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Setting the scene: the geological framework and history of Northumbria

Paul F V Williams, Staff Tutor in Earth Science, The Open University in the North

The ancient kingdom of Northumbria stretches from Berwick in the north, westwards to the Pennine watershed on the Cumbrian border, and south to the Tees. Geographically it contains the high Pennines in the west, the Simonside and Cheviot Hills to the north-west, the Northumberland and Durham coastal plains to the east, and the Tees basin to the south. The purpose of this paper is to present an overview of the geological structure and history of this ancient kingdom. Those wishing a more detailed insight are referred to the significant reference work, "Robson's Geology of Northeast England" (Johnson 1995), while guides to localities can be found in "Northumbria Rocks and Landscape"(Scrutton 1995). The geological history of Northern England is also covered in "The Geological History of the British Isles" (Hunter 2001) the text to accompany the Open University second level geology residential school course SXR260. The reader is also directed to two other papers relating to the underlying geological controls that established the tectonic framework of the area (Leggett *et al.* 1979; Leeder 1982).

Within the boundaries of Northumbria the rock record shows a folded Lower Palaeozoic basement overlain by a cover of ORS, Carboniferous, and Permo-Triassic sediments. Into this sedimentary pile Devonian and Lower Carboniferous intrusive and extrusive igneous rocks have been introduced, together with a later phase of minor intrusives of Permo-Carboniferous age, and also some Tertiary intrusives. Finally the whole has been sculpted and draped by glacial activity in the Quaternary.

Remnants of the Lower Palaeozoic basement can be seen to the north in an area west of the Cheviot Hills, the Cheviots themselves being the remains of an igneous complex of Lower Old Red Sandstone age. However, it is Carboniferous rocks that dominate Northumbria at outcrop, the gentle easterly tilt bringing progressively younger Carboniferous horizons to the surface coastwards. From an arcuate outcrop around the Cheviots to the north, the Lower Carboniferous rocks, striking NNE-SSW, form the extensive high ground of the Pennine fells in the west of the area. Upper Carboniferous rocks, with contiguous strike, occupy the lower lying Northumberland coastal plain and the site of the former Northumberland and Durham Coalfield. The south-eastern part of the region, from the Durham coast south to the Tees basin is underlain by Permian rocks, with a roughly N/S strike. The lowest horizons form a prominent escarpment to the east of Durham City. Early Permian igneous intrusives also occur in Northumbria, the Whin Sill being the biggest, both in terms of lateral extent and magma volume. It stretches from the high Pennine fells in the south-west of the area, through west Northumberland, to the coast south of Berwick in the north-east of the region, and is a major topographic feature. Dykes of the same age are also found, generally trending NE-SW, and are best recognised where they transect the Northumberland and Durham Coalfield. The final elements of solid geology are represented by further minor igneous intrusive dykes of Tertiary age, with a NNW-SSE trend. These are best recognised on the coastal plain in the coalfield area, although the Cleveland Dyke does form a modest topographic feature in the southeast of the region with a discontinuous outcrop of several tens of kilometres.

By the close of the Lower Palaeozoic, deep sea sediments deposited on the southern margin of an Iapetus Ocean separating a northern Laurentian landmass from a southern Avalonian microcontinent were caught up in the final phase of the Caledonian Orogeny. Ocean closing and collision along a continental margin subducting northwards under Laurentia finally resulted in what was to become an English landmass being welded to the Scottish continent to the north. During the Silurian, turbidites were deposited down the continental slope and out onto the floor of the Iapetus Ocean during the later stages of subduction and closure, and formed part of an accretionary prism developing as the leading edge of Avalonia moved northwards to collide eventually with Laurentia. Remnants of this accretionary prism can now be found within the area of Northumbria as turbidite deposits in the vicinity of the Cheviot Hills, close to the Scottish border. During this final collision phase the sedimentary package on the accretionary prism became folded, fractured and metamorphosed as crustal thickening and shortening took place along a NE-SW trending suture line, and resulted in what is today the Southern Uplands. It was the structural NE-SW lineations inherited from this event that were subsequently to play a major part in controlling the geological development of Northumbria.

Collision resulted in shortened, thickened and uplifted continental crust, which was then intruded by a series of post-orogenic, post-collision granites, probably generated by adiabatic decompression as the hot crust was rapidly uplifted. The Weardale granite, which underlies the central part of Northumbria, resulted from this magmatism, the intrusion being dated at around 390Ma. Further to the north-east corner of the region and northwards across the border into Scotland, a combination of localised crustal extension and strike-slip movement along major Caledonide NE-SW trending fault lines produced small pull-apart basins, acting as sites for magma generation. Magma delivery was likely to have been facilitated by the fractures acting as conduits. Magmatism in Northumbria began with a phase of explosive volcanic activity in which were built up around 70m of pyroclastics, from agglomerates containing rhyolite blocks, to fine ashes, and are best developed to the west of the Cheviot summit. The next phase saw eruptions of rhyolite which cap some of the high summits to the west of the Cheviot. Finally a major phase of volcanic activity saw many flows of andesite erupted, some of which are trachytic in character. In the last stage of evolution of this magmatic complex granite was intruded into the centre of the lava pile, metamorphosing the surrounding andesites. Roof pendants of metamorphosed lava can be found on the southern flanks of the Cheviot, the summit itself composed of granite. Exposures are generally poor, but some granite tors are also developed in the vicinity of the Cheviot. Northwards across the border, this phase of magmatism was more extensive.

The Caledonian uplift resulted in the formation of extensive highlands on a new continental landmass, which lay in the southern latitude desert belt. Rapid erosion of the uplands ensued, with the detritus accumulating as ORS continental deposits in intermontane molasse basins. Throughout most of ORS times however, Northumbria acted primarily as sediment sourcelands, and only in the north, close to the Scottish border, are small patches of ORS seen.

By the close of the Devonian the extensive upland topography had been reduced somewhat, and molasse basins filled to produce an undulating landmass of generally lower relief. The area of the British Isles now lay in the equatorial belt, continuing its northerly drift as part of a continental landmass, with a Rheic Ocean to the far south. As the Carboniferous began there were major global changes, with a eustatic rise in sea level linked to the melting of Gondwana ice sheets. As the resultant marine transgression proceeded, submergence of remaining Devonian uplands took place. In Northumbria, as the Cheviot massif was inundated, basal conglomerates were deposited on its flanks. The Roddam Dene beds are around 150m in thickness and comprise a series of fining-upwards clastics beginning with coarse cobble conglomerates and ending with fine sands. These are interpreted as alluvial fan deposits. Above are finer grained sediments containing silty and clay horizons, thought to represent deposition in a permanent body of water, possibly lacustrine in origin.

