of sufficient water has proved elusive. As far as is known the merits of contrasting explanations have not been assessed for the various Solway drumlin tracts.

The Scottish side of the Solway Firth

As the evidence for ice movement and the associated deposits and landforms on the Scottish side may well be less familiar than that for the southern side of the Solway the landforms and deposits there are considered a little more fully (Figure 5). Dumfries and Galloway is much larger than north Cumbria with more extensive upland nuclei for ice accumulation. Corries and ice discharge troughs are less concentrated than in the LD but are locally well-developed. They have rather different distributions, the troughs were associated with substantial outflows of ice from plateaux and mountain areas with narrow outlets. Corries may be seen as sites of restricted ice accumulation in favoured sites whereas general glaciation requires snow-ice first to be accumulated widely across uplands. The landforms of glaciation in Dumfries and Galloway are diverse and composite. Charlesworth (1926) mapped, largely from locations of kame terrain, the outer limit of a post-main glaciation ice readvance in southern Scotland. As Tipping (1999) observed, later work has not corroborated the mapping. That does not rule out the occurrence of local ice readvances in the Late Pleistocene.

A recent general survey of Late Pleistocene glaciation in Dumfries and Galloway (Tipping 1999) does not refer to more than one Late Pleistocene glacial episode other than the short, final, Loch Lomond Stadial which is not part of this study. Most features in the following account appear to be contemporary with the broad flow of north Cumbria. Some in upper valleys could be compatible with ISC-NSC ice transfer but it is difficult to believe many in the south of Dumfries and Galloway belong to that episode. As there appears to be continuity between upper valley and lower ground landforms it seems that most of the former could be from broad flow times. But the area had been the source for much of the ice which moved in main glaciation times to the eastern side of

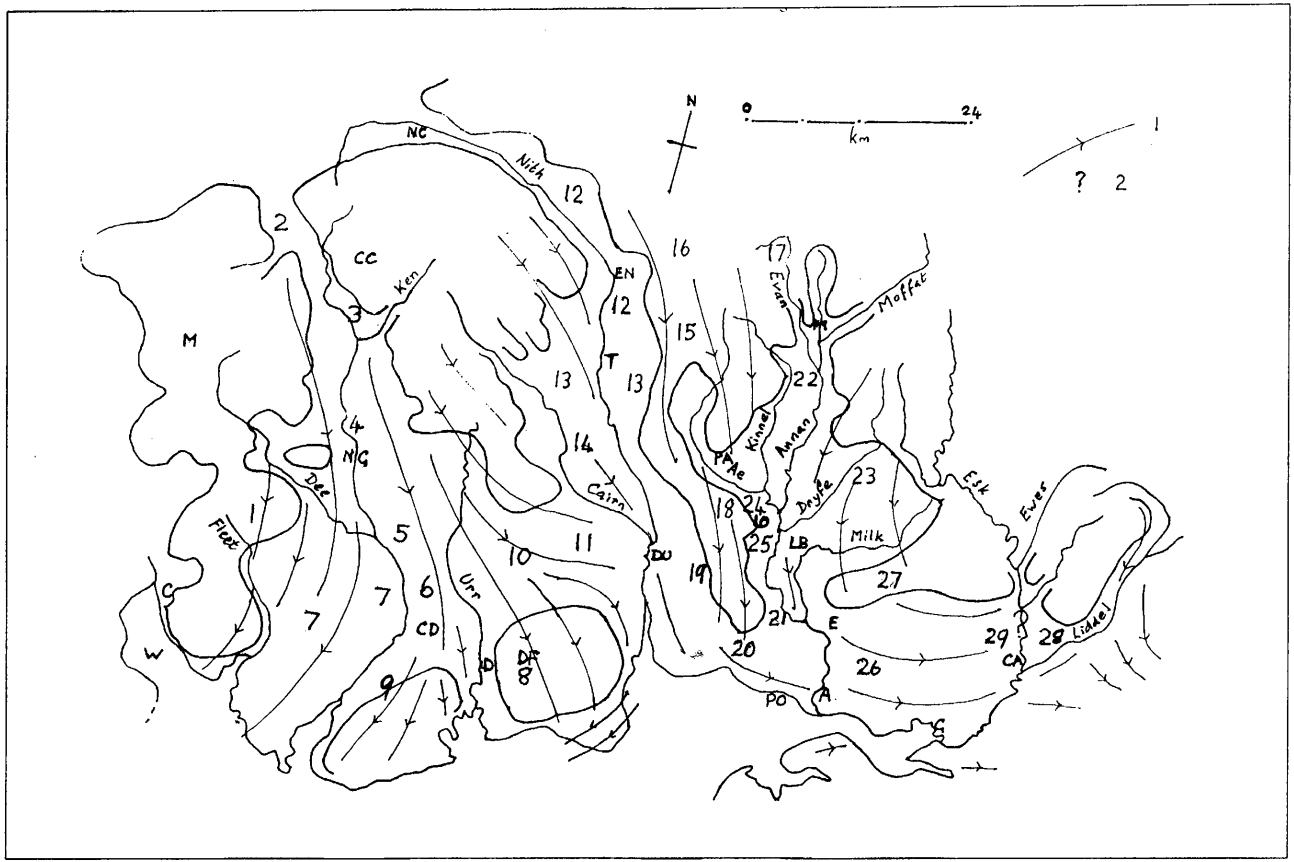


Figure 5 - The area north of the Solway Firth. Key: 1 ice movements; 2 uncertainty.

England, and it was also probably the source for ice that moved onto the Cumbrian side of the Solway as the Scottish Readvance.

From the Rhinns of Galloway east for 120km indicators of ice direction tell of a general southward movement. Over the greater part of the area west of Wigton Bay much ice came by way of the Firth of Clyde and some from the hills (Merrick 843m OD, MK on Figure 5) north of Newton Stewart. East from Wigtown Bay (W) most of that ice was probably generated within Dumfries and Galloway. From near Creetown (C) to near Ennerdale Water, the likely width of a combined ice stream from north and south of the Solway Firth, was about 70km. That assumes the two inputs were contemporary. Both are discordant to movements necessary to carry locally derived granites to NSC. Landforms in the hilly granite landscapes of Dalbeattie Forest (DF) require a local ice surface not less than 350m, possibly over 400m, OD. That is not high compared with the northern parts of the district but is for a coastal area close to the Solway Firth.

A zone of balance, not necessarily static, between Scottish and Cumbrian ice would develop when the two ice masses met. Possibly before a balance was attained ice would have entered the low ground between Carlisle and Brampton. Southeast of Carlisle towards Cotehill and west towards Kirkbampton, many drift mounds are broader and shorter than drumlins on the arcuate path just to the south and are differently and less consistently aligned. The significance of this distribution is unknown and it could be valuable to investigate whether there was here interference (ice-push ridges?) from conjunction of northern and southern ice.

1. Carsphairn to Kirkcudbright

East from Merrick, for over 100km to Liddlesdale, the hills generated their own ice and largely excluded ice from the north. South of a line from the head of Wigtown Bay to New Galloway (NG) ice movement was to the S, towards the Cree and Fleet valleys (1 on Figure 5), gradually turning west of south. Concentration of meltwater from a wide northern area into the lower Fleet valley led to major sand-gravel accumulation there.

Granite erratics have been distributed in all directions from outcrops at Cairnsmore of Carsphairn (CC) east of the head of the Carsphairn valley (Sissons 1967) but the sequence of ice movement and of redistribution of drift is not clear. In the head of the valley (2) there are signs of meltwater input from the Doon catchment to the northwest. That would indicate a south-east downslope of ice surface into the Carsphairn valley from a higher ice surface over south Ayrshire. The Carsphairn valley (3) is notable for its cross valley drift ridges (Rogen moraine) being one, if not the first, of recorded sites in Great Britain (Cornish 1979). The ridges, transverse to ice flow, are moulded and fluted in direction of ice flow but not to the degree that the ridges are wholly divided into drumlins. Rogen moraine (named from a locality in Sweden) remains enigmatic. It has generally been explained, as have drumlins, by

erosion or deposition of sediment under moving ice. Downstream the valley is less open with hilly flanks. The cross valley drift ridges are succeeded (4) by a mosaic of erosion-grained rockhead and ice-moulded drift displaying a variety of forms. These include closely-ranked drumlins, intermixed 'plump' and 'thin' drumlins, short transverse drumlinised ridges. East of New Galloway there are discrete and linked horned drumlins, the horns pointing down ice. South, towards Castle Douglas (CD), the terrain (5) changes to less crowded, mainly 'plump' drumlins and grained rockhead. These variations among landforms reflect the range of ice bed environments experienced within a relatively small area.

South from about Parton (10km south of New Galloway) in the Water of Ken-Dee valley the low ground (6) is encumbered with glacigenic sand-gravel deposits and there are many meltwater channels and eskers. On the west side of Loch Ken and the R. Dee is a broad tract (7) of ice-eroded rock, drumlins, sands and gravels, and meltchannels that lead south and south-west. Ice cover must have controlled water movement after ice stagnation for channels lead to eskers which show that water under hydrostatic pressure was taken over ridges.

2. The Nithsdale area

In the hilly granite country (8) east of the Dee estuary, col channels led water south-east, parallel to erosional grain in the hills and drumlin alignment on the low ground to the north-west. Only at the west end of the granite hills (9), near the Dee estuary, did meltwater drain to south and south-west. North of Dalbeattie (D), in the valley of the Urr Water upstream of its crossing of the granite hills, drumlin alignments diverge, those in the eastern section leading towards Dumfries (DU) in the Nith valley. Probably as the local ice mass diminished, or as ice discharge rates in the Nith valley increased, Urr valley ice and meltwater abandoned its route south over the granite hills for a lower passage (10) to the east. Nevertheless, the way east is crossed by hills that rise 50 - 150m above the Shawhead - Lochfoot area. Ice moving over these hills then turned south-east into Nithsdale. Meltwater deepened clefts between the hills, the still restricted exits facilitating extensive deposition (11) of glacifluvial sands and gravels among the drumlins.

The R. Nith rises north of the Dumfries and Galloway hills, enters them at New Cumnock (NC) and leaves them to enter a broad valley at Thornhill (T). It has no major tributaries from the east but several from the west joining in succession to Dumfries. Sissons (1967) noted that erratics of kylite from outcrops north of Dalmellington in Ayrshire had been carried into the Nith valley east of New Cumnock. In the upper Nith valley (12), between New Cumnock and Thornhill, the courses of melt discharge channels from close to valley floor up to over 300m OD indicate a generally south-east sloping ice surface. There is a low-amplitude north-west to south-east ice-moulding up to about 300m OD on Nithsdale hillsides in the Sanquhar area. A valley floor esker near Enterkinfoot (EN) and others further south shows subglacial deposition after

onset of ice stagnation. As in the Doon-Carsphairn gap, there is evidence that there had been thick ice with high ice surface in southern Ayrshire along the north side of the Southern Uplands.

Ice movement south-east in Nithsdale and along and between its right-bank tributary valleys is shown by pervasive erosional grain on rockhead (13), drift tails and meltwater channel directions. The kame and esker tract (14) near Dunscore, part of a larger complex, occupies a broad saddle across hills between the Nith and Cairn valleys. It shows how restricted outlets for meltwater concentrated subglacial accumulation of sands and gravels at a site which also facilitated ice stagnation. Ice had moved south-east, parallel with both valleys. Meltwater entered the saddle from west and north-west and from the north at 160 - 90 OD. A narrow high sill at c 130m OD on the south side and a lower valley at about 80m OD on the east led water to the Nith valley. Sediment accumulated to various levels, mostly at 100 - 80m. The several eskers across the kame mounds vary in sharpness, possibly reflecting that complete immobility of ice was attained during the span of their construction. The main eskers, flanked by kettle pools and mires, extend from lowest input site to lowest exit.

Extensive meltwater channel systems (15) occur between valley floor (about 50m OD) and 500m OD on the hills east of Thornhill. Some led water from Nith to Water of Ae and Annan catchments. The highest meltwater channels are above the level of some of the higher cols (420 - 300m OD) on the upper Clyde-Kinnel Water (Annandale) and Clyde-Evan Water watersheds. Some of these cols may have transferred ice and meltwater from Clyde catchment to Annandale. Linton (1964) considered the Dalveen Pass (16) to be an ice-eroded trough cut by ice escaping south from the upper Clyde catchment to Nithsdale. He also thought the trough between Clyde and Evan Water (Annandale) valleys (17), was cut by ice escaping southward. The southward slope of the ice surface would have sent water that way too. The locations and patterns of meltwater channels on the 30km long Nith-Annan divide show the ridge was wholly ice-covered with strong correspondence between erosional grain and channel directions. In the higher northern part most channels lead to the Ae valley. Further south most lead to the Nith valley as apparently for some 10km west from Lochmaben (LO) to near Auchencairn the ridge (18) was crossed by southbound ice from the broad hilly west side of Annandale.

Ice converging from north and west into the Nith valley moved south past Dumfries where it diverged, as far as evidence of late ice movement tells, into west- and east-going branches, the latter filling the eastern Solway Firth. Melt channels and sand-gravel deposits turn along the south side of the Nith-Annan dividing ridge (19). In the Ruthwell-Clarencefield area (20) these deposits merge with those south of Lochmaben in a kame-esker-channel complex which extends east, partly eroded along the Solway shore near and east of Powfoot (PO), to the mouth of the R. Annan. Its further course is a matter of speculation. The rather subdued landforms of parts of the sand-gravel complex raise the possibility of some ice movement after deposition.

3. Annandale and beyond

Near Dalton, on the sand-gravel tract south of Lochmaben, the depositional landforms and melt channels (21) seem to show a transition at about 65m OD from water flow south to a route east along the southern edge of residual ice. Thereafter Annandale meltwater reached the valley floor. This ice was held by a cross valley ridge that now diverts the R. Annan across the valley east towards Ecclefechan (E).

The narrow head of Annandale broadens near Moffat where north-south ice moulding is obvious. Just south of Moffat, Evan Water valley and Moffatdale join the main dale. The latter two were probably ice input troughs like the Evan Water valley, so described by Linton (1964). South of the confluence the high hills stand back to flank the 10km wide valley floor (22) which carries a north-south grain imposed by ice and meltwater from the broad upland to the north.

Near Lockerbie (LB) the Annandale ice sheet, between crestlines, would have been some 30 km wide. The flanks, particularly the west, show a north-south grain from ice and meltwater movement. The valley bottom has a corresponding drumlin alignment as far as the cross-valley narrowing and river diversion east to Ecclefechan. On the east side of Annandale the extensive tributary valleys of Dryfe Water and Water of Milk (23) also carry signs of north-south ice movement. In their upper reaches ice movement was to west of south as if from the upper Esk catchment.

The area round Parkgate (PA) on the west side of Annandale where Water of Ae reaches the floor of the dale was a focus of prolonged meltwater input. At some stage meltwater was directed south across the hills west of Lochmaben. Later, it built the thick deposits south from Lochmaben past Dalton and Carrutherstown (SE of Dumfries) to the sand-gravel complex already described. Some of the last deposits in 'stagnant ice' were eskers along the edge of the valley (24) west of Lochmaben. Eskers positions suggest that some were associated with southward movement of water in the sand-gravel tract, others with later access of water to the valley floor of Annandale.