Over the whole of Northumbria cooling and thermal relaxation of the thickened and uplifted crust resulted in lithospheric extension, which was probably driven in part by N-S tension as a result of subduction processes far to the south. This resulted in the formation of subsiding fault-bounded troughs, with axes aligned with the earlier Caledonide predominantly NE-SW trend. In the north of the region and into southern Scotland Late Devonian-Early Carboniferous lithospheric extension resulted in passive continental rifting and magma generation, with outpourings of basaltic lavas now seen close to the Scottish border. Across into Scotland this volcanicity started earlier, and was more extensive.

Intervening areas between the fault- bounded basins, which were underlain by granites, continued to rise as isostatic readjustment continued. The Alston Block, a major structural feature of Northumbrian geology, was established at this time. Between this and the Cheviot block to the north, the Northumberland Trough acted as a major site of sedimentation during the Carboniferous, with its southern faulted margin against the Alston Block delineated by the Stublick-Ninety Fathom fault system. To the south of the Alston Block lay another fault-bounded sedimentary basin, the Stainmore Trough, its northern margin delineated by the Lunedale/Butterknowle fault system, both sets of faults inheriting the Caledonide, predominantly NE-SW trend. Periodic syn-sedimentary movements along these faults resulted in episodic basin subsidence. This, coupled with epeirogenic sea-level fluctuations while predominantly fluvio-deltaic clastics derived from sourcelands to the north-east and shallow marine shelf carbonates accumulated in the troughs, became the dominant style of sedimentation in the Lower Carboniferous. By Westphalian times however, fluvio-estuarine conditions became more marked, and the style of overall tectonic control also changed.

In the Early Carboniferous sedimentation began with a transgressive succession of shallow marine to lagoonal carbonates, often dolomitised, together with interbedded sandstones and mudstones of the Cementstone Group. Many of the sands are cross-stratified fluvial channel and bar clastics, and many of the mudstones are of tidal flat origin. This widespread shallow marine to lagoonal environment was dominated by a generally arid climate, and experienced a restricted sediment supply at times. Further northwards more estuarine conditions prevailed while to the south the Alston Block was a site of non-deposition until later in the Carboniferous.

By the Middle Dinantian a westwards draining braided fluvial system feeding into a low energy shallow basin further to the west and south had become established. Coarse cross-stratified sands of the Fell Sandstone Group were deposited, attaining considerable thickness in the north of the region. The Fell Sandstone gives rise to the considerable topographic feature of the Simonside Hills in north-west Northumberland, where the succession is between 300 and 400m in thickness.

Later in the Dinantian the fluvial system that had given rise to the Fell Sandstone sediments had been replaced by a delta flat environment where periodic progradational clastic build-up followed by fault-induced subsidence and flooding resulted in the cyclic sediments of the Scremerston Coal Group. Again this facies was best developed in the northern parts of Northumbria. By the Late Dinantian, and up into the Namurian an extensive delta system became established over the whole area, with more shallow open marine conditions further to the south. Clastic sediment was sourced from the north-east and progradational deposits built out into open water as delta-fronts advanced south and south-westwards. Intervening shallow marine areas without clastic supply became sites for carbonate deposition. Periodic basin subsidence and flooding, followed by renewed sediment progradation gave rise to a series of cyclic sediments of limestone, shale and sandstone, in a classic Yoredales succession. In the Dinantian Lower and Middle Limestone Groups limestones are prominent in the Yoredales cycles, but these generally thin and die out shorewards towards the north and east. Some limestones however are more persistent and traceable throughout much of the region. These horizons represent periods of stability and quiescence over the whole of Northern England, with widespread establishment of tranquil offshore-marine conditions and deposition of limestones in quiet waters away from any significant clastic input.

The Yoredale facies continued into the Upper Carboniferous, with the same cyclic sediments found in the Namurian Upper Limestone Group, as the fluvially dominated deltaic conditions persisted. Again many of the limestones are significant and of wide lateral extent, indicating further periods of widespread stability and quiescence. However, higher in the succession the sandstone component begins to dominate, and by the top of the Namurian very significant fluvial channel and delta mouth bar sands are found. By this time there had also been a change in the tectonic regime that controlled sedimentation.

Whilst the tectonic elements of subsiding, fault-controlled basins separated by buoyant blocks underlain by granite acted as the major control of sedimentation throughout the Lower Carboniferous, the driving mechanism for basin subsidence changed with time. Later in the Namurian, lithospheric extension ceased to be significant, but continuing thermal relaxation of the crust plus continuing basin infill resulted in the development of broad, subsiding sag basins. With their formation, the influence of the uplifting blocks became less significant, as the phase of differential subsidence ceased, and was replaced by broad regional downwarping. It was this tectonic style that governed sedimentation in the Westphalian.

Initially, Early Westphalian Coal Measures sediments were deposited on a broad, relatively flat lower delta plain, within the tidal zone, and with open sea to the south. In this setting, basinal downwarping affected sedimentation, but with time, continuing sediment progradation resulted in the transition to an upper delta plain setting much less affected by basinal processes. The environment of alluvial plains, backswamps and numerous distributary channels, with sediment sourcelands to the north, produced a cyclic series of sediments dominated by clastics, in which coals were prominent. Within the cycles sea-level changes and incursion are represented by the presence of marine shales, while the delta plains and backswamps were the sites of coal formation. These deltaic sediments have a maximum thickness of around 900m, and their presence in the Northumberland and Durham Coalfield was a major factor in the economic prosperity of the Northeast from the time of the industrial revolution onwards. The deep mines have now all closed, but open-cast working continues to exploit this resource. Topographically the easily weathered coals and shales give areas of low relief, as seen across the coastal plain of east Northumberland. However, many of the channel and delta sands are of considerable thickness, and form prominent topographic features throughout the region.

By the end of the Carboniferous, Britain had continued its drift northwards and now lay north of the equator at a position equivalent to the modern day Sahara Desert. Westphalian coal measures in Northumbria show increased reddening towards the top of the succession, indicative of the onset of more arid conditions. The Rheic Ocean to the south of the continental landmass, of which Britain was a part, had been closing and the Variscan Orogeny began to affect southern Britain. Northumbria also experienced tectonic activity as a result, with the extensional, thermal relaxation-driven style which dominated most of the Carboniferous being replaced by E-W transpressional effects. Inversion and uplift of rift-basins, and reverse reactivation of faulting resulted in folding of the Carboniferous sediments. In the north of the region the Lower Carboniferous sediments are folded into the Holburn and Lemmington anticlines by compression against the resistant Cheviot block which remained unaffected. In the far north of the area Carboniferous sediments are compressed against the rigid Southern Uplands block in the Berwick Monocline, an east-facing structure with a north-south trend, together with many minor associated folds in the Lower Carboniferous strata. The Westphalian Coal Measures were also folded at this time, and subjected to erosion. Offshore, to the east of the region the Coal Measures were folded into a series of N-S trending domes. Onshore the Westphalian sediments show the effects of a eustatic fall of sea level, as continental accretion, and growth of southern ice-sheets continued. Emergence features are observed, with the formation of continental land surfaces and sub-aerial weathering of the Coal Measures. Earlier Caledonide NE-SW lineations were also rejuvenated in the Late Carboniferous, the Thieves-Gyle-Harthope fault-system being one such example, which transects the Cheviot massif. Further south, other characteristically east-facing structures were produced, notably the Dent Fault and its east-facing monocline.

Whilst trough areas responded to Variscan E-W transpression, the blocks remained relatively unaffected due to the shallow depth of the rigid, granitic basement. On the Alston Block the only significant Variscan element is the Burtreeford Disturbance, another east-facing structure. It was in post-Westphalian times too, that extensive lead-zinc mineralization of the Alston Block occurred, with the formation of the North Pennine orefield. The mineralization follows faults and fractures in the Carboniferous Limestone, and wall-rocks and solution cavities are also mineralised in places. Lead and zinc sulphides are the main metalliferous ores, together with chalcopyrite. Fluorite and barite are the most common gangue minerals, and in recent years the economic significance of them as a resource has increased considerably. Mineralisation is thought to have occurred at around 290Ma and resulted from hot, metal-bearing brines driven by a geothermal circulatory system. Both the Coal Measures and the Lower Carboniferous are invoked as sources for the brines, and the Whin Sill magmatism implicated as a probable heat flow event.

Whilst the end-Carboniferous Variscan transpression effects were witnessed in Northumbria, further north into the Scottish Borders extensional tectonics continued into the Permian. Passive continental rifting in response to tensional stress again resulted in decompression melting and sourcing of within-plate basaltic magmas which were intruded as the Midland Valley Permo-Carboniferous sills in Scotland and as the related Whin Sill of Northumberland and Durham. The emplacement has been dated at around 295Ma. The Whin Sill forms a prominent topographic feature in the region, especially so in mid-Northumberland where Hadrian's Wall follows the crest of the escarpment formed by the sill. Throughout the area the dolerite is a valuable economic resource, and its outcrop is marked by numerous quarries.

By Permian times the Variscan Orogeny had resulted in major continental reorganisation and the formation of the Pangea supercontinent. Tensional effects that produced the Whin Sill magmas became more extensive, and resulted in the formation of major Southern and Northern North Sea intracratonic basins, which later became connected to the emergent Tethyan Ocean, far to the south of Britain. In northern Britain extensive Variscan highlands to the north, south and west acted as source areas for detritus, and were subjected to arid Early Permian continental weathering and erosion. Molasse and piedmont deposits collected eastwards in playa basins surrounded by desert dunefields, and the topography gradually reduced. The area east of Durham fringed an arid gulf of the southern North Sea Basin, and here Westphalian strata uplifted and tilted in the Late Carboniferous were eroded and overlain by desert-derived sands. The Yellow Sands of County Durham show large-scale dune cross-stratification, and have a discontinuous outcrop at the western edge of the Permian escarpment in the east of the county.

In the Late Permian, the Zechstein transgression began to enlarge the epicontinental sea, linking together many of the playa lake basins into one restricted shallow marine environment. Initially euxinic deposits of the Marl Slate Formation formed in a stratified water body of moderate depth, characterised by the absence of any significant current activity. The sediments are fine-grained, finely laminated calcitic siltstones, rich in organic matter and containing metal sulphides. They also contain a fauna of bony fish. This very characteristic deposit reaches a maximum thickness of around 2 to 3m.

As the Zechstein transgression proceeded westwards and enlarged the epicontinental sea, carbonates and dolomites were deposited. Above the Marl Slate, the Magnesian Limestone is divided into two formations. The dolomitic carbonates of the Raisby Formation were deposited in shallow water, and are shelly in part. They are interpreted as basin-margin deposits, and parts of the formation show evidence of submarine slumping from the shallower marginal areas into deeper parts of the basin. The formation attains a maximum thickness of around 70m in north Durham and forms the prominent west-facing scarp that runs almost north-south through the east of the county.

Later in the Late Permian, fringing reefs developed along the margins of the enlarging Zechstein Sea. The Ford Formation is composed of dolomitic limestones and shelly oolitic dolomites, interpreted as being of reef origin. Shelf-edge, reef, back-reef, and basinal sedimentary facies can all be identified, and a reef-crest detected along the Permian escarpment from Sunderland southwards to Hartlepool, for a distance of around 30km. The back-reef facies lies west of the crest, and is composed of cross-laminated oolitic dolomite, while the reef-crest facies is recognised by an abundant fauna of brachiopods, bivalves, bryozoans and stromatolites, in a dolomitic matrix. Eastwards, reef-talus deposits are identified, containing fragmentary organic remains in a dolomitic matrix. Further east these sediments grade into finer grained and thinner dolomitic carbonates of the basinal facies. At its maximum development the Ford Formation is around 100m thick.

During later Zechstein times periodic eustatic sea level changes under continuing arid conditions resulted in the cyclic formation of evaporitic horizons, which continue up into the Triassic. These Late Permian deposits comprise anhydrites, carbonates, and higher evaporites. The carbonates are dolomitic and oolitic in part, and were thought to have formed in two distinct environments within a stratified water body, the lower part of which was likely to have been anoxic. The Roker Dolomite Formation is a granular oolitic dolomite, with fine lamination and cross-lamination. Some parts are richly fossiliferous, and are likely to have formed in shallow, high-energy oxygenated waters as marine shelf deposits, probably as a barrier-bar system fringing the shelf edge. Eastwards the formation dies out and is replaced by the deeper water facies of the Concretionary Limestone Formation. These deposits are finely laminated dolomitic limestones containing slumped turbiditic horizons and are thought to have been deposited in the deeper anoxic parts of the basin in either a low slope, or unstable high slope environment. At its maximum development in the north of County Durham near Sunderland, the formation is around 100m thick. It is notable for its numerous calcitic concretions.