For some 6km, from north of the R. Ae south-east past Lochmaben to the R. Annan, there are kettle depressions, some with lakes to about 1km across, drumlins, eskers, and areas of fluvial aggradation (25). The northern end of this tract was one of concentrated meltwater input. This landform assemblage resembles that associated with channels of Late Pleistocene (Wisconsin) subglacial rivers near the southern edge of the Laurentian Ice Sheet (Clayton et al 1999). Perhaps a major subglacial watercourse (a tunnel channel) at Lochmaben was overrun by Annandale ice in drumlin mode flow, followed by kame and esker construction as ice stagnated, and then deposition of alluvium

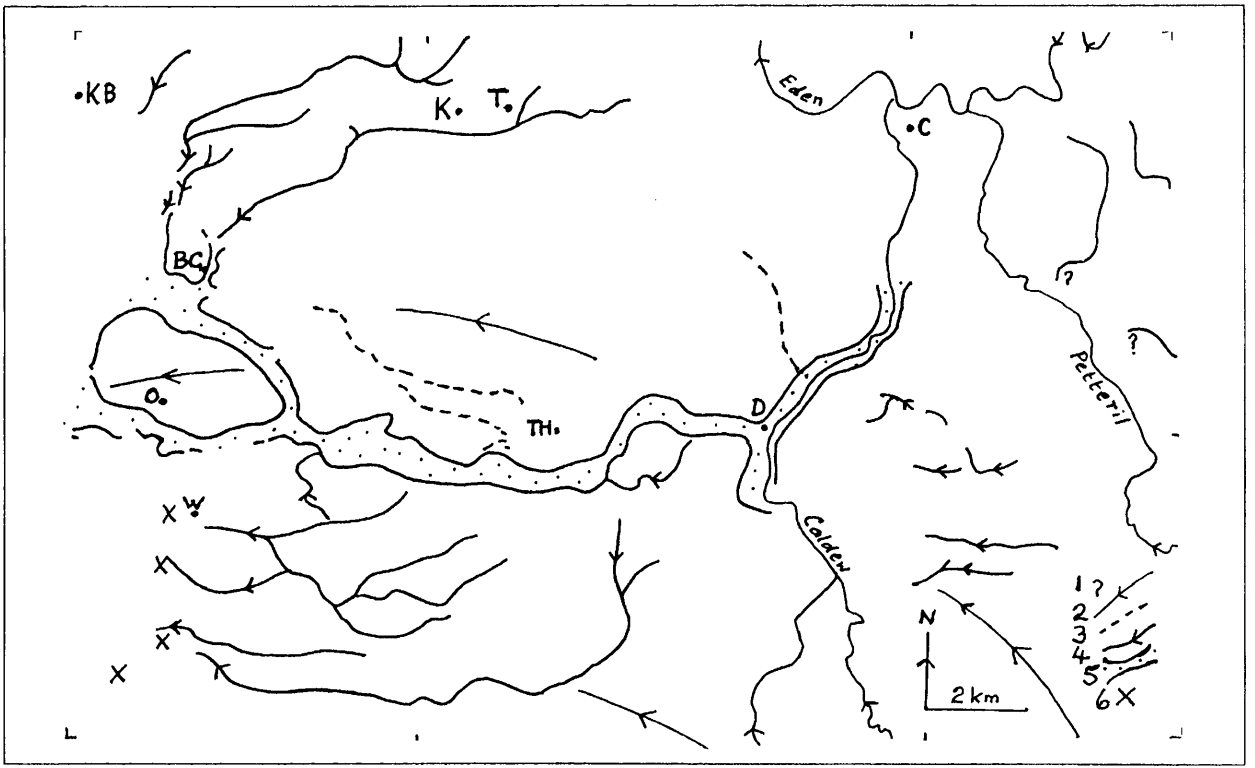


Figure 6 - Principal meltwater routes in the area between Wigton and Carlisle.
Key: 1 uncertainty; 2 ice movement; 3 eskers (after Huddart 1973); 4 meltwater channel; 5 Cummersdale-Wampool channel; 6 Wigton sand-gravel area (schematic); BG Biglands; C Carlisle; D Dalston; K Kirkbampton; KB Kirkbride; O Oulton; T Thurstonfield; TH Thursby; W Wigton.

mainly from the Ae valley. Melting of buried ice would form depressions which survive where beyond reach of glacial outwash and younger alluvium.

The coastal lowland (26) east of the R. Annan has a west-east grain of drift moulding with many rather subdued drumlins. Meltwater was fed in from the west presumably before the lower valley of the R. Annan could discharge freely to the Solway. Channel patterns implie an ice surface falling east and ice over the present Solway estuary thick enough to prevent free southward movement of water. This coastal lowland is on the path of the main south-ward ISC - NSC ice transfer, but its landforms, though compatible with that movement, probably reflect the later eastward diversion of Annandale ice by the spread of Nithsdale ice. That east-going ice could not have been part of the main transfer of ice to NSC for, not having crossed or received ice from the Dalbeaattie-Criffel granite outcrops, it could not have taken granite clasts to the east. This area extends east to the lower course of the R. Esk and towards Liddesdale. For 15km of its extent it received ice and meltwater from across the ridge (27) along the south side of the Water of Milk catchment: col meltwater channels to over 250m OD indicate local ice thickness. On reaching the lower slopes south of the ridge the meltwater flowed east or south-east in approximate correspondence with direction of ice movement over the coastal plain.

Evidence has already been noted for ice movement south-east from Liddesdale across Black and White Lyne valleys. In view of ice movement from the Howgill Fells, the more extensive upland from the Hermitage area to Peel Fell and Carter Fell at the head of Redesdale would be expected to accumulate and distribute ice. In lower Liddesdale the drumlin and melt channel alignment is along the valley (28), down valley, in the case of the channels, presumably also down for the drumlins. Yet west of the R. Esk are the drumlins of the coastal plain (29) and near Cannonbie (CA) they are parallel with those in lower Liddesdale. Thus, separated by the R. Esk, are drumlin suites, one apparently associated with ice that moved to the east, the other with ice that moved south-west. Here is a problem to be resolved. Not only that, but south of Liddesdale and the Black and White Lyne valleys with their different directions of drift moulding, is the Carlisle-Brampton lowland with a west-east grain. There are, then, matters of both contrary drumlin alignments and of degrees of ice encroachment onto the lowland by northern and southern ice masses to be clarified. Given the local relief, the thickness of ice suggested by altitudes of col channels from the Water of Milk area, and the more-or-less parallel west-east ice movement, it would seem likely that ice spread eastward across the R. Esk. Thus there may have been ice from north-west and west in the Carlisle-Brampton lowland and, on its southern flank, broad flow ice from the south. This may have been the ice that sent water east by Gilsland when the Brampton Moraine was being built, and which in decline led to the lower accumulation levels on the moraine.

Water movement in the Carlisle area

Huddart noted a series of levels (67 - 30m OD) to which deltas had accumulated in a lake impounded by *'retreating Main Glaciation ice'* (Huddart 1981, 102) in the Carlisle-Brampton lowland. He identified the channel (Figure 6) at Caldew Mires, west of Dalston which links Caldew and Wampool valleys as *'the only one possible drainage channel from this lake'* (Huddart 1981, 102). The Wampool channel has great capacity (floor widths in hundreds of metres, like the Gilsland-Haltwhistle valley) and was obviously important. It perhaps started further east at Cummersdale, south of Carlisle. It is incised below about 50m OD, with the lower Caldew now running up-channel to Carlisle. That the Wampool at times discharged large volumes is also shown by its bifurcation north of Wigton, where it breaks through drumlin terrain to isolate the 5km long Oulton 'island' of drumlins. The channel transgresses drumlin alignments and is younger than effective movement of broad flow ice. If it did drain a lake, the lake and deltas too, are younger. Huddart thought SR ice had also impounded a lake east of Carlisle but if a separate and earlier broad flow from the south and its Scottish equivalent had filled the lowland with ice, then several phases of water impounding and its escape through, under or past ice cover could have occurred. The size of the Wampool channel could be linked to ice across the Solway having sent all water, Esk (Annan?) to Caldew, that way.

South of the Wampool channel are other higher channels, on each side of the R. Caldew. Those on the east side of the Caldew form a series at 120 - 50m OD. Their altitudes and plan imply that the lower courses of Eden, Petteril and Caldew were not in use when the channels were. These channels transgressed drumlin alignment and, like the Wampool, post-date movement of broad flow ice. The highest lake levels proposed by Huddart would match only the lowest of these channels which look like ice-maginal or sub-marginal routes. The higher channels match lower levels of the Brampton Moraine. This channel set should be considered with the set west of the Caldew. The latter consists of deep channels south of the Wampool, some reaches parallel with drumlin alignments but others cutting across the drumlin lines. Their upstream ends are open to the north, perched, as if they received water direct from within ice or from impounded lakes. On all the main channels the highest ground crossed is some way south of the present entrances. It is as yet unclear whether the channels were initiated at the high points and were extended back during incision or began as up-and-over routes with water under hydrostatic pressure. All these channels have high points on their floor long profiles but these may be related to late aggradation rather than being evidence for hydrostatic flow persisting during incision. Altitude of highest ground cut through varies, declining westward, 125 - 60m: floor humps vary 65 - 35m OD. All but the highest channel have cross links implying overall contemporary formation. East of Wigton, the lowest had a cross link to the Wampool channel. At Caldew west of Dalston, a small shallow channel leads from and returns to the Wampool channel, evidently in use before final deepening of the Wampool channel.

The exits from these channels, near Wigton, are also perched and led into the lower drumlin country west of Wigton. Only the lowest, northern channel seems likely to have overlapped in use with the Wampool channel. Water from the others seems to have 'got away' among the drumlin country, much of it at a higher level than that to which the Wampool channel discharged meltwater. Sands and gravel deposits near the channel and exits between Wigton and the R. Waver and up to 70m OD (Eastwood et al 1968) suggest some constraint on free westward drainage. In view of the exit of the lowest channel to the Wampool, that influence was relaxed during the later part of formation of the Wigton channel set.

There are other features west of Wigton, not yet fully explained, which mark locations and altitudes of impediment to free water movement. Two are quite near coastal sites, Risehow and Harrington, reached or approached by SR ice (Huddart 1977). One of these is near Allonby where the Brunscow Beck channel, floor mainly below 30m OD, is open at its coastal end and leads south-east into the Ellen valley. The other, near Dearham, is higher and probably older: it took water from Ellen to Derwent valley, cutting through land reaching 70m OD. It is shallow, its main part cut to about 60m, and it discharged into Derwent valley at some 40m OD. A large area in the Ellen valley east of Dearham carries evidence of accumulation to that and similar levels. The control over that level was imposed at or near the present coast and presumably by ice: its relaxation allowed incision which has not yet removed all trace of the 40m aggradation level. The Hayton-Aspatria sands-gravels, parallel to drumlin trends and Ellen valley, may be related to ice control of meltwater movement by broadflow ice but they are not known in detail. There is a mix of Scottish and Lake District material. The channels and deposits from water movement at the foot of the fells between Pardshaw and Arlecdon and so towards Egremont are better known than the later stages of meltwater escape by way of Marron valley, Branthwaite and Distington and then by lower levels towards the coast.

The Thursby eskers (Huddart 1973) belong to a group of eskers west of Carlisle and are significant to interpretation of the Wampool channel. The eskers are clearly younger than broad flow drumlins which they cross. Their alignments suggest contemporary ice surface downslope to the south-east. They do not appear to continue south of the Wampool channel. The local broad flow ice surface would have sloped down to the west when the drumlins were being made. Huddart ascribed the eskers to water flowing to between east and south under Scottish Readvance (SR) ice. He noted a significant Scottish component in the included gravels and compatible depositional fabrics. Two of the Thursby eskers end at 30 - 40m OD at the north edge of the Wampool channel which, in the absence of obvious alternatives, presumably took their water west. The altitude of ground crossed by the eskers, 60 - 70m OD on the higher part of the Lias plateau west of Carlisle, give some indication of ice thickness and surface height over the Solway Firth. That ice would have closed the firth to passage of water from the east. It is likely that such ice would also have occupied the Kirkbride - Silloth lowland and thus have prevented Wampool

water moving north to Moricambe inlet. Possibly 'Scottish' water moved south at some time(s) to the Wampool route by way of Moricambe inlet.

A set of small channels north of the Wampool and the Thursby eskers is important. It lies between Thurstonfield west of Carlisle and Biglands 4km north of Wigton. There are two main routes, sinuous and broadly parallel, and smaller ones. Long profiles are gentle. The higher, southern channel has a perched entry at about 35m OD and falls to below 15m near Biglands. The northern channel is below 10m OD throughout. Towards Biglands the ends of the southern channel impinge on the north edge of broad flow drumlins. The channels cross the ice flow direction assumed for the Thursby eskers. Their location means that access of water to the Solway was still limited and their capacities are much less than the Wampool channel's: possibly they collected only local water. Their turn south away from the Solway towards the Wampool near Biglands and their small size suggest the firth was still ice-blocked and that the Wampool still in use.

The Cumbrian location of these features may well be explained as the result of direct contact of ice from across the Solway on the northern margin of the broad flow terrain, allowing Scottish ice in the Solway to impede water flow and divert it onto the Cumbrian side. Obstruction and diversion could have occurred during the broad flow episode and also during a later Scottish Readvance to which some of the channels and eskers have previously been referred. The history of water escape seems more complex than has previously been portrayed and merits further study.

About a Scottish Readvance

Merritt and Auton (2000) recognised the effect of minor spreads of ice into the Sellafield area after GOS. The strongest of these, SR, formed a push moraine at St Bees and disturbed deposits in a narrow coastal zone (Merrit and Auton 2000), also diverting drainage water along its front. In the Sellafield area GOS and SR outer limits are only 6km apart at most and differ little in height. Merritt and Auton found no evidence for SR ice in the LD fell country. As the St Bees push moraine has been ascribed to SR ice and as onshore deposits attributed to that ice are very limited in extent, a recent study (Williams et al 2001) of tectonic style of the moraine is pertinent. This concluded that the sediment was deformed by thick glacier ice with surface sloping down to the south-east. The complete succession is shown to be disturbed, and thus by a late ice mass that may also have, they thought, affected the Black Combe coastlands. How thick the *'thick ice'* was not discussed but that it was substantial must be taken into account in interpretation of the SR episode.

Broad flow ice converging on the Solway extended offshore for unknown distances as well as having onshore paths up to 50 - 70km in length. Features in North Cumbria ascribed to SR extend only a few km onshore, over terrain where the broad flow had taken different directions. Possibly SR ice spread occurred due to weakening of the Cumbrian broad flow ice earlier than that north



Figure 7 - The Scottish Readvance in the Solway area.
Key: 1 ice movements; 2 approximate outer limit of readvance; 3 uncertainty.

of the Solway. The incursion would have been a late adjustment between northern and southern ice masses. Alternatively, new ice was generated after a significant period of ice loss as Merrit and Auton (2000) have proposed for SR on the coastlands south of St Bees Head. Whichever the case, there was either no corresponding generation of ice in Cumbria or a limited response yet to be identified. Evidence for a readvance of ice distinct from the Scottish equivalent of Cumbrian broad flow has not yet been reported from Dumfries and Galloway. Whether SR ice, which presumably reached north Cumbria from the north, left traces in Dumfries and Galloway is important. A large ice mass had to be generated to extend from source areas across the Solway towards and possibly beyond Low Furness.

Several sites interpreted by Huddart as evidence for SR ice have been mentioned. Another important one is the Holme St Cuthbert complex. There, eskers from north-west fed sediment to a kame-kettle moraine 4 - 5km south-west to north-east along an ice margin. Outwash built a distal delta plain, mainly 30 - 50m OD. The site is directly opposite the mouth of Nithsdale and the ice was clearly land-based with the Solway Firth being blocked. The Wampool would still (or again) have been discharging to the Holme Dub-Black Dub route along the SR ice front or into a lake impounded by SR ice impinging on the present coastlands south of Allonby.

The sand-gravel mounds (up to 30 - 40m OD) and flats near Gretna are of interest in this respect. Dixon et al (1926) explained them as lesser eskers fed by a major esker alongside the Kirtle Water having fed ice front deltas. Thus they resemble the Holme St Cuthbert features. Both are low ground sites. If they mark outer limits of SR ice could that ice have also crossed the Lias plateau west of Carlisle to leave Thursby eskers across the drumlins on the south side? Would not ice able to cross the plateau have reached beyond Holme St Cuthbert towards Aspatria and beyond Gretna towards Carlisle? May Gretna or both these sites and the Thurstonfield channels record later SR ice margins?

If the Gretna feature was SR, so too was the feeder Kirtle Water esker-channel tract. In that case, all that area might carry Scottish equivalents to both the broad flow and the SR features identified in Cumbria. Landforms in lower Nithsdale and Annandale so far regarded as northern equivalents of broad flow may belong to more than that one episode. Did Scottish Readvance ice north of the Solway ever produce drumlins?

The sand-gravel tracts that flank the Nith valley floor to the north of Dumfries converge on the town (Stone 1959). To the south are ice-moulded rock ridges, scattered drumlins and fragments of sand-gravel terrain, outwash, marine sediments and mire. Upstream of Dumfries the glacial sands-gravels have been much eroded and concealed but may have previously extended across the whole valley floor. Does the arc of kame mound terrain across the valley at Dumfries represents an important ice front position? It is about 20km behind (or within) a Holme St Cuthbert-Gretna line.

An extrapolation

Two major ice movements have been recognised in the Solway region, one when ice from the west crossed high ground to augment ice generated further east, a second (broad flow) when ice converged on the Solway Firth and moved west. The two main episodes were separated, Merritt and Auton (2000) suggested for GOS, by several thousand years. Broad flow and GOS episodes may be identical. There is, though, a need to reconcile evidence for a large broad flow ice mass with ice surface perhaps reaching over 450m OD in the Ennerdale area with a lesser ice mass which Merritt and Auton (2000) appear to assume for the GOS. There were then the fluctuations of the Scottish Readvance.

On the south side of the LD the general direction of ice movement was to the south, clearly shown by erosional and depositional forms and drift lithologies. Apart from any lesser ice regeneration such as Gresswell (1952, 1962) wrote of, this has been seen as a single major episode. It would be surprising if ice generation which, from Howgill Fells to the western LD, fed the broad flow of the Solway region, had not also nourished a southward flow on the other side of the Lake District. From the west side of the Howgills across the Lune valley to the fells north of Windermere, ice has moved mainly southwards on a 20km wide front. Drift cover has been ice-moulded down from about 300 - 250m OD with longitudinal, transverse and oblique ridges showing various degrees of transition to drumlins, a major drift landform below about 200m OD. Similarity with landform suites north of Shap, Birkbeck and Howgill Fells does not, of course, prove contemporary formation. But a second ice movement, equivalent to the broad flow or GOS, would be expected. As first and second ice movements on the south side might be very similar, can field evidence for two movements be found? If a southern version of broad flow occurred then (by analogy with the area to the north) its ice would have reached to Morecambe Bay and beyond. In that case the fringe of readvance features at Barrow-Rampside impinging on the Low Furness drumlin country could not be contemporary with the drumlins and thus, applying the Merritt and Auton time scale, would be not GOS but later.

And since the northern LD fed a broad flow of ice and the Howgill Fells participated in that, how much ice was then generated to the east in uplands from Craven to the Tyne Gap and beyond? Where and with what effects? Did a new upper Teesdale ice mass appear?

Similar questions apply to the Scottish sides, for example, about ice generation in hills where Annan catchment meets Tweed, Ettrick, Teviot and Esk headwaters. Did the upper Esk basin feed ice to both Annan and Teviot sides? Merritt and Auton (2000) suggested correlation between GOS and Dimlington Advance of ice in East Yorkshire. The contribution of Tweed and Forth ice to a Dimlington ice lobe down the east coast (Teesdale and Hughes 1999) is indicated by characteristics of drift and landforms. The large Scottish contribution to Solway ice during broad flow time suggests outflow by way of the Firth of Clyde would be even greater. Its eastern edge, crossing the Wigtown

Moors and Machers, could have pushed Solway ice to a southerly path so keeping the Cumbrian ice near the coast from Silloth southwards.

It is important to recall that there are few ice margin locations in the Solway region other than at some discrete sites in north Cumbria that have been referred to SR and those, more lateral than terminal, sites between St Bees and Morecambe Bay. It seems both broad flow and SR ice reached beyond the Solway and Cumbria but it is not part of this discussion to speculate on where traces of their margins might be sought.

Conclusion

The present time is one of active development of a general Late Pleistocene chronology for N Atlantic - NW Europe, largely constructed from seabed core and Greenland ice core data. There is prospect of a firm time scale to which regional glacial histories can be attached. One element of this general chronology is a repetition of events identified from layers of coarse sediment in seabed sediment cores. This is rock waste carried across the N Atlantic in icebergs from land ice discharged in vast quantities over short periods mainly from the Laurencian Ice Sheet. This happened every few thousand years. As these ice outpourings from N America have been linked to fluctuations in ice masses on the east side of the Atlantic, they are vital markers in a chronology of glaciation in NW Europe to which it is likely the Solway glacial episodes will, in time, be fitted. There is now a real need for many sets of stratigraphic data from the Solway region to underpin refinement of correlations within the region and to establish chronological links with adjacent areas.

This review has sought to portray the spatial and temporal complexity as well as the unity of the region, to outline previous interpretations, and especially to examine persistent and newly-recognised ambiguities and uncertainties. There are opportunities at a range of scales, topics and localities to further our understanding of the region as it was in the latter part of the Pleistocene.

References

ARTHURTON, R. S. and WADGE, A. J., 1981. The Geology of the Country around Penrith, Inst. Of Geol. Sciences, London, HMSO.

AVEBURY, RT. HON. LORD, 1906, The Scenery of England, London, Macmillan.

BOULEDROUA, A., TARLING, D. H. and LUNN, A. G., 1988. Glacial drift thickness in the Tyne Gap, Northumberland, Transactions of the Natural History Society of Northumbria, 55, 20 - 27.

BURGESS, I. C. and HOLLIDAY, D. W., 1979. Geology of the country around Brough-under-Stainmore, Geol. Surv. GB, Inst. of Geol. Sci., London HMSO.

CHARLESWORTH, J. K., 1926. The readvance, marginal kame-moraine of the south of Scotland, and some later stages of retreat, Transactions of the Royal Society of Edinburgh, 55, 25 - 50.

CLARK, R., 1970. Aspects of Glaciation in Northumberland, Proceedings of the Cumberland Geological Society, 2, 4, 133 - 156.

CLARK, R. and SMITH, R. A., 1998. The recent investigations into the Quaternary geology of West Cumbria, Proceedings of the Cumberland Geological Society, *6, 2, 203 - 225.*

CLAYTON, L., ATTIG, J. W. and MICKELSON, D. M., 1999. Tunnel channels formed in Wisconsin during the last glaciation, in Mickelson, D.M. and Attig, J.W. (eds), Glacial processes past and present, Geological Society of America, Special Paper 337.

CORNISH, R., 1979. Glacial geomorphology of the west-central Southern Uplands of Scotland, with particular reference to Rogen moraines. Unpubl. Ph.D. thesis, University of Edinburgh.

DAY, J. B. W., 1970. Geology of the country around Bewcastle, Geol. Survey Gt. Brit., London, HMSO.

DIXON, E. E. L., MADEN, J., TROTTER, F. M., HOLLINGWORTH, W. E. and TONKS, L. H., 1926, The Geology of the Carlisle, Longtown and Silloth District, Geol. Survey of Gt. Brit., London, HMSO.

EASTWOOD, T., HOLLINGWORTH, S. E., ROSE, W. C. C., and TROTTER, R.M., 1968, Geology of the country around Cockermouth and Caldbeck, Geol. Survey Gt. Brit., London, HMSO.

GRESSWELL, R. K., 1952. The Glacial Geomorphology of the South-Eastern part of the Lake District, Liverpool and Manchester Geological Journal, 1, 57 - 70.

GRESSWELL, R. K., 1962. The Glaciology of the Coniston Basin, Liverpool and Manchester Geological Journal, 3, 1, 83 - 96.

HAY, T., 1944, Mountain Form in Lakeland, Geographical Journal, *103, 263 - 271.*

HOLLINGWORTH, S. E., 1931. Glaciation of Western Edenside and Adjoining areas and the Drumlins of Edenside and the Solway Plain, Quarterly Journal of the Geological Society of London, 87, 281 - 357.

HUDDART, D., 1973. The origin of esker sediments, Thursby, Cumberland, Proceedings of the Cumberland Geological Society, 4, 59 - 69.

HUDDART, D., 1981. Fluvioglacial systems in Edenside, in Boardman, J. (ed), Field Guide to Eastern Cumbria, Brighton, Quaternary Research Association.

HUDDART, D., 1991. The glacial history and glacial deposits of the North and West Cumbrian lowlands, in Ehlers, J., Gibbard, P.L. and Rose, J. (eds), Glacial deposits in Great Britain and Ireland, Rotterdam, Balkema Press.

JOHNSON, G. A. L., 1952. A glacial boulder of Shap Granite in South Northumberland, Geological Magazine, 89, 361 – 364.

KING, G. A. M., 1976. Northern England, London, Methuen.

LETZER, J. M., 1981. The upper Eden valley, in Boardman, J. (ed), Fieldguide to eastern Cumbria, Quaternary Research Association, Brighton.

LINTON, D. L., 1964. The Forms of Glacial Erosion, Presidential Address 1963 to Institute of British Geographers.

LUMSDEN, G. I., TULLOCH, W., HOWELLS, M. F. and DAVIES, A., 1967. The Geology of the Neighbourhood of Langholm, Geol. Survey Scotland, Edinburgh.

LUNN, A. G., 1995. Quaternary, in Johnson, G. E. L. (ed), Robson,s Geology of North-east England, Transactions of the Natural History Society of Northumbria, 56, Part 5.

MERRITT, J. W. and AUTON, C. A., 2000. An outline of the lithostratigraphy and depositional history of Quaternary deposits in the Sellafield district, west Cumbria, Proceedings of the Yorkshire Geological Society, 53, 2, 129-154.

MITCHELL, W. A., and CLARK, C. D., 1994. The last ice age in Cumbria, in Boardman, J. and Walden, J. (eds), The Quaternary of Cumbria: Field Guide, Quaternary Research Association, Oxford.

RAISTRICK, A., 1931. Glaciation, Proceedings of the Geologists' Association, 42, 3, 281-291.

RILEY, J. M., 1987. Drumlins in the southern Vale of Eden, in Menzies, J. and Rose, J. (eds), Drumlin Symposium, Balkema, Rotterdam.

SISSONS, J. B., 1967. The evolution of Scotland's scenery, Edinburgh, Oliver and Boyd.

SMITH, B., 1912. The glaciation of the Black Combe District, Cumberland, Quarterly Journal of the Geological Society of London, 68, 402-448.

SMITH, B., 1932. Glacier lakes of eskdale, Mitredale and Wasdale, Cumberland: and the retreat of the ice during the Main Glaciation, Quarterly Journal of the Geological Society of London, 88, 57-83.

STONE, J. C., 1959. A description of glacial retreat features in mid-Nithsdale, Scottish Geographical Magazine, 75, 164-168.

TEASDALE, D. and HUGHES, D., 1999. The Glacial History of north-east England, in Bridgland, D. R., Horton, B. P and Innes, J. B. (eds), The Quaternary of north-east England. Field Guide. Quaternary Research Assocaition. London.

TIPPING, R. M., 1999. Quaternary Landscape Evolution of Dumfries and Galloway, in Tipping, R. M. (ed), The Quaternary of Dumfries and Galloway, Field Guide, Quaternary Research Association, London.

TROTTER, F. M., 1929. The glaciation of Edenside, the Alston block and the Carlisle plain, Quarterly Journal of the Geological Society of London, 85, 549-612.

WELLS, A. J., 1957. The glaciation of the Teesdale-Swaledale watershed, Proceedings of the University of Durham Philosophical Society, 12, 82-93.

WILLIAMS, G. D., BRABHAM, P. J., EATON, G. P. and HARRIS, C., 2001. Late Devensian glaciotectonic deformation at St Bees, Cumbria: a critical wedge model, Journal of the Geological Society, 158, 125-135.

WRIGHT, W. B., 1937. The Quaternary Ice Age, London, Macmillan.

Acknowledgements

I am grateful to Mervyn Dodd and Alan Smith for their help in improving the text, to Angus Lunn for discussion of various aspects of its content and to Elizabeth Clark for preparation of the text.

Dr R P K Clark

[redacted]

EXCURSION REPORTS 2000

To celebrate the Millennium, Part 3 of these Proceedings, published in May 2000, was devoted to a series of articles describing the lives and work of some of the pioneers of Lake District geology. Each of the field excursions of the following summer was devoted to one of these pioneers. Some of the localities described by these geologists were visited and, in retracing the steps of the pioneers, their interpretations were placed in the historical context of the development of the subject.

BORROWDALE VOLCANIC GROUP ROCKS IN CAT GILL - IN THE FOOTSTEPS OF *JAMES CLIFTON WARD*

Leader: Dr Alan Smith (Cumberland Geological Society)

Wednesday May 10th 2000

A large group of members met at Great Wood Car Park, Derwentwater for the first of the Millennium excursions retracing the steps of some of the pioneering geologists of the Lake District.

The leader reminded the group that J. C. Ward had been sent to Keswick at the age of 26 in 1869, to carry out the first survey of the Northern Lake District for the Geological Survey of Great Britain. It was Ward who first mapped the volcanic rocks and offered an interpretation of the succession. It was he who also first named them the Borrowdale Volcanic Series. Ward used Cat Gill as the type section for the Series. He drew a section along the gill showing around 600m of volcanic rocks dipping consistently eastwards and made up of 12 lava flows with intervening ashes and breccias – roughly in 50/50 proportions, (Geological Survey of Great Britain, 1876, *The Geology of the Northern Lake District*, plate V, facing page 13). The lavas tend to make hillside features, standing out as craggy outcrops, with the ashes and breccias being worked back by weathering and erosion – producing benched hillsides. More recently parts of the lower section of the gill have been commented on by J. F. N. Green (1915), Marr (1916), Edgar Shackleton (1966) and R.J. Suthren (1990). Re-mapping by BGS for the Keswick Sheet (No. 29) has offered a new interpretation of the succession.

Only the lowest part of the succession was examined on the excursion. On the lake shore the faulted contact with the Skiddaw Group was seen close to the water's edge (NY 269208). Above it, the huge blocky exposure of the basal volcanic material was examined. Ward simply described it as a purple breccia. Marr interpreted it as a fault breccia and Green as an explosion breccia. Shackleton discounted the fault breccia origin. Suthren and the recent BGS

survey interpret it as a mudflow deposit – a chaotic, unsorted mass of clasts from sand to boulder size, mostly volcanic material, but with noticeable pieces of Skiddaw Group rocks.

Following the gill section above the road the succession is less clear. The purple breccia is less coarse. Coarse tuffs, distinctly mottled and greenish-blue in colour form most of the ground. Just below the footbridge carrying the footpath to Falcon Crag, the section described by Shackleton (*Lakeland Geology* page 28), was examined in some detail and caused some discussion between members. The narrow band of 'Green's Flow Breccia' was located – a very distinctive tough grey-green fragmental rock in a fine ground mass. Green suggested it was an auto-brecciated lava. Immediately above it is a very clear, distinctly bedded, fine tuff.

At the footbridge the gill has cut a small gorge section through the first of Ward's lava flows. It is a compact, well-jointed andesite showing conchoidal fracture and notable for its content of small but easily seen garnets.

On the stiff climb up the path on the right bank of the gill, a coarse tuff is well-exposed but difficult to relate precisely to Ward's section. Above it, brecciated lavas are traversed by the path.

The gill was crossed at an obvious crossing at a gate. Here, some time was spent illustrating the nature of the lava flows in forming strong outcrops and waterfalls in the stream bed. The discontinuity running down the gill illustrated by the BGS survey was noted – Ward failed to illustrate this to any extent.

The group then moved out on to the hillside south of the gill below Falcon Crag. Here it is possible to see how the second, third and fourth of Ward's lava flows can be picked out in the topography. All are andesitic in nature and form prominent crags with aprons of scree beneath. The intervening ashes and breccias are not exposed, but can be interpreted from the topography. The steep slope beneath was descended back to Great Wood Car Park.

THE FURNESS OF *JOHN BOLTON*: LINDAL, PLUMPTON, GLEASTON AND STANK

Leader: David Kelly (Cumberland Geological Society)

Sunday June 4th 2000 (Joint meeting with the Furness Geological Group)

A large group of members and guests met in Lindal Village where the leader explained that John Bolton's main geological studies began after he returned to Furness in 1851 and took up residence in the house in Swarthmoor which he was to name *Sedgwick Cottage.* At the time only A. Sedgewick and E.