Between these dolomites and the underlying Ford Formation lies the remains of what was an anhydrite bed of probably some considerable thickness. As with most of the higher cyclic evaporite horizons on-shore, dissolution by groundwaters in Tertiary times has removed the soluble salts, leaving only a residue of fine sediment. The Hartlepool Anhydrite is now represented by beds of fine grained dolomitic limestone and laminated dolomite, which thicken eastwards, but in general are nowhere more than 80m in thickness. Other former evaporite horizons are considerably thinner. Dissolution of these anhydrite and evaporite beds has caused the overlying strata to founder, and all higher Permian horizons are considerably disrupted. Many of these evaporite horizons are thought to have formed on extensive coastal plains under very shallow water conditions, perhaps in a sabhka environment. These evaporite horizons and their residues floor the south-eastern part of the region southwards from Hartlepool towards the Tees. Inland exposures are not common, but those on the coast are plentiful. It was the presence of these evaporite horizons that gave birth to the Teesside chemical industry, now centred around Billingham and Middlesbrough.

By the Early Triassic the Zechstein Sea had enlarged, and the mudstones and sandstones that overly the evaporites suggest that the coastal fringing alluvial plains were now subject to more frequent flooding, and a higher clastic input from rivers as climate amelioration took place, with increasing rainfall. Both the Sherwood Sandstone Group, and the overlying Mercia Mudstone Group sediments are found only in the far south-eastern corner of the region, close to the Tees.

After the Early Triassic in Northumbria, no rocks are preserved until the Tertiary, when the region was intruded by basic dykes originating from the Tertiary volcanic centres situated to the north- west, in Scotland. The Cleveland Dyke, the most notable of the Tertiary intrusions in the region, is basaltic in composition, and runs ENE-WSW across the far south of the region in a discontinuous outcrop that can be traced north-westwards across Cumbria and into the Scottish Borders. It is thought to be part of the series of dykes centred on the Tertiary Igneous Province on the Isle of Mull in the Inner Hebrides.

The final chapter of the geological history of Northumbria took place in the Quaternary. During the Devensian glaciation extensive tills were developed over the region as ice flowed eastwards and southwards, and mantled the topography. Once ice-melting began, sub-glacial drainage resulted in erosion of meltwater channels and gorges (known locally as ‘Denes’), deposition of glaciofluvial sediments, and formation of kettle-holes. In the subsequent Loch Lomond Stadial, periglacial weathering was intense, and resulted in many of the Cheviot granite tors being formed, together with many of the Whin Sill scree fields. Lastly, in the Flandrian temperate stage the final mantling of the region with blanket peats took place, and the development of extensive coastal vegetation when sea-level was lower than at present. As sea levels rose after the glacial period these coastal forests were submerged, but their remains can still be seen today along the Northeast coastline, under favourable conditions of low tide.

The geological development of Northumbria has left a rich legacy. Lead, coal and evaporites laid the foundations of the industrial prosperity of the area. As a result of the geological framework the region has a wealth of spectacular and varied scenery, and is much visited. The rocks are witness to two major orogenic events, and many aspects of global geological development. The on-shore Permian deposits of the Northeast coast are unique in the British Isles. For the geologist, Northumbria has a lot to offer.

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The Yoredale Cycles of Northumbria: High-Frequency Clastic-Carbonate Sequences of the Mid-Carboniferous Icehouse World

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Abstract

The Mid-Carboniferous Yoredale cycles in Northeast England are high-frequency clastic-carbonate sequences produced by glacioeustatic sea-level changes caused by the Gondwanan glaciation in the southern hemisphere. The sequences, 5-50 metres in thickness, typically consist of a lower well-bedded marine limestone (TST) passing up into a coarsening-upward mudrock to sandstone deltaic succession (HST), capped by a palaeosoil and coal. Major down-cutting linear sand-bodies are incised-valley fills resulting from forced regression (FSST/LST). Individual cycles are most likely the product of the short-eccentricity Milankovitch rhythm (112 kyr), and a bundling of the cycles in some parts of the succession relates to the long-eccentricity rhythm (413 kyr). A less negative trend in $\delta^{18}O$ up the succession is interpreted as reflecting increasing Gondwanan glaciation. A less negative $\delta^{18}O$ excursion in the late Asbian correlates with sedimentological evidence of aridity. Patterns in bed-thickness variation and in the $\delta^{18}O$ -isotope stratigraphy in one of the thickest Yoredale limestones, the Great, indicate the effects of the precession rhythm, with the beds themselves most likely being the result of millennial-scale variations in climate.

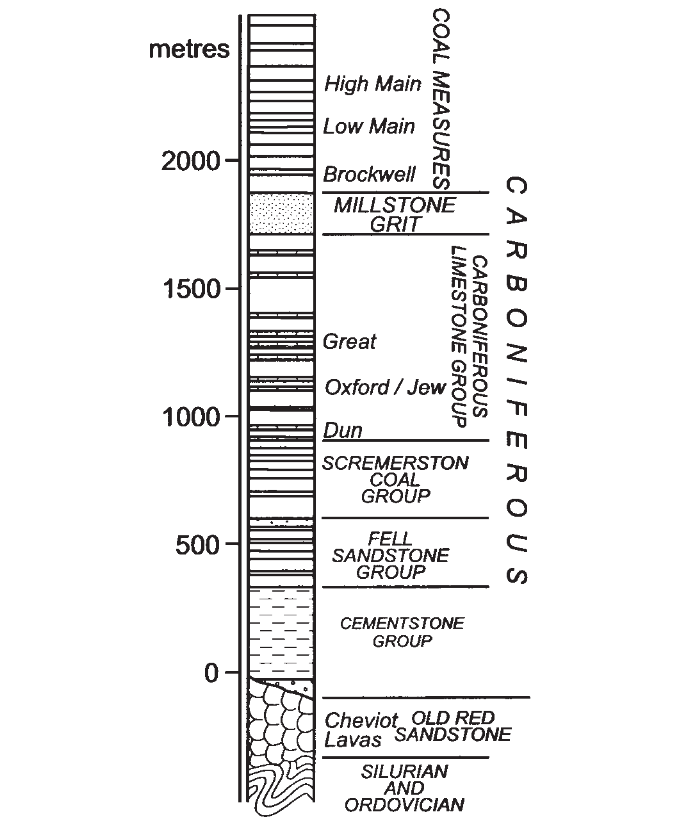

Figure 1. General stratigraphy of the Carboniferous succession in N.E. England. The Yoredale cycles occur in the Scremerston Coal and Carboniferous Limestone Groups (Asbian, Brigantian, Pendleian, Lower Arnsbergian). The horizontal lines there represent major limestones; lines within the Coal Measures are important coal seams.