W. Binney had published research into the geology of Furness and the pioneering work of J. D. Kendall was not published until after Bolton's death. The primary survey of the Furness peninsula was carried out in 1865 - 70 by W. T. Aveline and A. C. G. Cameron. Bolton became a friend and correspondent of many of the leading geological figures of the day, including Adam Sedgwick. This was the time of the Furness iron mining boom with much of the ore being transported by the Furness railway to the port of Barrow for shipment. The invention of the Bessemer process in 1856 gave the local hematite a short-lived commercial advantage. In 1857 the completion of the Ulverston - Lancaster railway, and its viaducts across the Kent and Leven Estuaries, linked the Furness Railway with the national network and allowed coking coal to be brought in from Durham. As a result Barrow-in-Furness briefly became the major centre of iron smelting in Europe.

The first part of the day was spent exploring the Lindal Moor mining area. Lindal Moor has the largest concentration of vein-like ore deposits in Furness. These occur along a complex north-west – south-east fault system, the Lindal Moor Fault. This is a normal fault system with the footwall generally in the relatively impermeable Silurian mudstones, siltstones and greywackes (Bolton's "clay-slate") and the hanging wall formed by the Carboniferous Limestone (Bolton's "Mountain Limestone"). Mineralisation occurs for about 2500 metres along the fault system and is richest where it meets east - west "cross-faults". The limestones are replaced selectively with the non-shaley Red Hill Limestone Formation and the lower Dalton Formation being favoured. The "top slicing" mining method resulted in much subsidence and the line of the fault system is indicated by the elongate depression of broken ground.

The highest and most north-westerly mining area seen on this visit was in the Buccleuch Royalty at SD248769. A small subsidence pond occurs close to the Carkettle road and the wall built from Silurian rocks indicates the proximity to the footwall of the fault. The ore bearing Carboniferous strata dip to the south-east and the earliest workings were open cast diggings in the Martin Limestone at Poaka at the north-west end of the fault system some 700m from this locality.

In Furness, Bolton noted that the Carboniferous and Silurian are "indented into each other". He imagined an upland, coastal landscape of Silurian rocks with bays into which the Carboniferous carbonate sediments were deposited. The landscape was, however, almost certainly a lowland one and the "bays" are where the boundary is displaced by the north-west - south-east faulting. The Lindal Moor Fault displaces the base of the Carboniferous by about 1500m. Bolton describes a "conformable sequence at Carkettle", however this is where the ore bodies occupying faults with Carboniferous rocks on the hanging wall and Silurian rocks on the foot wall.

At the site of the B30 pit (SD245766) a small adit entrance has been restored. This was the main production pit in this part of Lindal Moor. Some ore from the Muncaster Royalty was raised through this shaft. It closed in October

1914. Hematised specimens of corals were found in the spoils heaps; Bolton recognised the significance of these to the origin of the ore deposits. The party examined a well-preserved engine pit close to the adit entrance.

Further south-east at Diamond Pit (SD254762) the mines were much deeper, -120m OD with the surface at + 82m OD. At the end of the ore body at Lowfield, the Dalton Formation is at the surface but ore was won from the Red Hill Formation at - 180m OD. The vertical extent of the ore body here being almost 300m. Water was a problem in this area and Diamond Pit was the main pumping pit in the area, being 612 feet deep. The engine house now used by a meat company. The mines in this area were part of the Pennington Royalty of Lord Muncaster and mostly worked by Harrison, Ainslie and Co. which later became part of the Millom and Askam Haematite Iron Company. The Lowfield mines were worked for a time by the Parkside Mining Company of West Cumberland. At GB4 Pit the footwall is formed by the Low Furness Basal Beds which were also proven at 91m in a borehole on the hanging wall side.

The party examined Daylight Hole (SD253763), an impressive subsidence hollow. A search on nearby spoil heaps produced specimens of low grade hematite, calcite, dolomite and fluorite.

Lunch break was taken at the car park close to the Bay Horse Inn (SD313776) which provides an excellent view of the Ulverston - Lancaster Railway's Leven Viaduct, opened in 1857. This venture of the Brogden family of Ulverston linked the Furness Railway with the national network and allowed coking coal to be brought in from Durham. Barrow and other localities in Furness were then able to develop iron smelting industries.

300m northwards along Plumpton Bight (SD312781) the Park Limestone Formation is exposed in low cliffs and a wave cut platform. A minor fault is seen at the southern end of the exposure. The locality is noted for large coral colonies up to 1m diameter. The large size and restricted range of species are attributed to stressful environmental conditions. Lithostrotion minus, Siphonodendron martini, gastropods and crinoids are present.

At SD312784 piles of hematised debris indicate the eastern end of a west north-west – east-south-east trending hematite vein. The extensive quarries to the west in the upper and middle Dalton Formation have now been filled by tipping and only small exposures remain.

The Carboniferous - Silurian boundary, described in detail by Bolton, occurs in the area around Plumpton Hall but is note exposed.

The party then visited the small quarry near the roadside north-east of Gleaston Castle (SD263715). This quarry was described by Bolton and visited by the CGS under the leadership of Murray Mitchell in June 1975. The proceedings of the society note the following. "*After parking the cars in front of*

the ruins of Gleaston Castle (261714), the old Norman manor house of the de Fleming family, a small nearby quarry in the D_2 Gleaston Formation was visited; this horizon is considered to be the next main limestone above the one exposed at Humphrey Head (395740). The very dark well-bedded limestones yielded excellent examples of Lonsdaleia which is one of the main D_2 fossil horizons in the NW Province; whilst in the shale partings samples of the brachiopods Rhipidomella, Spirifer bisulcatus and the coral Aulophyllum were obtained"

On the way to Newton in Furness the party drove through the hamlet of Stank (SD234703). The Magnesian Limestone (St Bees Evaporite Formation) described by Bolton is no longer exposed but has been used as a building stone in Stank, Newton and Leece. At Newton (SD228717) the party walked across the fieldds to view the remains of the Yarlside Mine, one of the last to be worked in Furness. The ore body, associated with the north - south Yarlside Fault, is unusual in that the hanging wall of the fault is in the St Bees Sandstone and is separated from the Urswick Limestone Formation and Gleaston Formation of the footwall by a fault zone up to 30m wide composed of black shale from the Gleaston Formation. The ore was largely within the Urswick Limestone Formation, although, unusually for Furness, it appears to be partly an infilled vein rather than a replacement deposit.

The working life of the mine was prolonged by the extraction of foundry sand. It is uncertain whether this was poorly lithified St Bees Sandstone or a fluvioglacial sand. The site provides a good view of the town of Barrow in Furness which owed its rapid growth to iron ore export and then the iron and steel industry. At the time of John Bolton's return to Furness in 1851 the population was a few hundred. By the 1861 census it had risen to 3,000. The 1881 census, eight years after Bolton's death, records the population as 40,000.

THOMAS HAY – GLENRIDDING

Leaders: Dr Alan Smith, Dr Dick Clark (Cumberland Geological Society)

Saturday June 24th 2000

Participants met in Glenridding carpark to follow a route walked many times by Hay, from Ullswater to the head of Glenridding at Keppel Cove in the shadow of Helvellyn, and which passed his front door. The intent was to examine features he described and to consider the questions he posed and conclusions he reached. It is a 10km round walk. Glenridding runs west-east, is steep sided and for much of its length is flanked by hills that rise to over 600m OD. The opposed aspects lead to different environmental conditions which, especially from the Ice Ages, have left contrasting landforms and materials. What Hay saw and thought in Glenridding probably affected the interests he took to other parts of the fell country.

Hay knew Glenridding had been full of ice and the hills around covered: he described trails of erratics across the top of Sheffield Pike on the north side of the valley. He worked at a time when every separable layer of till (boulder clay) was thought to represent a distinct episode of glaciation. He recorded two tills in several Glenridding beckside locations. At the best of these, now much degraded, two tills are separated by delta beds, and there is a real case for a readvance of ice over the delta. Glenridding screes on the south-facing side of the valley are impressive, being about 1.5km east-west, and reaching almost to the road. They can be seen to have encroached over a till cover with some boulders having got further. Ice-worked bedrock projects through the lower margin of scree! The effects of several processes are displayed contiguously.

Across the valley, facing north, are Little Cove and Blea Cove, on the steep end of Birkhouse Moor. Hay thought each had held a small glacier at the end of the latest glaciation. The sites are appropriate, the evidence less than compelling. Little Cove was not visited; Blea Cove is too steep to be ideal for preservation of moraines. Hay may have been right, and the sites were probably at least locations of persistent snowfields. Above the narrow, steep part of the valley, past Greenside mine, the northern side has a thick cover of till. Hay mapped frontal moraines there. That would have implied a valley glacier some 3km long. It is not always easy to distinguish drift cut by gullies from moraine ridges: here the balance seemed to favour moraine, terminal or recessional. But when were they formed? This could have been after main glaciations but before the formation of those moraines at the head of the valley.

This is quite near a stretch of valley where Hay mapped upper margins of a valley glacier. He recognised rather faint lines high on the hillside, small changes in slope and changes in size of hillside debris as if some impediment (glacier ice?) had checked downslope movement of debris. Also in this vicinity, and just above the track, is a large rock bluff which nicely illustrates the contrast between processes of ice-erosion, abrasion on up-ice side, plucking or quarrying on down-ice side. This is opposite the impressive steep 'gable-end' of the Catstycam ridge.

Time allowed only Keppel Cove to be visited of the two valley-head corries in the flank of Helvellyn. The large compact arcuate terminal moraine indicates that its glacier varied rather little in length for much of its existence, and the paucity of recessional moraine suggests that it didn't linger once the ice front retreated from the moraine arc. That contrasts with moraine patterns in several other high valley heads. Well-preserved striae and abraded rock surfaces were noted on the west side of the cove. The moraine impounded a tarn after loss of ice and a delta accumulated into the tarn. Need for plentiful and reliable water supply for mining led to leats, diversions and dams being built in the upper valley. A dam was built across the outlet through the moraine to raise the tarn. It collapsed in 1927, the flood causing extensive damage to beckside properties in Glenridding. Hay's house was one such. He wrote briefly about the flood.

The differently-sited replacement dam failed in 1931. There is no longer a Keppel Cove Tarn: the delta and old shorelines are exposed.

The return journey began on the other side of the valley on one of the leats, at the foot of Catstycam where Hay had mapped a small terminal moraine. Hillfoot mounds and ridges are more extensive. Examination suggested that they probably accumulated at the foot of a broad hillside snowfield, hardly a glacier, when Brown Cove and Keppel Cove held their corrie glaciers. The path took us back along the base of Blea Cove and the question, glacier or snow patch, was revisited but inconclusively.

In all, a variety of landforms and problems of their origin, characteristic of Hay's interests and style, were encountered in the course of the day.

WATCH HILL AND ELVA PLAIN THROUGH THE EYES OF *TOM EASTWOOD*

Leader: Dennis Dickins (Cumberland Geological Society)

Saturday July 8th 2000

This field excursion was the seventh 'In the footsteps of Geological Pioneers in the Lake District' and commemorated Tom Eastwood's association with the area. Members assembled at Cockermouth School where it was explained that the sequences being examined belong to the Skiddaw Group of the Ordovician Period and represent some of the oldest rocks in Cumbria. It was explained that the objective of this visit was to elucidate the correlation of strata in the Watch Hill to Elva Plain area from the earliest interpretations, including the Geological Survey mapping from the latter part of the nineteenth century, which was resurveyed between 1922 and 1932, at first by Dr. B. Smith, then mainly by Tom Eastwood who both supervised and undertook a considerable part of the survey. However, it was not until 1968 that the Geological Survey Memoir 'Geology of the Country around Cockermouth and Caldbeck' was published, after some additional work which included interpretation of the petrography and palaeontology. More recent interpretations include those made by Jackson in 1978 and Hughes in 1993, the latter leading a Cumberland Geological Society field excursion to the area in 1991. The group then travelled along the unclassified road towards Cockermouth Golf Course and Higham Hall, and parked on the roadside, to the east of Greenlands Farm below Watch Hill, at Grid NY 150314, and proceeded uphill to the first location, a former quarry face at Grid NY 149317, which forms a prominent feature on the southern flanks of the Setmurthy ridge, which includes Watch Hill and Elva Hill. This exposure a now a RIG site but has had a controversial history of interpretation.

This former quarry face can be traced, with exposures ranging in thickness from about 1m in the west, at Grid NY 147318, to approximately 10m towards the east, before finally being recovered by vegetation at Grid NY 151317. This exposure displays prominent columnar jointing and is a pinky cream colour when fresh. Although the basal contact of this exposure is hidden, on careful examination a rubbly roof contact can be discerned which is identified as a breccia. In the 1968 Geological Survey Memoir, this quarry is captioned "Grits of the Skiddaw Slates Plate IIA". Jackson interpreted the same exposure as a fine grained, even textured felsite and because of the breccia exposed in the roof contact with the overlying Watch Hill Formation, he concluded that this breccia was the rubbly top of a lava flow. Hughes and Kokelaar in their 1993 paper have re-interpreted the exposure as an intrusive sill of a pink weathered, very fine grained to cryptocrystalline, porphyritic rhyolite. Although the basal contact is hidden, the Watch Hill Formation is exposed a few metres down slope from the quarry.

The Watch Hill Formation consists of sparsely fossiliferous, marine, turbidite sandstones which have been dated by graptolites and acritarchs as belonging to Late Tremadoc or early Arenig age (British Geological Survey, 1988). The exposures of this sequence at Watch Hill are mainly thin to medium bedded, fine to coarse grained greywackes and arenites. These sediments are intercalated with mudstones, silty mudstones and thin, parallel, wavy laminated siltstones. Banham, P. H. et al in 1981 had interpreted the strata as forming the inverted limb of a major nappe, but recent mapping by the Geological Survey (1991), indicate that the sequence is the right way up, based on the sedimentary structures in the turbidites, with the succession younging slightly to the west of north.

The Watch Hill Felsite is not considered to be older than the Eycott and Borrowdale Volcanic episodes and may have an association with the Eycott Volcanic Group or could possibly have been intruded at a later stage, especially since there is substantial evidence to suggest that the sediments into which the sill was intruded were partly lithified. A possible range of dates is from <476 Ma (late Llanvirn) and >444 Ma (late Caradoc), which represent the two volcanic episodes, and is associated with the major episode of continental destructive plate margin magmatism. If the Watch Hill Felsite had been a lava flow it would have meant that to be contemporaneous with the sediments onto which it was extruded, magmatism would have had initially occurred in the region between 24 and 29 Ma before the onset of the Eycott and Borrowdale Volcanic episodes.

After a detailed examination of this site a brief visit was made to the summit of Watch Hill (Grid NY 149319), where small quarries had been excavated into the diorite which had been intruded into the Watch Hill Formation during the Lower Palaeozoic. After lunch at the roadside, the group motored to Elva Plain Farm (Grid NY 175316), where the owners had kindly given prior permission for the Society to park in the farmyard.

Walking northwards along a track for about 300m the party traversed the concealed boundary between the Bitter Beck and the Watch Hill Formations. A former quarry in diorite was reached at Grid NY 174319 and the enclosing sedimentary strata consist of the Watch Hill Formation. This site is surrounded by isolated exposures of both the Bitter Beck and Watch Hill Formations. Some time was spent examining the features of these exposures, however time, and the onset of rain, terminated the excursion before a typical Bouma turbidite sequence in the Watch Hill Formation could be visited in an enclosure about 100m further north at Grid NY 172320.

Finally, those members who did not mind a drenching from the now inclement weather took the opportunity to view the remains of the stone circle at Grid NY 177317 in the enclosure to the east of Elva Plain Farm.

Thanks are made to Mr. & Mrs. Richardson of Greenlands Farm and to Mr. & Mrs. Marr of Elva Plain Farm for allowing the excursion onto their land. Members are reminded that prior permission should be sought from the above landowners if they wish to visit the various exposures mentioned in the above article.

Geological succession

		{Kirkstile Formation
	{Arenig	{Loweswater Formation
Ordovician		{Hope Beck Formation
	{?	Watch Hill Formation
	{Tremadoc	Bitter Beck Formation

References

BANHAM, P. H., HOPPER, F. M. W. & JACKSON, J. B. 1981. The Gilbrea Nappe in the Skiddaw Group, Cockermouth, Cumbria, England. Geological Magazine 118, 509-16.

EASTWOOD ET AL. 1968. Geology of the Country around Cockermouth and Caldbeck, Memoir, Geological Survey of Great Britain, NERC/IGS.

HUGHES, R. A. & KOKELAAR, P. The timing of Ordovician magmatism in the English Lake District and Cross Fell Inliers 1993. Geological Magazine, 130[3], pp. 369-377.

HUGHES, R. A. 1991. Skiddaw Group of Watch Hill and Sale Fell, Proc. of the Cumberland Geological Society, 1990-91, vol. 5, pt. 3, pp. 361-363 and 380-382.

JACKSON, D. E. 1978. The Skiddaw Group, in The Geology of the Lake District, Yorkshire Geological Society Occ. Pub. No. 3, pp. 79-98. Moseley, F. [editor].

JACKSON, D. E. 1977. New Assessment of the Stratigraphy of the Skiddaw Group along the Northern Edge of the Main Skiddaw Inlier, Proc. of the Cumberland Geological Society, 1977-78, Vol. 4, Pt. 1, pp. 21-31.

SHIPP, T. 1980. The Watch Hill Grit and the igneous rocks of the Embleton area, Proc. of the Cumberland Geological Society, 1979-81, Vol. 4, Pt. 2, pp. 153-155.

TAYLOR ET AL. 1971. British Regional Geology - Northern England, NERC/IGS

WADGE, A. J. 1978. The Classification and Stratigraphical relationships of the Lower Palaeozoic rocks, in The Geology of the Lake District, Yorkshire Geological Society Occ. Pub. No. 3, pp. 67-78. Moseley, F. [editor].

IN *CHARLES EDMONDS*' DAY: LONGLANDS AND CLINTS

Leader: Mervyn Dodd (Cumberland Geological Society)

Wednesday July 19th 2000

A large party met at Longlands car park alongside the section of the River Ehen, which was diverted and straightened to protect the Longlands hematite mines from flooding. The leader explained that these mines worked, from 1878 to 1924, a more or less horizontal flat of very good hematite up to 10m thick in the Seventh Limestone. A second flat 3m thick lay beneath this. There were several small shafts about 60m deep under, or near, the southern edge of the lake. Soft, loose sands and gravels covered the hematite. When this was stoped (worked upwards from a horizontal gallery) the sands were likely to flow down to fill the void. Water would flow down afterwards if this happened.

Mining could only proceed with great care. There was only one shift per day and much of the ore, which extended north to south across the 13° dip to the west-south-west, had to be left as pillars under the river. The ore was near to faults running north-north-west – south-south-east, but rather irregular in its form. Annual output was only about 12 – 15,000 tons per annum but was very high quality. Hand-picked lumps were sent to special steel manufacturers at Sheffield but most was smelted at Moss Bay.

The party walked down the west side of the lake and saw the remains of two railway bridges across the Ehen. The first served numbers 1 and 3 pits, now

under the lake, the second numbers 2 and 4. Across the river is the remains of an old mill, now a house.

The leader explained that the lake only developed after 1938 due to subsidence and flooding. At the south-east corner of the lake is a pipe to transfer water to and from the river and the lake which now accommodates winter wildfowl.

Two small mines lay south of Longlands near the river. Bain's Woodend Number 10 was west of the Ehen and the Rowfoot mine just east of the river. They worked very small ore bodies in the Seventh Limestone immediately above the Skiddaw Group. Their shafts barely reached sea level and mining ceased by 1900.

The party examined the remains of Number 4 pit, the last one to be worked. The well-preserved ruins provoking interesting speculation about their former use. From this site, diagonally across the lake, by its north-east corner, is a hollow marking the former course of the river.

The second part of the evening was spent visiting Steelbarrow Quarry (NY006123). Cars were parked, with permission of the farmer, at Langhorn Farm and the group walked along the track south from the farm and then across the footbridge over the A595. West and east of the road the Carboniferous First and Second limestones and shales, dipping west-north-west, form scarp and vale topography. Steelbarrow Quarry lies in the upper part of the Brigantian Fourth Limestone.

The upper 5m of exposed beds is the Junceum Limestone. These are pale, rubbly, fossiliferous limestones. Fossils identified on this visit included Siphonodendron junceum, Lonsdaleoid corals and brachipods. Beneath this lies the 0.5m thick Saccamina Shale, named after the pin head size algae. The shale has been interpreted as a palaeosol. The lowest beds exposed are 3m of the grey, crinoidal Saccamina Limestone. Fading light prevented a more detailed fossil search.

THE CARBONIFEROUS LIMESTONES OF YEWBARROW AND BECK HEAD

Leader: Dr Iain Burgess (University of Leeds)

Sunday 10th September 2000 (Joint excursion with the Westmorland Geological Society)

This account is re-printed, with permission, from Westmorland Geological Society, Proceedings, 28

The trip had been organised as one of the Society's millennium series of "in the footsteps of pioneers of Lake District geology". This was to have been "in the footsteps of Garwood" and led by Murray Mitchell. Unfortunately, Murray was unable to take the trip and Dr Burgess had kindly taken over with a tour of the limestones of Yewbarrow and Beck Head. Thirty-four members of the two societies assembled in the rain near the Derby Arms. The aim was to trace the Dinantian succession, first comprehensively examined by Garwood in the early 1900's, and discuss the depositional environments, illustrating how contemporaneous and later tectonic movements had affected the present distribution. Dr Burgess was well qualified to lead the trip as he had recently mapped the same succession for the BGS on the adjacent Kendal Sheet.

The geology of the area

The Lower Carboniferous limestone blocks of Yewbarrow and Whitbarrow dip gently to the east and are outliers within Silurian country rock. Large bounding faults to these blocks generally follow the Caledonian north-north-west – south-south-east trend and probably stem from the Lower Palæozoic basement. In some cases they have been active in the Carboniferous and Tertiary and some still show movement today. The limestones were deposited in shallow water at the southern margin of the Lake District block on a subsiding and uneven Lower Palæozoic landscape. The blocks subsided more slowly than adjoining basins where sedimentation was more rapid and continuous. In 1913 Professor E J Garwood published his seminal paper on the limestone succession of the NW England. He divided the succession on the basis of faunal zones, following the scheme devised by Vaughan in the Bristol area (1905). Rose and Dunham's work during the War and in the 1970s divided the succession into formations based on lithological grounds, but largely following Garwood's zones. The formations have been applied to all the Dinantian successions fringing the southern part of the Lake District. From Ulverston to Kendal there is a more or less continuous sequence, though in the Witherslack area there seem to be significant breaks in sedimentation. These may represent movement on the blocks so that the individual units may well be separated by long periods of time.

Wooded slopes on old Barrow road near the Derby Arms – Bannisdale Slates

The Silurian Bannisdale Slates are part of a huge mud and silt turbidity sequence. The cliffs, 25m high, formed sea cliffs in glacial times (10,000BP). They are covered by a marine sequence of 30 – 40m. Nearby the road shows the effects of subsidence, probably of the post-glacial deposits.

Bear Boat Bridge – outcrops of Bannisdale capped by yellow crushed and sheared limestone

This is probably the line of one of the large north-north-west – south-south-east trending block boundary faults. At a low angle it downthrows the limestones. A noticeable bump in the road surface represents the unexposed gently dipping Dalton Formation. Between here and the outcrop of Red Hill Formation a small marine clay inlet occupies the lower ground on the dip slope of the Red Hill Limestone Formation.

Cat Crag – Red Hill Formation near southern end of outlier

The remains of a large lime kiln provide a reminder of the widespread quarrying of limestone, leading Dr Burgess to stress that much of the surface seen today in limestone areas has been modified by man. Any easily removed bedding plane outcrops have gone. The field geologist, therefore, has to be very careful that false dips are not being recorded. A further confusion was 'cambering' of limestone escarpments during the Ice Age. Freeze/thaw action, leading to bedding planes being 'lifted', could give apparent dips greater than true dips. The Red Hill Limestone Formation was usually a medium to coarse grainstone representing a high energy environment. The clasts included single plate crinoid ossicles, intraclasts and rounded pellets (originally thought oolitic) and calcareous algae. It frequently has red patches of hematite and associated mineralisation. The foopath northwards follows the strike direction, but there is not the typical limestone dip and scarp topography here. Red Hill Limestone Formation often has a massive appearance with little bedding and few clay partings. Deposited in a high energy environment, it is also generally well bioturbated.

Cat Crag Quarry – Red Hill Limestone Formation

Here, unusually, the Red Hill Limestone Formation has clear bedding surfaces with 25-30° cross bedding. There are subvertical joints, and two crush zones, which allowed hæmatite to percolate into the limestone to produce mineral veins. The origin of the hematite has been debated for many years with theories suggesting a source from below, or above, the Carboniferous limestone. Perhaps the most likely source is warm, iron-rich solutions from the Permo-Triassic red beds. One interesting and surprising feature is the overlying red soils. They are not post glacial deposits, but post mining – say 200 years – and yet they are comparatively thick. The soils doubtless come from loess deposits blown from Morecambe Bay.

Holy Well – junction of Red Hill and Martin Formations

Formerly the site of an old spring, the outcrop is heavily dolomitised, making it hard to distinguish the junction of the Red Hill and the underlying Martin Formation. Normally, they are easy to recognise, but here there was too much dolomite recrystallisation. It appears to be non-conformable, with both calcrete and recrystallisation affecting the top beds of the Martin. This cliff outcrop is again thought to be ancient sea cliffs, perhaps developed only 6000BP. The adjacent marsh is underlain by interglacial marine sediments which obscure the junction of the Martin Limestone and the Bannisdale Slates. It was previously covered by 5-6m of peat, since stripped off.

Halecat Quarry – large Martin Limestone exposure

The Martin Limestone is well bedded and has clearly been extensively quarried for building stone, with its regular bedding making it quite suitable. It was usually a fine grained dolomitic limestone. From his field work and experience of teaching BGS mappers, Dr Burgess emphasised two points. (1) If there is no obvious evidence of a fault, don't assume one; and (2) it is preferable to map a boundary, even if it subsequently had to be changed. With limited time it was vital to retain the prime object: to make a map. In any event, the eventual map scale often prevented [redacted] over the top of the quarry but its junction with the underlying formation is not exposed. The shape of the land determines the boundary by a change in topography. The Martin gives a 'stepped' topography whereas the Red Hill produced 'chunky' dips and scarps. It thickens northwards and attains an overall thickness of 50-60m. In establishing a boundary between these formations confusion can arise, as some beds of the Martin are oolitic-like, giving a superficial resemblance to the overlying Red Hill.

Tennis Court below Old Vicarage Hotel – exposure in lower Dalton Beds

Nearby, the junction of the Red Hill with the overlying Dalton Beds was crossed. While not exposed, it has a clear characteristic feature, easily traced along strike: a small valley formed in the Red Hill, with a scarp slope and gentle dip slope marking the Dalton Beds.

Wooded slopes near St Paul's church – lower Dalton Beds

The lower part of the Dalton Beds is typically exposed as small crags, with small slacks or depressions. Beds are nodular, with shale partings. Higher up the slope the higher beds in the Dalton are more massive, with fewer shale partings, and above these are continuous outcrops of massive beds forming a cliff (3-5m high) representing the upper part of the Dalton. Their exposure reflects not so much their strength, but more the relative weakness and susceptibility to weathering of the underlying beds. The lowermost Dalton Beds are probably cut by several small faults.

Old quarry near base of wood (NE of Key Moss) – Red Hill

Dr Burgess considered the land surface was the dip slope of the top beds of the Red Hill and formed a palæokarst surface before the lower Dalton Beds were

deposited. Again, a pronounced gully, followed by the public footpath, was the surface expression to the base of the Dalton Beds and was likely to have been a shale at one time. Murray Mitchell had earlier found examples of a characteristic fossil from the lower part of the Dalton Beds, the brachiopod *Delepinea carinata*. It is one of the most valuable Dinantian brachiopod species due to its restricted stratigraphic range and its ease of recognition. It only appears in the lower Dalton Beds. Dr Burgess advised against trying to map the Dalton Beds as three distinct units as there weren't any defined lithological features to justify that. After lunch the party ascended the main slopes of Yewbarrow.

Viewpoint amidst the juniper bushes immediately above the Church

The party paused to view the surrounding country, though it was too misty to see much. But on a fine day there are good views of Newton Fell and the Silurian ground in between. In the vicinity of Slate Hill there is a noticeable ridge (often surmounted by trees) across the valley, which had provided a rock barrier to glacier ice or melt water in the last Ice Age. Helton Tarn is remnant of the resultant glacial lake. There is borehole evidence of marine deposits there. To the south of the barrier the surface deposits are intertidal marine, while to the north of the barrier they are essentially estuarine. There was some discussion about the tectonic history of the area, with Dr Burgess thinking there was movement on the major north-south lineament to the west of Newton Fell – the Lindal Fault – with a right curvature pattern, formed at the end of the Lower Palæozoic. Mention was also made of the small (3.0 magnitude) earthquake recorded on this fault in 1993.

Yewbarrow upper slopes and eastern dip slope – Dalton Beds

Exposure becomes more limited and the terrain consists of ridges characteristic of the top of the Dalton Beds. Moving down the eastern dip slopes of Yewbarrow towards Beck Head and into the Witherslack Valley the party was presented with a view of the larger limestone block of Whitbarrow. Dr Burgess pointed out that the prominent humps in the valley were Silurian rocks projecting through a cover of glacial till. The ephemeral spring here runs when it rains and marks a place where the local water-table intersects the ground surface.

Field to east of Town Head to Witherslack Hall road

Dr Burgess pointed out the effects of an east-west fault cutting out the Martin and the Red Hill above Beck Head. These formations were exposed in nearby swallow holes, though they were not examined on this occasion. Garwood was of the view that they onlapped the Silurian country rock, but Dr Burgess thinks the contact is faulted. There was some discussion of the thickness of the Holkerian (Park Limestone), which also suggested later movement in the Lower Palæozoic.

Beck Head permanent stream issuing from Red Hill

There is no evidence of lower Palæozoic rocks. The water is from rain penetrating the Dalton Beds on Whitbarrow which travels down impermeable clay bands and issues here.

Alan Smith, on behalf of both societies, elegantly and wittily thanked Dr Burgess for his trip and the insight into the mapping of such an area which would be particularly valuable for WGS members currently grappling with such a venture.

OTHER EXCURSIONS

The following excursions were also held in 2000 as part of the "Lake District Pioneers" programme.

Sunday May 14th 2000

The Skiddaw Granite north of Threlkeld as seen by *Edgar Shackleton*. Leader: Tom Shipp. The visit followed the excursion in Lakeland Rocks and Landscape, pp101 - 106

Wednesday May 24th 2000

The Mell Fell Conglomerate described by *J F N Green.* Leader: John Rodgers.

Wednesday June 14th 2000

R. Harkness: The Eden valley. Leader: Eric Skipsey. The visit followed the account in Proc. Cumb. Geol. Soc. Vol. 6, Part 2, pp 149 – 163.

EXCURSIONS 2001

As usual, the Society arranged a full programme of field visits for the summer of 2001. However, early in the year it became apparent that the foot and mouth disease outbreak, which was to have serious effects in Cumbria, would severely restrict access to the vast majority of geological sites. The Council of the Society therefore decided to abandon its original plans and produce an emergency programme of evening visits, all led by Society members, mainly to urban areas. These were as follows.

Wednesday May 2nd 2001
A geological walk in Keswick. Leader: Dr Alan Smith
An account of the localities visited can be found in: Smith R. A. and K., The building stones of Keswick, Proc. Cumb. Geol. Soc. Vol.6, Pt2, p.233.

Wednesday May 23rd 2001
Coal Measures rocks from Bransty to Parton. Leader: Mervyn Dodd
An account of the localities visited can be found in an excursion report in Proc. Cumb. Geol. Soc. Vol.6, Pt2, pp273 - 275.

Wednesday June 13th 2001
Quaternary Sediments of St Bees. Leader: David Kelly
Accounts of the localities visited can be found in excursion reports in Proc. Cumb. Geol. Soc. 5 pp476 - 480 and 6 pp82 - 84

Wednesday July 11th 2001
The building stones of Whitehaven. Leader: Margaret Fox
A paper on this topic is published in these Proceedings pp505 – 510.