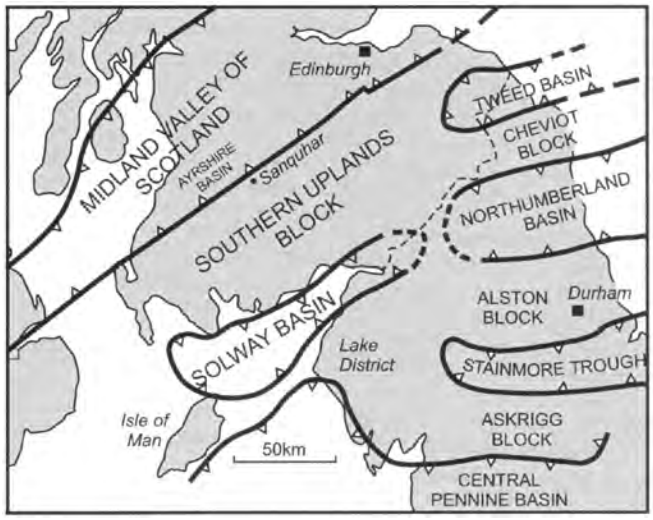

Figure 2. Palaeogeography for northern England in Mid-Carboniferous time. Apart from thickening of strata, there is no change of facies from block to basin/trough, except into the Central Pennine Basin, which was a real deep-water basin.

Introduction

High-frequency sequences are a feature of the Mid-Carboniferous strata of Europe (e.g., Wright & Vanstone 2001; Barnett *et al.* 2002) and North America (e.g., Smith & Read 2000; Olszewski & Patzkowsky 2003), and they are particularly well-developed in northern England, where they are referred to as Yoredale cycles (Tucker 2003a). They occur within the upper Viséan and lower Namurian Carboniferous Limestone Group (recently renamed Liddesdale and Stainmore Groups) and Scremerston Coal Group (Figure 1) of the Northumberland and Stainmore Basins and Alston and Askrigg blocks (Figure 2). The cycles have an average thickness of around 20m, although they are generally thicker in the basins and thinner on the blocks.

My presentation at the 2003 Open University Symposium on Northumbrian Rocks held in Durham in July, of which this is a summary, addressed the topics of the controls on deposition and the causes of the repetition of the Yoredale cycles. The talk reported new stratigraphic information and the results of isotope analyses, deriving from the PhD studies at the University of Durham of Kirstin Lemon on the Yoredale cycle succession and Jim Gallagher on the Great Limestone.

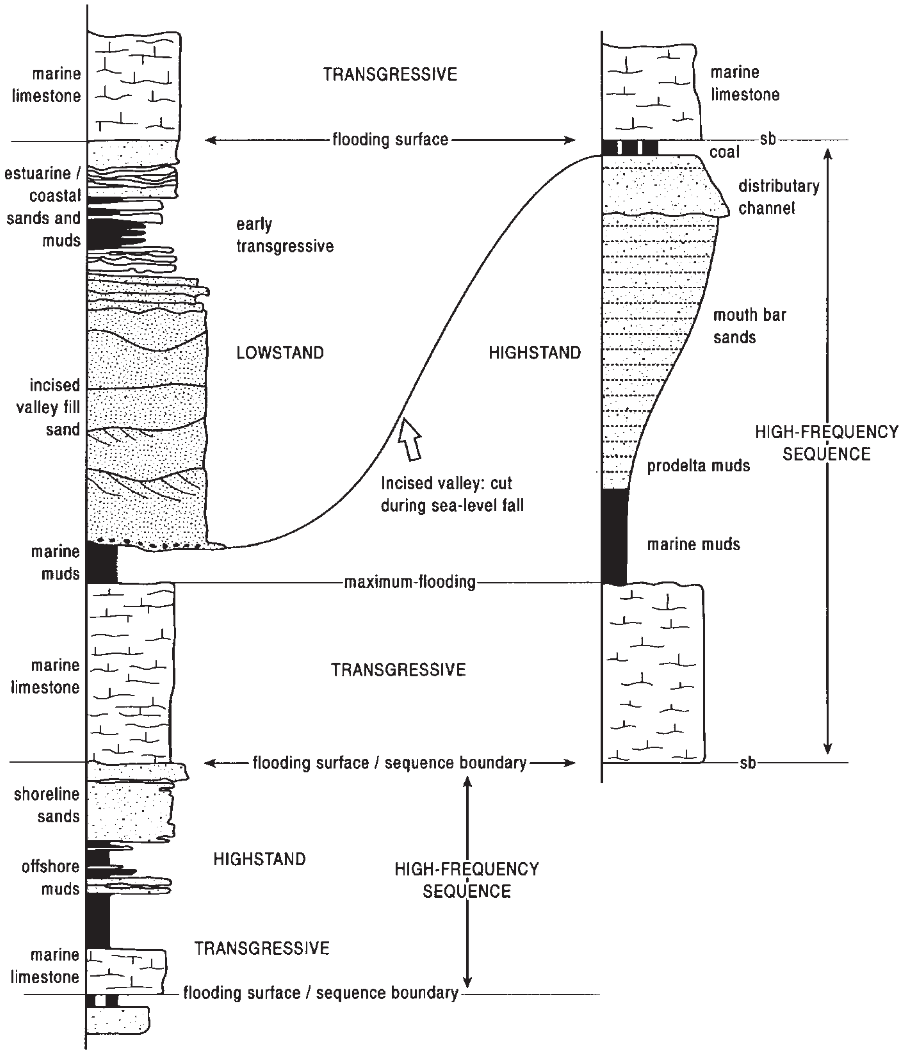

Figure 3. Stratigraphic logs and interpretations based on the Cockleshell and Scar Limestone cycles (Brigantian) in Teesdale, Co. Durham. These logs show a typical delta-dominated Yoredale cycle (on right) and one with a shoreline clastic section (left log lower part), and one with an incised-valley fill (left log upper part).

Yoredale Cycles

The Yoredale cycles are mixed clastic-carbonate high-frequency sequences varying from 5 to 50m in thickness. At least 70 cycles are present through the Asbian, Brigantian, Pendleian and lower Arnsbergian stages, a period of around 12 million years. Typically, the cycles consist of a lower limestone overlain by coarsening-upward clastics, capped by a palaeosol and a coal (see Figure 3).

The limestones are 0.5 to 30m thick and can be correlated over the whole region (~10,000km^2). At the very base of some cycles is a prominent sandy-muddy bioturbated bed with fish scales and brachiopods. The limestones are generally dark grey, well-bedded, bioturbated packstones to mudstones, with abundant bioclasts including crinoids, brachiopods, corals, calcareous algae, foraminifera, bivalves, gastropods and bryozoans. The matrix is generally a lime mudstone/micrite, but this has commonly recrystallised to microspar. Some limestones contain scattered dolomite rhombs. There is frequently evidence of storm reworking of the skeletal debris and locally there are coral biostromes or thickets, as in the Great Limestone, see below. The depth of deposition was of the order of 20-50m.