Wednesday September 5th 2001
The geological collection at Tullie House. Leader: Tony Rigby.

ERUPTIONS OF THE VOLCANIC ISLAND OF MONTSERRAT: MONITORING AND UNDERSTANDING AN EXPLOSIVE VOLCANO

A lecture by Dr Sue Loughlin (British Geological Survey/Montserrat Volcano Observatory)
on 18th October 2000
at Westlakes Science and Technology Park

Montserrat is part of the Lesser Antilles island arc, formed as a result of the Atlantic Plate moving west and being subducted beneath the Caribbean Plate. Water and sediments are also subducted, producing viscous magmas and explosive vulcanicity. The most active volcanoes are in the central part of the arc where the rate of subduction may be greatest; these include those on Montserrat, St Vincent and Martinique. In 1902, eruptions on Martinique and St Vincent resulted in 30,000 deaths; this lead to the establishment of observatories in volcanic areas in various parts of the world such as Japan and Hawaii, to attempt to predict future eruptions.

The island of Montserrat is 16km from north to south and 7km from east to west. The oldest volcanic rocks in the north are 4 million years old; those of the Central Fells area are 2 million years old, whereas the active area is the Soufriere Hills Volcano in the south. The most recent phase of activity began in 1995 and took the 12,000 inhabitants by surprise. It began with earthquakes every 6 – 10 minutes, which were monitored by seismologists from Trinidad. This was followed by the formation of steam vents near the summit. This indicated that magma was rising, causing cracking and heating the groundwater. A cold base surge reached the capital, Plymouth (population 8,000), causing considerable concern. The volcano had a C-shaped crater open to the east and the Tar River valley; fortunately this is a relatively sparsely populated area. However, prevailing easterly winds meant that ash was blown to Plymouth on the west coast.

The next significant event was the development of a lava dome within the crater. Lava reaches the surface at 600^0C, is unable to flow and can form spines up to 70m tall. Successive collapses of the lava dome lead to pyroclast flows. The early flows were channelled down the Tar River valley, destroying plantations. When flows reached the sea they separated into an ash and gas surge cloud on the surface of the water and a base flow on the seabed. By 1996 this had formed a significant delta. At this stage explosive activity occurred, blasting material up to 2km away from the vent and damaging property.

By 1997, growth of the lava dome was presenting much greater danger. The dome was growing by $10m^3s^{-1}$ and was higher than the crater walls. This

meant that collapse of the dome would allow pyroclast flows to escape to the north, threatening villages and farmland. The economy of Plymouth continued to operate in difficult circumstances. Scientists developed risk maps for the island, which required continual updating. Exclusion zones were established and by June 1997 farming was only possible in some parts of the island.

Seismic monitoring stations were established around the volcano, along with GPS pins and tiltmeters. The purpose of this was to monitor growth rates at different locations and to assess risk. Evidence from tiltmeters and seismic monitoring showed that 8 hour cycles of inflation and deflation were occurring. Magma accumulating in the vent released gas, became more viscous and caused a blockage. The increase in magma pressure beneath the block of solid lava caused inflation and earthquakes. Scientists would go onto the mountain during the inflation phase of the cycles to maintain equipment. Release of the blockages resulted in deflation, gas emissions and pyroclast flows. Such an eruption on June 25th 1997 resulted in 19 deaths in the exclusion zone and closure of the airport in September 1997. Some 7km from the crater, the rocks maintained a temperature of 400^{0}C for several months.

Specimens of pale grey andesite contained dark blebs of basalt, which led to the development of a theory of the cause of the eruptions. The magma chamber 7km below the volcano may have suffered an influx of hot basaltic magma, adding heat and volatiles, thus triggering the eruptions.

A series of volcanian explosions produced eruption columns, which lead to pyroclast flows. These were not confined to valleys as were the pyroclast flows caused by dome collapse. These flows produced pumice and lasted for only 2 – 3 minutes. There was no precursor seismic activity.

Increasing risk led to the movement of population to the relatively underdeveloped northern part of the island. The UK Government built some emergency housing and an emergency jetty to allow people to evacuate the island. However, the lava dome continued to grow and ash falls occurred in the north. These were cleared daily and affected solar powered monitoring equipment. Meanwhile Plymouth was severely damaged by ash falls which, uncleared, led to building collapse. Mudflows were triggered by tropical storms eroding previous pyroclast flow deposits.

Emissions of sulphur dioxide were remotely monitored by helicopter. Amounts were not intense but sufficient to cause problems in rainwater collected for drinking. Safe ground water supplies were identified for the new settlements in the north of the island.

In December 1997 earthquake frequency increased to a continuous tremor. This culminated in a major event on December 26th which devastated an area in the southwest including Plymouth and St Patrick. The volcano collapsed under

the weight of the lava dome producing a landslide of yellow, hydrothermally-altered, old volcanics. The dome was then left unsupported and collapsed itself.

The information gathered in Montserrat is relevant to hazard management in other explosive volcanoes. Mount St Helens, Pinatubo and Montserrat are among the most intensively monitored volcanoes in the world, although Montserrat has been monitored over a longer period. As a result of the information gathered, neighbouring Dominica should be better prepared for volcanic events in the future. In the case of Naples, it would be impossible to evacuate a population of 1 million people from a threatened area and the information from Montserrat will help in the development of safe forms of housing.

There is now a permanent observatory on Montserrat. The population is much reduced and the economy is dependent on tourism.

On behalf of the large audience, Dr Jeremy Dearlove of Westlakes Scientific Consulting Ltd. proposed a vote of thanks to Dr Loughlin.

A TALE OF TWO VOLCANOES: MOUNT ST HELENS AND KILAUAE

A lecture by Dr Alan Smith
on Wednesday February 21st 2001
at the Kirkgate Centre, Cockermouth.

The lecture described and illustrated two of the world's largest and most famous volcanoes – brought together simply to draw attention to the contrasts between them.

The significance of 'The Pacific Ring of Fire' formed an introduction to the talk – the circum Pacific Belt containing 75% of the world's approximately 520 active volcanoes. Its relationships to the major plate boundaries was shown. Kilauae, part of Mauna Loa on Hawaii, in the middle of a plate is in a completely different geological location.

Mount St Helens

Part of the chain of the Cascades in the extreme north-east of the USA, the activity at Mount St Helens is related to the activity of the Juan de Fuca and Gorda Plates moving eastwards from a spreading ridge and subducting beneath the westward moving North American Plate. A situation basically similar to the one that created the Borrowdale Volcanic Group rocks in the Lake District. There has been extensive plate margin activity in the Cascades since early Tertiary times. The Miocene flood basalts of the Columbia Plateau were illustrated and the building of the chain of composite volcanoes through the Quaternary explained.

On 18th May 1980 Mt St Helens erupted in a dramatic way – recording by far the largest eruption of any of the Cascade peaks in historic time. It caught the attention of the world. It is one of the best understood and best documented volcanic eruptions ever. The main parameters of the event were explained. Certain aspects were illustrated with slides of the area taken in 1999. The inner blast zones where complete devastation occurred were seen. Channelled blast zones, 'tree-down zones' and seared zones were also illustrated. Aspects of the ash fall were illustrated. The extent and nature of the debris flows generated were perhaps the most widespread features of the landscape to be seen today. The example of Cold Water Lake – completely created overnight by the debris flows damming Coldwater Creek were explained. The present lake (bigger than Crummock Water) was striking. The problems of coping with the mudflow and the debris from the event were seen and the very extensive Sediment Retention Schemes of the Tootle River were explained.

The scale of the eruption however had to be put into context, It generated about 0.3 cubic miles of material – less than several earlier Mt. St Helens eruptions. It was tiny by comparison with the Whorneyside Tuff event in the Borrowdale Volcanics where estimates of 4.16 cubic miles of material have been made. Finally it was even tinier than the Mt Mazama (Crater Lake) event in Oregon to the south, when of the order of 10 cubic miles was produced.

Kilauea, Hawaii

This is part of the world's largest shield volcano – a vast pile of lava nearly 9 kms high built up from the floor of the Pacific Ocean. The summit is 4169m above sea level (13,360 ft). The base of the pile is over 100 kms across. It lies over a stationary 'hot spot' in the lower mantle. The Pacific Plate is moving north-west over this plume – hence vulcanism on the surface has migrated 6000 kms during the last 60 million years. There are a series of sea mounts stretching in a line on the floor of the ocean. In the north-west the first of these to reach above sea level is the island of Midway, then the island of Leysan and then the group of the Hawaiian islands. They range from Palaeocene in age in the north-west to the present in the extreme sout-east tip of Hawaii where Kilauea is sited. The distinct bend in the line of islands and sea mounts is thought to point to a directional change in the movement of the plate in the mid-Tertiary. Gradually the 'hot spot' will move off the present south-east tip of Hawaii where a new mount named Loihi is already building. A series of slides illustrated the topography of several of the main Hawaiian islands - Oahu, Molokai, Lanai and Big Island (Hawaii) itself – demonstrating the younging of the volcanic forms in a south-east direction.

About 99% of Mauna Loa is basaltic in composition, with very few pyroclastics. It is a polygenetic volcano with a very complex plumbing system. Eruption, while not continuous at any one location, tends to be occurring somewhere in the pile. The lavas are highly mobile and of low viscosity.

Consequently the volcano oozes and leaks lava almost continuously. The cone therefore has a complex stratigraphy. Mauna Loa has built in less than 1 million years. Erosion of the pile is insignificant – the shape and topography is controlled by the way the lava is extruded. There are myriads of individual flows. Although there is a central summit crater, most of the lava is erupted from fissures along rift zones on the flanks of the pile. Gravity sliding and slumping of the flanks of the pile constantly displaces material southwards – significant faults running east-west reach deep into the cone and make significant scarp features in the present landscape. The huge pile also sinks into the mantle as the weight accumulates. A range of photographs from a visit in 2000 illustrated different lava flows and different forms of aa and pahoehoe flows. The position of the current flows into the sea near Kalapana were seen. The effects of lava engulfing trees and the formation of 'lava trees' was also discussed.

LIMESTONE PAVEMENTS IN CUMBRIA – THEIR ORIGIN AND CONSERVATION

A lecture by Simon Webb (English Nature)
on March 7th 2001
at Tullie House Museum and Art Gallery, Carlisle

This was a well attended joint meeting with the Carlisle Natural History Society, a talk profusely illustrated by excellent slides. Mr Webb began by explaining the sequence of events which led to limestone pavements being confined to approximately 3000ha in the North of England, with small areas in parts of North Wales and Scotland. The sequence began with reef conditions in the Lower Carboniferous punctuated by episodes of emergence and land erosion. The thick, hard limestones represented stable conditions, the intervening shales and sandstones rapid change. The Ice Age was the next significant episode, especially glacial deposition in the last major ice advance, the absence of limestone pavements from the Peak District being because it was not affected by this last event. Soils developed early in our present interglacial. The "Wildwood" grew on these soils, as a climatic climax system. Organic acids from this vegetation attacked weaknesses (usually joints) under the soil in the limestone. Human occupation with sheep grazing led to soil erosion and the exposure of the pavements.

Minor surface features were forming actively today on the limestone pavements. Small hollows shaped like drill shafts were probably where trees had grown. The pattern of active surface runnels depended on the dip of the limestone. Near horizontal rock showed centripetal patterns running into surface depressions, steeply inclined rock parallel "rakes" of runnels with dendritic patterns where dips were moderate. The MoD range at Warcop had dramatically folded lines of pavements.

Plants growing in the sheltered micro-climates of the grikes were in many cases survivals of the Wildwood, examples including dog's mercury and primulas with their rather poor dispersal mechanisms. Ash and hazel were the dominant trees with some sycamore and the shrubbier yew and juniper. Ferns include the rustyback and various buckler and male ferns. Showy flowering plants like bloody cranesbill and shrubby cinquefoil brought colour to the rather grey landscapes. Many plants were specifically adapted to limestone conditions, like the limestone bedstraw, and others were at the northern end of plants of predominantly southern distribution like spindle.

Limestone pavements were at risk from demand for garden rockeries. In England the Limestone Pavement Protection Orders had reduced removal to smaller, more informal quarrying. Sadly the break up of limestone pavement into rockery size blocks destroyed the fragile ecosystem of the grikes beyond any possible reinstatement. It had been difficult to get firm evidence to justify prosecutions and the one successful case had only been followed by a derisory fine. The problem of excessive removal had been transferred to Eire, now exporting 10,000 tonnes pa to the UK. The only effective protection in the Burren was in the designated European SAC area. There were no planning controls on quarries of less than 5ha and limestone pavements outside the Burren in Eire had no statutory protection.

Mr Webb advised those present not to buy rockery limestone that appeared to come from pavements. One hope for the future was that large aggregate and quarrying companies would be very happy to supply quarry waste (very profitably) to garden centres which would be equally suited to rockery use without damaging limestone pavements. Better management of stock raising on the pavements usually required reducing the number of sheep grazing, which would allow more luxuriant plant growth to spill out from the grikes onto the clints. Some wooded pavements were improved by felling some of the trees and scrub to allow more light to reach the pavement floor. After answering many questions – which showed how successful his talk had been, Mr Webb ended by encouraging those present to visit and enjoy the limestone pavements and asking them jealously to guard this part of our precious natural heritage.

OTHER LECTURES 2000 – 2001

September 27th 2000, Kirkgate Centre, Cockermouth
An introduction to gems and gemmology. John Harris

November 15th 2000, Queen Elizabeth Grammar School, Penrith
Putting tectonics into plate tectonics. Dr Andrew Bell (Open University)

December 6th 2000, Friends' Meeting House, Keswick
Members' night

January 24th 2001, Kirkgate Centre, Cockermouth
Isle of Skye – the last geological chapter. Dr Will Williams

DRY STONE WALLS

A lecture by Dr Eric Robinson (Geologists' Association)
on September 26th 2001
at Newton Rigg College, Penrith

Dr Robinson began his talk by pointing out that the wall pattern seen on aerial photographs was an essential features of the English landscape, not seen in areas such as the steppes. Northern England in particular has more walls than hedges. The walls reflect the local geology as stone was not carried far by farmers for fencing material. Many of the original quarries have disappeared and the walls retain local fossils of significance.

Dr Robinson then elaborated on this theme using a vast array of slides. In the Skipton area and in Derbyshire, the walls running up and down hill change to reflect the different levels within the Carboniferous limestone; stone often being carried downhill but rarely up. In the Craven area Palaeozoic slates are used with rounded blocks of white limestone from the river. In Dentdale benched hillsides of the Yoredale Series have buildings with limestone walls and sandstone roof slabs; sandstone is preferred for field walls as it is more easily shaped. In upper Swaledale the green lanes have walls of white Great Scar Limestone and, at the top of the valley at Tan Hill, there is more use of sandstone with through stones for stability. Although Hadrian's Wall is stands on the Whin Sill, the Romans used dressed sandstones from the Yoredales to the north and south of the wall for facing. The wall is filled with Whin Sill rubble puddled with clay. Much of the dressed stone has been robbed for wall building material. At the Roman outpost of Bewcastle, sandstone from the Cementstone Series is dressed for gravestones.

In many areas local design features are evident. In the sandstone country around Bellingham slabs are crudely dressed with long slabs within the wall. Some of these techniques were brought in by the Irish walling teams. Blackster Quarry produced good quality stone, some of which is used in local walls. The massive sandstone is used for freestone, slabs for field walls and flags for roofing. In the Windermere Group country of south Cumbria, building walls are stuccoed but the field walls are left bare revealing the local stone. Walls of the Eden Valley demonstrate a wide variety of materials, including rubble from the boulder clay, although lintels etc are usually from Penrith Sandstone.

Slides of wall materials and walling techniques from further afield were shown. In Kirkudbright rounded granite boulders from the beach are set in clay. At Cleeve Common in Gloucestershire flat tablets of oolite produce a distinctive effect. At Purbeck in Dorset the flaggy rocks are stacked like a pack of cards.