The limestones are generally succeeded by a coarsening-upward siliciclastic unit consisting of mudrocks through to coarse sandstones (see Figure 3). Two quite different clastic packages occur:

1) a dominantly deltaic unit of prodelta mudrocks passing up into distal mouth-bar muddy sandstones then fine to coarse proximal mouth-bar sandstones. Sedimentary structures are common, especially cross-lamination and cross-bedding, and bioturbation. In some cases a distributary channel sand-body cuts down several to ~5 metres into the mouth-bar sandstones.

2) a deep to shallow-marine succession of mudrocks to sandstones with tempestites and HCS from storms, and then shoreface-foreshore sandstones with a range of trace fossils and cross- and flat- bedding.

At the top of the Yoredale cycles, there are frequently palaeosols, which may be ganisters, seatearths or calcretes, depending on the host sediment and climate of the time. A thin coal seam caps many cycles. At the top of some cycles, there occur several thin, metre-scale ('minor') coarsening-upward cycles, representing delta-plain facies, especially interdistributary-bay fills and lacustrine deltas.

At several horizons in the succession, major lenticular and elongate sand-bodies composed of cross-bedded medium to very coarse sandstone cut down 10m or more into the coarsening-upward unit. They may almost reach the limestone at the base of the cycle (Figure 3). They pass up into finer-grained clastics before the next limestone. These represent incised-valley fills and were the result of forced regressions.

Thickness and Facies Patterns in the Yoredale Cycles

The origin of the Yoredale cycles has been much discussed with tectonic, eustatic and sedimentary mechanisms all put forward (see Leeder & Strudwick 1987 and later section here). Useful information in this respect can be obtained from the pattern of cycle thickness variation through the succession. The thickness of each cycle is compared successively with the average cycle thickness, in a so-called Fischer plot (see Tucker 2003b for technique). For cycles that shallow up to sea-level, the Fischer plot obtained is roughly a reflection of long-term changes in relative sea-level or, better put, accommodation space.

Broadly similar patterns in the cycle thickness are found for the Yoredale successions both in block and basin localities. This indicates a control on deposition affecting the whole region, i.e. eustasy and/or regional tectonics, and rules out a purely random sedimentary mechanism, such as delta/shoreline progradation, or local fault activity. However, there are differences in the average cycle thickness between localities and these are a reflection of dif-

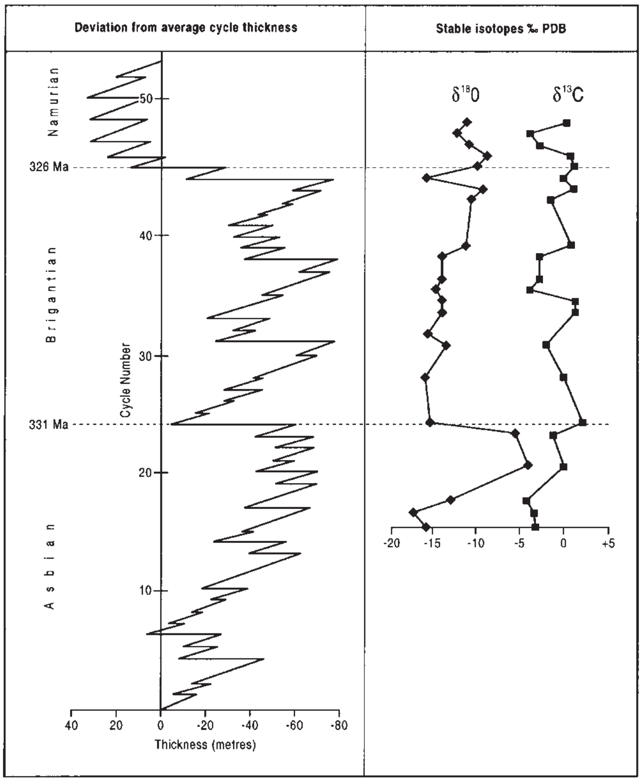

Figure 4. Fischer plot and oxygen and carbon isotope stratigraphies for the Yoredale succession. The Fischer plot shows the thickness of individual cycles (horizontal lines) successively through the section, compared with the average thickness (diagonal lines). This plot is derived from 1100 m of strata with 60 cycles (average cycle thickness 18 m) from offshore Sunderland. Note the bundling of cycles (a thick cycle followed by several thinner cycles) in the Brigantian suggesting composite eustasy, and the extra thick cycles representing more major transgressions/increases in accommodation space. The isotope stratigraphy is based on the average composition of individual limestones derived from several/many analyses of whole rock and brachiopods.

ferential subsidence across the region. Extra-thick cycles in the succession record stronger relative sea-level rises, creating more accommodation space; these occur in the mid-Asbian, at the Asbian/Brigantian boundary, in the mid-Brigantian and at the Brigantian/Namurian boundary (Figure 4). These major transgressions are recorded worldwide (Ross & Ross 1988), suggesting a eustatic mechanism.

Also revealed, especially in the Brigantian part of the succession, is a bundling of the cycles, whereby a thick cycle is followed by several thinner ones (Figure 4). This is most simply interpreted as the consequence of composite eustasy; i.e., two different orders of eustatic sea-level change superimposed upon each other.

There is also a pattern in the facies distribution within cycles through the succession. Those in the Viséan (Asbian-Brigantian) being more carbonate dominated and those in the Namurian more clastic dominated. This is related to the general decrease in marine influence and increase in clastic supply through the Mid-Carboniferous, a consequence of plate movements and uplift, ahead of the Variscan orogeny.

In addition, cycles in the upper Asbian tend to be sand dominated compared to those above and below, which have more finer-grained clastics. There is also a change in the colour of the clastic sediments in the cycles, with those in the upper Asbian tending to have more of a red colour, compared with the more yellow-brown sandstones of younger and older cycles. Calcretes occur in the upper Asbian, whereas vertisols (mostly seatearths with rootlets and siderite nodules) are more common elsewhere in the succession. All these features indicate a more arid climate during the late Asbian, and more humid conditions before and after.

The Great Limestone

This is the thickest Yoredale Limestone, at ~20m, and occurs at the Viséan-Namurian boundary. It is a packstone-wackestone with prominent brachiopods and corals, the latter well-developed in the famous Frosterley marble with numerous *Dibunophyllum bipartitum*.