Some of these distinctive features are in need of conservation. In Derbyshire the walls show the pattern of the original strip enclosures. Peak District National Park planning restrictions demand that local stone is used for repairs, destroying the field pattern. New buildings at St Fagan's, west of Cardiff, demonstrate the vernacular architecture of various parts of Wales but unfortunately not the walls.

In conclusion Dr Robinson noted that walls are an essential feature of the landscape which is at peril. In a similar way to which he issued a similar challenge on building stones a few years ago, he challenged groups such as the Cumberland Geological Society to record information on stone walls. Wall materials and styles can be recorded on 1:25,000 maps, producing information which is relevant to planners and to our heritage.

VOLCANIC ERUPTIONS UNDER ICELAND'S GLACIERS

A lecture by Hugh Tuffen (University of Lancaster)
on October 31st 2001
at Tullie House Museum and Art Gallery, Carlisle

Mr Tuffen's talk was based on recent fieldwork on subglacially erupted rhyolitic volcanoes in Iceland, part of the research towards his Ph.D. at the University of Lancaster. The fieldwork involved traditional geological mapping and sampling of volcanoes emplaced during the last glacial period at Torfajökull, southern Iceland, together with mathematical modelling of the processes of melting and ice deformation during eruptions.

Subglacial eruptions can trigger extremely rapid melting of ice (the 1998 eruption of Grímsvötn in Iceland melted through a glacier 150m in only 10 minutes). The meltwater formed during eruptions can be released in a catastrophic flood (jökulhlaup), especially if a meltwater lake accumulates at the eruption site. For a few hours, a normally gentle stream at the snout of a glacier is transformed into a torrent of Amazonian proportions, which can destroy all in its path – as was witnessed during the dramatic flood in southern Iceland in November 1996.

Explosive eruptions are another hazard posed by ice-covered volcanoes, as rising magma interacts with meltwater. This can generate plumes of ash and steam many miles high. Curiously, lava flows can sometimes disappear down crevasses and flow beneath the glacier, as was observed during the 1972 eruption of Villarrica, Chile. Although dramatic and destructive subglacial eruptions have been observed in Iceland and elsewhere during the twentieth century, these are miniscule compared to those that occurred in Iceland during

the last glacial period (roughly 115-10 thousand years age). These much larger eruptions were of both basaltic and rhyolitic magma.

Basaltic subglacial volcanoes are relatively common in Iceland and their eruption mechanisms are reasonably well understood. Many appear to be formed within subglacial meltwater lakes where pillow lavas and hyaloclastites form, followed by melting to the surface with subaerial eruptions producing alternating ash and lava layers.

Subglacial rhyolitic eruptions are far less common and are little understood. Approximately 10% of Iceland's subglacial eruptions were of this highly viscous magma type. Mr Tuffen's research has focussed on ancient, subglacially-erupted rhyolitic volcanoes at Torfajökull, a volcanic complex measuring some 18 by 12 km in southern Iceland. Detailed field studies of the deposits formed during subglacial eruptions have yielded new information about the explosivity and hazards of ice-covered rhyolitic volcanoes. Two types of subglacial rhyolitic volcanoes have been identified at Torfajökull, both of which were erupted beneath glaciers about 500 metres thick. Bláhnúkur is an example of a small-volume volcano formed during gentle, effusive eruption that failed to pierce the ice surface. Rauðufossafjöll is an order of magnitude larger, and formed during a more explosive eruption that pierced the ice surface and formed a flat-topped 'tuya', or table mountain.

The eruption of Bláhnúkur, the smaller type, appears to have followed a four stage sequence. Initially, sediments were deposited in channels cut into the bedrock by flowing meltwater that was draining away from the eruption site. Lava lobes formed next, these are pillow-like bodies of lava typically 5 m across, set in breccias. Many lava lobes have distinctive patterns of columnar joints that are best explained by chilling of the lava within ice caves melted into the glacier base. Ice caves may have formed ahead of the rising bodies of lava, and acted as moulds once the lava reached the glacier base. Pipes cutting through the breccia are interpreted as fossilised steam jets that efficiently transferred heat from the lava to the overlying ice.

Mr Tuffen's model for the formation of ice caves predicted that cave sizes depended strongly on pressure (i.e. the thickness of the overlying ice) but weakly on the size of the rising lava body. 'Reasonable' sized ice caves were thought to form when the roof of ice was 200–400m thick – an ice thickness that corresponds well with estimates based on the overall stratigraphy of the deposits. He suggests that the sizes of ice caves may reach an equilibrium – at which the rates of enlargement by melting and closure by ice deformation are perfectly balance. Ice caves melted by fumaroles within the summit crater of Mount Rainier in Washington State, USA also seemed to fit the model.

The third stage in the smaller eruptions occurred when ice walls melted while the lava was still hot. This destablilised the lavas, and hot avalanches cascaded down the volcano flanks. The fourth and final stage was marked by

much larger lava flows. The organisation of columnar jointing within the lavas indicates that the ice caves were now 20 metres high. It was probably the enlargement of the ice caves that led to this new style of eruption – and the ice-moulded lava flows are similar to those formed during the 1972 eruption of Villarrica.

The larger eruptions formed distinctive flat topped tuyas up to 500m high. The base of tuyas are made up of very fine grained ash, attributed to explosive subglacial eruptions within an enormous ice cave. Inspection of the ash particles under an electron microscope reveals that the explosions were triggered by interaction between magma and meltwater. The explosive eruption may have continued once the ice roof was pierced, forming a plume of ash and steam. However, there is not evidence preserved at the volcano itself, as any ash would have settled onto the surface of the adjacent glaciers that have since disappeared. There may be thin layers of ash in Greenland, Scotland and elsewhere that were formed by this and other similar eruptions in Iceland and these will be studied in the future. The flat top of the volcano comprises subaerial lava flows up to 150m thick. These were formed once the surface of the ice had been pierced. The final phase was of ice confined lava flows with peperitic lavas and sills forming within ice caves washed by ashy meltwater.

Mr Tuffen had found models of energy exchange mechanisms difficult to develop, as there were so many variables involved. Therefore numerical models were nonlinear and complex. As so often, research had answered some questions but generated several new queries. Some generalisations were possible, particularly the close relation between high rates of eruption and the production of ash. His models showed that the effects of horizontal ice deformation on subglacial eruptions may be important, as flow of ice into the eruption site could maintain a thick roof of ice above the volcano and delay the onset of a subaerial eruption.

This lecture was a real *tour de force*, delighting his large and appreciative audience, and Mr Tuffen was delighted to speak to familiar faces, including his physics teachers from Cockermouth School!

RIVERS, LANDFORMS AND MAN – A SYSTEM IN EQUILIBRIUM?

A lecture by Dr Steve Bradley (Westlakes Research Institute)
on November 14th 2001
at Westlakes Science Park, Moor Row, Whitehaven

Dr Bradley began his lecture by reminding us 'we knew all about rivers!', sinuous or meandering, gravelly or braided and many of us were aware of stream orders. Why rivers differed was not such common knowledge.

Process studies had to begin with data collection, particularly of rainfall, discharge and sediment movement. Modern rainfall gauging stations with their sophisticated equipment (samples of which were on display in the lecture room) could now measure the duration and intensity of rainfall as well as the traditionally quoted day's rainfall. Flood discharge levels, all important in river studies, could be measured on the ground. Debris marks near river banks and flood level lines on buildings, graphically illustrated on a wall near Worcester Cathedral, were common methods. As with the documentary evidence available these measures had to be interpreted critically.

The national network of hydrological gauging stations was the main source of discharge data. West Cumbria had about 20 of these stations and slides of the Braystones station illustrated the principles followed and some of the equipment in use, engineered sections, wells with recording gauges, all now electronically controlled to allow measurement at regular intervals. Cableways carrying instruments were used to measure flood velocities on the rivers above which they were suspended. Again examples of the equipment in use, particularly a current meter, were on display. The Jackmoor (tributary to the River Exe in South Devon) gauging station had the longest continuous records of flow, suspended and dissolved sediment loads. Its records were a reference often consulted.

Data on sediment transfer was much more limited. Methods of measurement were still being developed. The only information at present available about sediment transfer from upland catchments thought to be overstocked was from erosion pin studies on nearby river banks. Small pieces of Astroturf made excellent and cheap sediment traps to measure movement on flood plains and to allow suggestions of likely provenance. (The public were all too happy to recycle large pieces as doormats!). An interesting observation of Dr Bradley's was that sediments in West Cumbrian rivers were often organic rather that clastic.

Dr Bradley then described an interesting example of efficient mediaeval engineering practice from a tin mining area in the River North Teign catchment on Dartmoor, South Devon. These were parallel ridges and troughs, where the troughs had very similar width/depth ratios and stream power ratios between 80-250 Wm-2. Sediments in the troughs had remarkably low tin contents. This was a particularly good example of what could inferred from sediments. Often, though, it was necessary to compare a site where data had been collected with well authenticated worked examples or 'type sections' to help identify and explain the features.

To manage a river, comparisons had to be made between present day and past events. Sediment sources had to be identified. A wide variety of tracers were now available to help locate sources. These included the sediments' mineral content, colour and magnetic properties and more recently

radionucleides. Caesium-137 with its short half life of 30 years was very useful as it attached strongly to soil and was easily measured, even in very small concentrations. It had contrasting distribution profiles, allowing the clear identification of pasture, ploughland, areas of erosion and of deposition. This illustrates the value of new technology in understanding sediment movement and allowing appropriate modelling to simulate reality.

Dr Bradley answered several questions. The following observations are a selection of some of his answers. Pollution of public water supplies by lead and other heavy metals was much less in normal river flow than during flood events when pollutants in flood plain sediments were mobilised. The national network of hydrological gauging stations was too coarse to describe and measure localised flash flooding. He felt that, all too often still, the professionals involved, the Environment Agency, town planners and water engineers, could work more closely together in flood prevention etc.

Much has yet to be learnt about how farming practices in the UK affect soil erosion. This was but one aspect of Dr Bradley's general statement that the impact of man of riverine environments was only partially understood.

MAM TOR

A lecture by Christine Arkwright (Open University)
on December 5th 2001
at the Friends' Meeting House, Keswick

The speaker first outlined the main aspects of the geology and landscape features of the Edale and Castleton areas of the Northern Peak District. The emphasis of the lecture, however, was on the Mam Tor area and in particular her work on monitoring the landslide activity of the area. The deeply dissected area of the south Pennines where massive beds of sandstone form scarp features, but rest on less competent shales and mudstones which are prone to undercutting, produces unstable slope forms. Many rockslides and slumps have developed into long-term episodically creeping earth flows. The Mam Tor slide has been known for many years and, ever since the Manchester to Sheffield road was built across it in 1810, it has been a constant source of highway problems. Repairs on the road ceased in 1977 and the road abandoned.

As an M.Sc. project the speaker set up a measuring network on the slide in 1996, which has enabled some long term monitoring to take place. Annual re-surveying of installed markers on the slide is beginning to reveal a picture of movements and activity in the slipped mass (Figures 1 and 2).

Minor movements in an easterly direction was detected on 7 points after the first re-survey in 1997. In 1998, 21 points were judged to have moved, but again

in a minor way. However, after the 1999 survey it was clear that slippage was up to six times that recorded in the two previous years. Furthermore, this major movement occurred in most parts of the disturbed material, suggesting that the main basal slip plane may have been reactivated. The greatest movement was in the transition zone across the middle of the landslide where the ground surface is steeper than in other parts of the network and is consequently less stable. In contrast, the earthflow section below the lower road has a more gentle gradient which is nearer stability and so points in this area have not moved very far. Some *en echelon* cracking of the road surface indicates that the movement appears to be more rapid in the northern part. All these observations imply progressive steepening of the central transition zone which will in due course provide increased driving stress on the earthflow section at the bottom of the landslide.

Results correspond well with the pattern of movement observed during the 1980's. It was then noted that a high winter water table accentuated by heavy rainfall in January to March constituted ideal conditions for movement, since the higher pore water pressure weakened the rocks below the water table. Rainfall data for the period 1996 to 2000, together with the movement reported above clearly substantiate the hypothesis.

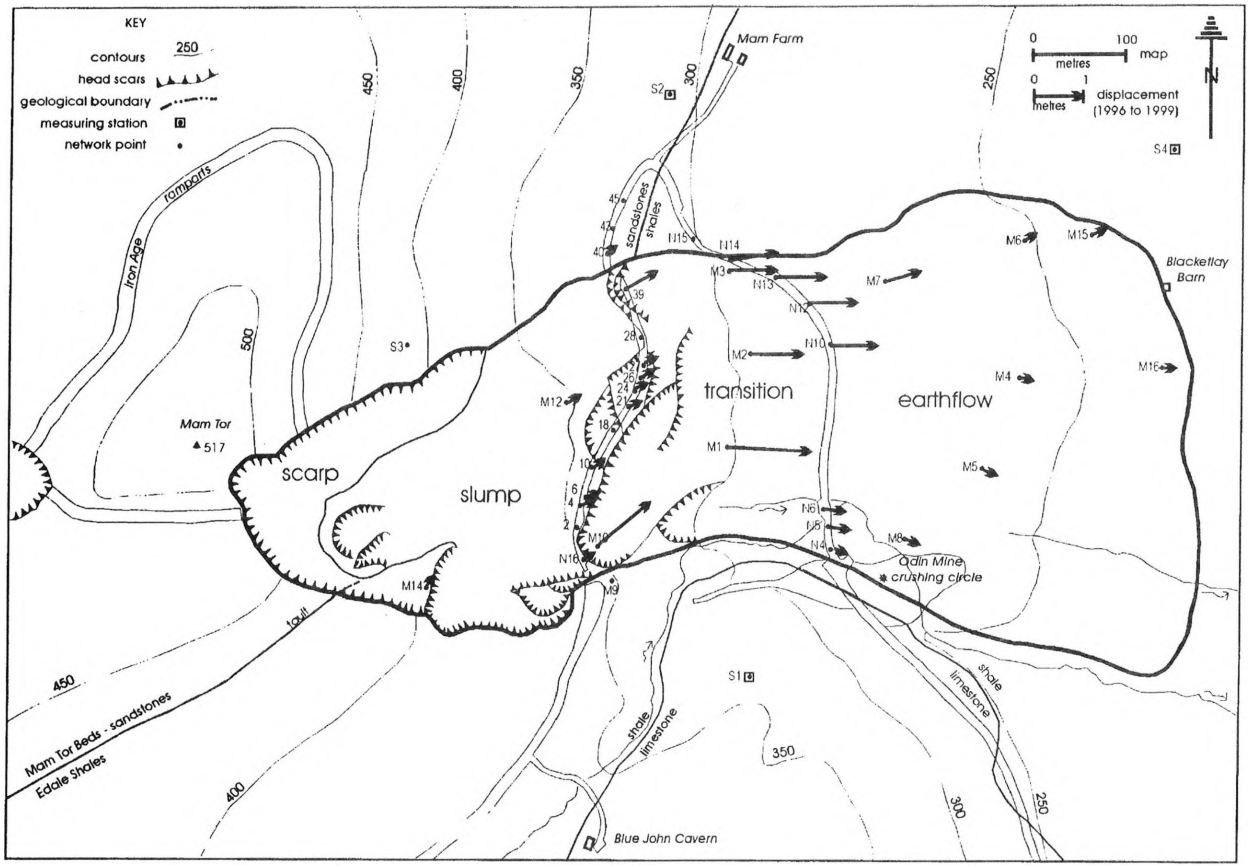


Figure 1 – The Mam Tor monitoring network

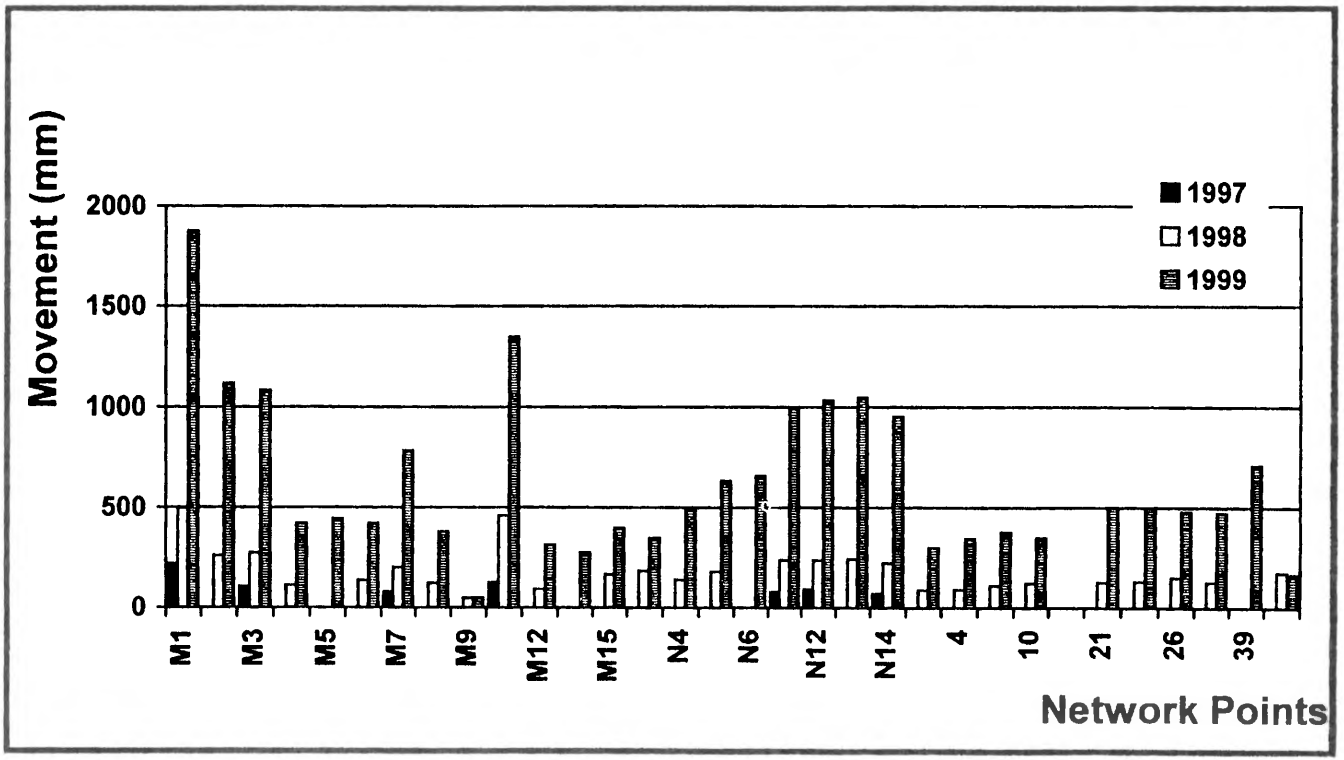


Figure 2 – Movement with respect to 1996 datum readings

THE ICE AGE IN LAKELAND

Presidential Address given by Dr Alan Smith, President of the Cumberland Geological Society
on January 16th 2002
at the Kirkgate Centre, Cockermouth

Dr Smith began by stressing the three recurring themes of his address. Firstly, that there was not a single Pleistocene ice age. Secondly that the Lake District is a difficult area in which to work, where there is little direct evidence of the recent geological past, particularly in terms of dateable material. Much of our knowledge is indirect, coming from lowland Britain, the surrounding sea bed and Arctic regions of the world. The evidence is fragmentary due to the destructive effects of successive glaciations and we only see clear evidence of the more recent events. Thirdly, the landscape is the product of long periods of climatic change.

Dr Smith used a series of graphs to demonstrate climatic oscillations since the start of the Pleistocene 2.4 million years ago. The warm temperatures of the Tertiary were succeeded by much colder conditions. A progressive cooling took place during the Pleistocene, where the cold phases get colder and the warm phases get shorter, culminating in today's warm phase. How these temperature changes affected the absence and presence of ice in the Lake District is not certain. At less than 1000m of altitude and 55^0N latitude, the area would be on the margins of glaciation. Dr Smith concentrated on the evidence in the Lake District for the last two cold phases.

In the Wolstonian, the last but one major cold phase, up to 129,000 years before present, there was ice over much of the British Isles but evidence in the Lake District comes from just a few sites. In the floor of Mosedale, south of Threlkeld, the lower of two tills is from this phase. In Scandale Beck near Crosby Ravensworth, peat beds no longer exposed have been dated to the Ipswichian Intergacial which followed. The Nirex drilling project in west Cumbria also found beds of this age.

The last major cold phase, the Devensian began about 120,000 years ago. It began with a very cold phase, dominated by continental high pressure, with low sea levels. Was there enough precipitation in the Lake District to produce ice? In the late Devensian there definitely was glaciation. Maritime climatic influences produced heavy snowfall and ice accumulation. This began 33,000 years ago, reached a maximum 18,000 years ago and was gone by 13,000 years ago. After a warmer phase, the Windermere Interstadial, there was a short reappearance of cold conditions in the Loch Lomond Stadial 11,000 years ago – 10,000 years ago. The extent of the glaciation is debatable. Analysis by Boulton suggested that the whole of the Lake District was inundated with the summits covered by 600m of ice which moved outwards. The ice took 15,000 years to build up and 5,000 years to melt so the time available for erosion was

limited and, Dr Smith suggested, possibly overestimated. It could be that a series of short phases of erosion occurred at various time during the Pleistocene. During very cold phases erosion may not have been possible.

The contrast between the mountain tops of the eastern and western districts was noted. In the east, e.g. Helvellyn and High Street, there is no evidence if ice erosion and earlier workers thought that these summits were high level planation surfaces. In the west of the district, ice scoured summits resemble the knock and lochan scenery of parts of Scotland. This is further complicated because the rocks of the Skiddaw Group show the effects of ice scour in a different way to other rocks. In the late 1990s Lamb and Ballantyne described evidence suggesting that ice did not completely cover the district and the high peaks such as Scafell and Great Gable stood out as nunataks. Trim lines below these summits may indicate the upper limits of glacial erosion, above which frost shattered block fields show much greater depths of open joints than do the surrounding areas. The summits also show soil samples with a different clay mineral content than lower areas.

A different view has been presented by McDougall, who has suggested that in the Loch Lomond Stadial, summits in the Ullscarf and Great Gable areas may have been the sites of plateau icefields. It is suggested that these glaciers were inactive and that evidence for their progressive retreat back to the plateau includes moraines at low levels such as those at Rosthwaite.

Dr Smith then pointed out that the main valleys must have contained substantial glaciers but posed the question of how many phases of glaciation would be needed to erode the valleys. Like the summits, the valleys show a west – east contrast. The western lake basins are lower, e.g. Wasdale 61m below sea level, and do not contain islands. However in the east, Ullswater is 240m and Haweswater 210m above sea level, suggesting a climatic difference. The Lake District does not have a great amplitude of relief and the troughs are not classical features on the same scale as those in the Alps.

The corries are mostly north-east facing, indicating the most favourable conditions for ice accumulation and survival. They are much higher in the east of the district. The corries have been documented in detail and many are complex features formed by more than one period of glaciation.

Dr Smith concluded his talk by referring to other questions still to be answered. At Farleton Fell near Heversham there is an ice-eroded pavement in the Carboniferous limestone with glacial erratics. How much erosion has occurred here? The drumlins next to the M6 motorway at Crooklands relate to Devensian ice from the Lake District, but at which stage? Ice has moved both up and down the Eden Valley, but exactly when?

The speaker was thanked by Mervyn Dodd for providing a comprehensive summary of the current state of our knowledge of the Ice Age in Lake District, illustrated by a variety of dramatic colour slides.

A GEOLOGIST IN THE ANDES OF ECUADOR

A lecture by Dr Richard Hughes (BGS)
on March 20th 2002
at Newton Rigg College, Penrith

Dr Hughes' talk described the work done by the British Geological Survey in Ecuador between 1995 and 1998. The central themes of the lecture were the geological setting of Ecuador and the Andes, the geodynamic evolution of the western cordillera of the northern Andes and the reasons for the work of the British Geological Survey outside the UK.

The BGS works in many continents, especially in developing countries, producing an income of £5 million per year. The work underpins effective infrastructure development such as dams and roads. It also aids sustainable economic development, helping countries to attract external investors and therefore to raise tax revenue. Work on the predication and mitigation of geohazards is also significant, especially in the context of global climatic change. Much work has been done on regional geological, geochemical and geophysical surveys, however this is diminishing as donor agencies favour more closely-focussed projects. Recent work has covered geohazards, groundwater, geotechnics and remote sensing.

In Ecuador the minerals sector has been underdeveloped compared with those of neighbouring Peru and Chile. Up to the early 1990s there was a lack of modern geoscience information about the area and a lack of local geoscience expertise. Artesanal mining for gold had led to environmental problems of mercury and arsenic pollution. Solutions to these problems have included building up modern geological and geochemical datasets to attract external investors, developing modern mining laws, developing highly-trained local geoscientists and developing cleaner mining technologists. Dr Hughes noted that modern, more benign gold mining involves processing with water only. The UK Government entered a partnership with the Swedish Government and the Ecuador Government known as the *Mining development and environmental control project.* This has involved mapping the Cordillera Occidental in its entirety.

The geodynamic evolution of Ecuador is complex as it involves two triple plate margins where the Chile Ridge and the Galapogos Ridge have converged with the Andean coast. This has resulted in several distinct geological provinces. The central Andean chain comprises two parallel ridges in the north:

the Cordillera Real in the east has Jurassic crystalline rocks, and the Cordillera Occidental which has Cretaceous and Tertiary sediments and plutons. The chains are separated by the inter-Andean graben. This is an earthquake zone with active faults on both sides; Quito, the capital, lies in the graben on its western edge. East of the Andes is the Amazon Basin with its Cretaceous and Tertiary sediments and oil reservoirs. West of the Andes, the forested Costa area is a Cretaceous and Tertiary foreland basin sequence resting on lower Cretaceous basement. The Galapogos Islands, 600-700km offshore, have active basaltic volcanoes over and oceanic hot spot.

The work of the BGS has been mainly in the Cordillera Occidental where the ground rises from 250m above sea level in the west to 5000m above sea level in the east, in a horizontal distance of just 40km. The area has been subjected to particularly rapid rates of uplift which has given rise to deeply-incised valleys in the dense, tropical, montane forest. The highest ground is more sparsely vegetated with tussock grass. The work of the BGS has identified two terranes, the younger in the west and the older in the east, separated by a shear zone, with a complex accretionary history. The eastern terrane includes mid to late Cretaceous turbidites and oceanic plateau basalts which can be up to 70km thick. The western terrane is an Eocene and Palaeocene island arc, with volcaniclastic sediments, low-potassium tholeiites and VMS (sulphide) mineralisation. The Toachi Shear Zone between the two terranes shows clear, dextral movement, hosts gold mineralisation and influences the distribution of modern volcanism. Like the rest of the northern Andes, the area has experiences two accretionary events. The first at the end of the Cretaceous, where the thick, buoyant, plateau basalts resisted subduction and were accreted/obducted, and the second in the late Eocene.

Dr Hughes concluded his lecture by referring to the significant geohazards of the area. The inter-Andean graben is an important earthquake zone. The area has unconsolidated pyroclast flows which pose a high risk in areas of dense population. There are several volcanic centres. Cotapaxi erupted in 1887 and is due a major eruption. Mudflows could reach 300km to the coast and a Plinian column could affect the city of Quito which is close by.

After many questions from the floor, Dr Hughes was warmly thanked by Ken Bond, past president of the Society, who spent eight years working in petroleum exploration in Ecuador.

ANNUAL GENERAL MEETINGS

THE 38TH ANNUAL GENERAL MEETING of the Society was held at Cockermouth School on Wednesday February 24th 1999. The President, Mervyn Dodd, took the chair and there were 25 members present. Good attendances were reported at both lectures and field meetings, the latter despite some very wet weather. Written reports on Society activities during 1998-99 were presented to members and approved. All formal business was completed by 7.23pm.

Following the meeting there was a lecture, delivered by Mr Chris Thompson, entitled *"On geophysical logging techniques. A geological perspective with examples from west Cumbria".*

THE 39TH ANNUAL GENERAL MEETING of the Society was held at the Kirkgate Centre, Cockermouth on Wednesday February 23rd 2000. The President, Dennis Dickins, took the chair and there were 23 members present. Written reports on Society activities during 1999-2000 were tabled and approved by members present. All formal business was completed by 7.19pm.

Following the meeting there were a series of geological presentations by members of the Society.

THE 40TH ANNUAL GENERAL MEETING of the Society was held at the Kirkgate Centre, Cockermouth on Wednesday February 21st 2001. The President, Dennis Dickins, took the chair and there were 30 members present. Written reports on Society activities during 2000-2001 were tabled and approved by members present. All formal business was completed by 7.25pm.

Following the meeting the incoming President, Dr R. A. Smith, spoke on *"A tale of two volcanoes, Mount St Helens and Kilauea".*

THE 31ST ANNUAL GENERAL MEETING of the Society was held at the Kirkgate Centre, Cockermouth on Wednesday February 27TH 2002. The President, Alan Smith, took the chair and there were 23 members present. Written reports on Society activities during 2001-2002 were tabled and approved by members present. The Society's new publication *The Rock Men – pioneers of Lakeland geology* is selling well. All formal business was completed by 7.25pm.

Following the meeting there were a series of geological presentations by members of the Society.

ANNUAL DINNERS

1999

The Annual Dinner was once again held at the Swan Hotel, Thornthwaite near Keswick on Saturday March 20th. 40 members and guests enjoyed a good evening of food and fellowship. We were particularly pleased to present the Charles Edmonds Prize for 1999 to Dr Dick Clark for his contributions to the geomorphology of Cumbria. Dick has written several papers for our Proceedings, lectured to the Society on a number of occasions and been a member of Council. Additionally he has contributed much on the geomorphology of the district through other journals and societies. Dick was joined by his wife Liz as guests of the Society on this evening and was presented with a series of geological maps for his award. We were also pleased to welcome Dr Brian Irving and his wife. Brian heads the Solway Rural Initiative Project, but spoke on the evening on his geological work under the title of 'From Umbria to Cumbria, by river'.

2000

On April 1st 2000 another full attendance at the Annual Dinner at the Swan Hotel, Thornthwaite enjoyed a pleasant evening. Our guest speaker was local architect David Grech from Kirkland who gave a fascinating talk 'From Head to Head'. This was a long distance walk across the geological grain of England from Beachy Head to St Bees looking particularly at the contrasting architectural styles and the use of different geological materials in the buildings. It was illustrated by some of David's excellent watercolours which featured in his new book, which a great number of members found irresistible souvenir of the evening.

2001

The popularity of the Annual Dinner has become well established with a record attendance of 46 members once again at the Swan Hotel, Thornthwaite on March 31st. The food and arrangements all went perfectly to plan and a good evening was enjoyed by all. Our Guest Speaker was Andrew Williamson who gave us a short but interesting talk on his work as a land agent in Cumbria.

2002

Another full house, once again at the Swan Hotel, Thornthwaite rounded off our winter season on March 23rd. We were pleased to make an award of the Charles Edmonds Prize once again, this time to Dr Audrey Brown for her work in Cumbria with the Open University, Cumbria Rigs and the Westmorland Geological Society. A presentation of books was made to Audrey, who was accompanied by her husband Chris. Eric Skipsey presented the citation for the Award on behalf of the Society, paying particular reference to her work for Rigs and the OU. Our Guest speaker was Alan Diggles from the Open University Geological Society who entertained members with his amusing and well illustrated talk with numerous visual aids on 'Association of Madiera'.

THE SOCIETY SMALL AWARDS FOR STUDENTS

The Cumberland Geological Society Small Awards for Students Fund was established in 2002 primarily to assist students who have limited funds, to undertake geological fieldwork. Preference will be given to students who have Cumbrian connections. Applicants will be required to outline their research and indicate how this funding will assist their project. Applications will be judged by a sub-committee of the Society.

Successful applicants will be required to deliver a presentation of their work to the Society.

The sum of money donated will be at the discretion of the Society and will be no more than £200.

Those who may be interested in applying for an award should, in the first instance, contact the General Secretary:

Dennis Dickins
[redacted]

More details and an application form will be provided.

Printed by
imprint
Stationery and Print
8 High Street, Cleator Moor, Cumbria CA25 5AH
Tel/Fax. 01946 810110