The Great Limestone is very well bedded (beds 20-75cm in thickness) through the presence of thin shale partings and pressure dissolution seams. Indeed, individual beds can be correlated over the Alston Block and into the Northumberland Basin and they were given specific names by the lead miners (Fairbairn 1978). Remarkably, Fischer plots of the deviation of bed thickness from the average bed thickness for many localities reveal region-wide thinning-up and thickening-up bed patterns (see Figure 5). In fact, $2^1/_2$ cycles of bed thinning and bed thickening are revealed, with a long-term rising trend (Figure 5). This pattern suggests an external, allocyclic control on the deposition of the beds. The most likely explanation is a regular change in carbonate production and/or terrigenous clay input. This could be due to changes in water-

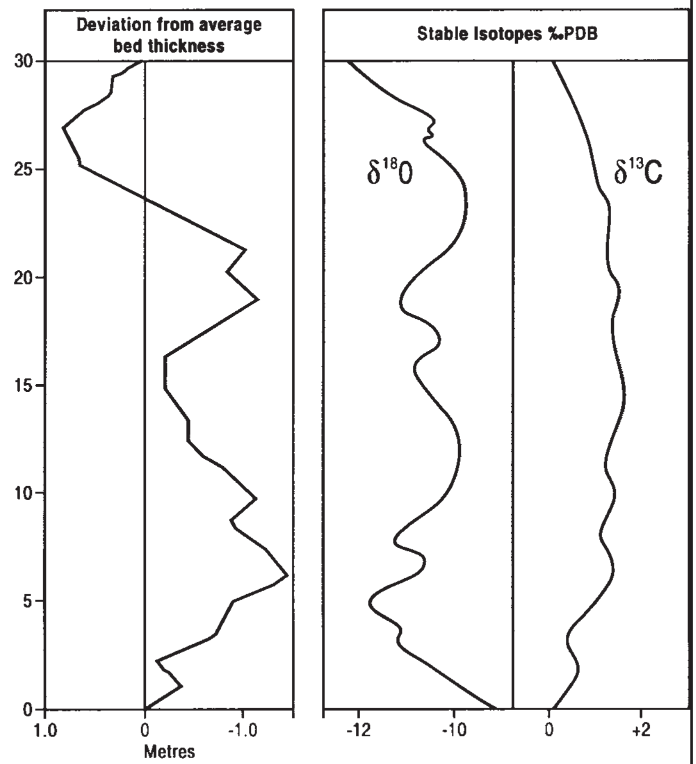

Figure 5. Fischer plot trend and oxygen and carbon isotope stratigraphies for the Great Limestone of Teesdale. The Fischer plot shows the pattern of bed-thickness variation relative to the average bed thickness. The isotope stratigraphies are the generalised trend from ~140 whole-rock analyses.

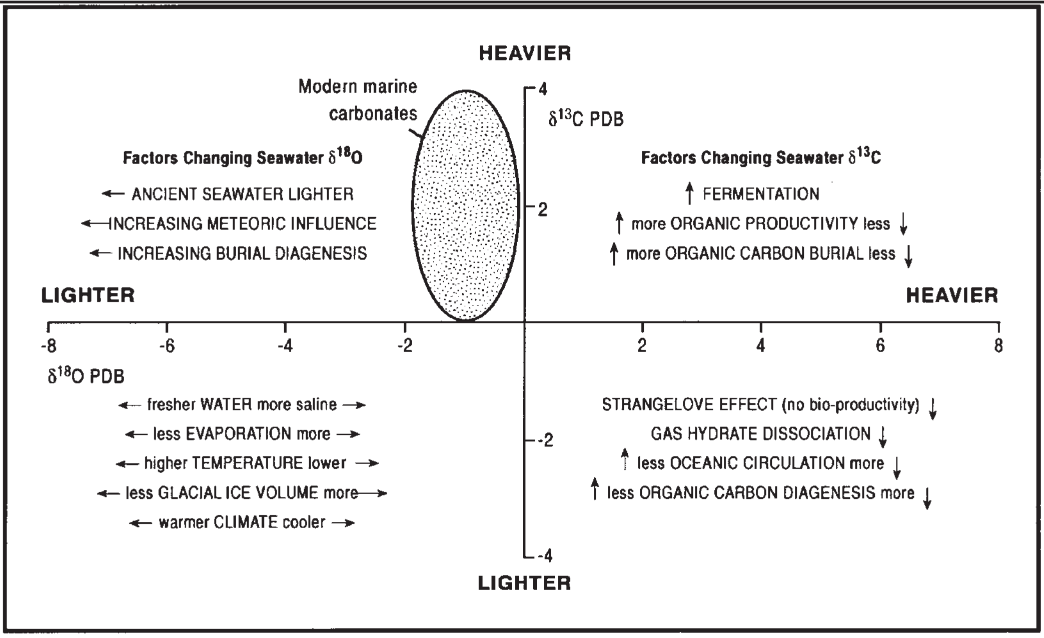

Figure 6. Diagram summarising the main controls on the carbon and oxygen isotopic composition of carbonate sediments and rocks.

depth/accommodation space/sea-level, or climate, water temperature, nutrient supply, salinity or other environmental factors.

Stable Isotope Analyses

Analyses of the carbon and oxygen isotope signatures (δ^{13}C and δ^{18}O) of limestones can help with interpretations of their deposition and diagenesis. There are many factors controlling the isotopic composition of a carbonate and these are summarised in Figure 6.

Samples for isotopic analysis (whole rock and brachiopods) were collected from all Yoredale limestones by Kirstin Lemon and at 10cm intervals from the Great Limestone by Jim Gallagher (see Figures 4 & 5 for results). Analyses were undertaken at BGS Keyworth under the direction of Melanie Leng using routine procedures for calcite carbonate. The results are extremely exciting.

The δ^{13}C values are quite uniform, range +2 to -4‰PDB (see Figures 4 & 5) and most are typical of marine limestone (Figure. 6). However, the oxygen isotope values are extremely light and variable, with a range of -5 to -16‰ $\delta^{18}O_{PDB}$ (average -10‰). The average European Mid-Carboniferous marine carbonate signature is ~-5 to -6‰ (Bruckschen *et al.* 1999). The difference of -5 to -4‰ could indicate:

1) higher seawater temperature during deposition (~ +16-20°C),

2) fresher water during deposition,

3) lighter $\delta^{18}O_{seawater}$ during deposition, and/or

4) recrystallisation of the limestone during burial/low-grade metamorphism (Figure 6).

Apart from normal burial diagenesis, recrystallisation could be due to the effects of the Whin Sill intrusion (latest Carboniferous, Johnson & Dunham 2001), and high heat flow through the underlying Weardale granite (Devonian).

In spite of the very negative values for δ^{18}O and their variability, the results for both the Yoredale Limestones (Figure 4) and the Great Limestone (Figure 5) show broad, systematic variations up–section. These are interpreted as primary stratigraphic trends, even though there was undoubtedly some alteration (lightening), from their original values.

Generalising the δ^{18}O pattern in the Yoredale succession overall (Figure 4), there is a long-term trend towards less negative values (-16 to -10‰), with an excursion to much less negative values (-5‰) in the upper Asbian. Stratigraphic trends in δ^{18}O are generally related to changing water temperature, salinity, $\delta^{18}O_{seawater}$ and/or ice volume (Figure 6). In this case, the long-term trend could indicate global cooling and an increase in ice volume in the southern hemisphere, at this time of developing Gondwanan glaciation. The excursion in the late Asbian, could indicate a major cooling event or mini-ice age at this time. It does correlate with a time of thinner cycles (Figure 4), which could suggest lowered sea-level. It also coincides with the sedimentological evidence of aridity, and interestingly, a time of few conodonts, which preferred warm-water environments (Howard Armstrong, pers. comm.).

The generalised δ^{18}O stratigraphy in the Great Limestone is remarkable for revealing a pattern in the data of several more negative-less negative cycles (Figure 5). In fact the δ^{18}O pattern correlates with the bed-thickness pattern (Figure 5), namely:

A) a trend to more negative δ^{18}O values correlates with an upward-thinning bed pattern; and

B) a trend to less negative δ^{18}O values correlates with an upward-thickening bed pattern.

These bed thickness patterns most likely reflect changing environmental conditions; thus pattern A could be due to more freshwater input and/or higher temperature and/or less ice (Figure 6).

Origin of the Yoredale Cycles

The Mid-Carboniferous was a time of developing glaciation in Gondwana and this would have had a profound effect on sea-level change and climate through orbital forcing and the Milankovitch rhythms. With at least 70 cycles in 12 million years giving a maximum cycle duration of 170,000 years (assuming all of same duration – risky!), plus the likelihood of missed beats (sea-level changes not recorded in the strata), the Yoredale cycles are most likely the result of the short-eccentricity rhythm of 112kyr (Figure 7). The limestone units were clearly the result of rapid flooding and transgression across a low-relief coastal plain, with local reworking of underlying sediments. A glacioeustatic mechanism best explains this, since a sea-level rise as a result of a deglaciation is generally very rapid (10s metre/1000 yrs). The bundling of some cycles as revealed by the cycle thickness plots (Figure 4) could indicate the operation of the long-eccentricity rhythm (413kyr). Wright & Vanstone (2001) also preferred the short-eccentricity rhythm as an explanation for Mid-Carboniferous

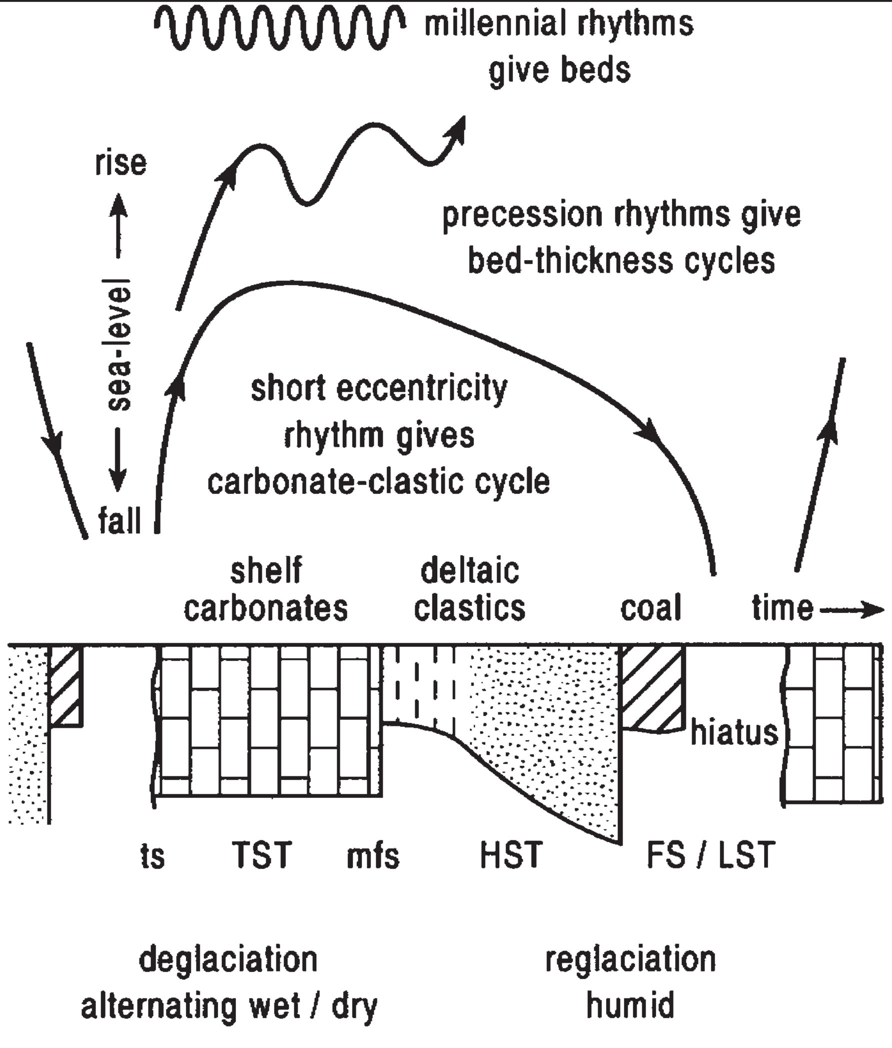

Figure 7. Model for the origin of the Yoredale mixed carbonate-clastic cycles, based on the role of orbital forcing and climate change.

cyclicity in Wales, although Smith & Read (2000) advocated long eccentricity for time-equivalent cycles in the mid U.S.A.

In terms of sequence stratigraphy (Figures 7 & 8), the limestone was deposited during the transgressive (TST) part of the high-frequency sequence, with the base representing the sequence boundary, coincident with the transgressive surface. The progradation of a deltaic shoreline or storm-dominated shoreface leading to the coarsening-upward clastic unit would represent the highstand (HST). The major downcutting sand-bodies which occur at specific stratigraphic horizons are interpreted as incised-valley fills. They represent times of sharp relative sea-level falls, and so are the falling stage (FSST) and lowstand (LST) of the sequence; they represent extra low glacioeustatic sea-level falls, i.e. forced regressions. These valleys would have supplied coarse clastics to the basin-margin and floor (LSW, Figure 8), located farther south in Yorkshire (Figure 2).

The patterns of bed thickness and oxygen isotope trends within the Great Limestone suggest a higher-frequency cyclicity. This would most likely have been the precession rhythm (~17kyr and 21kyr in the Carboniferous) (Figure 7), indicating a duration of around 50,000yrs for the Great Limestone. The beds themselves within the Great Limestone, numbering about 30, would then be the result of millennial-scale changes in environmental factors. Milankovitch rhythms, causing changes in insolation and so changes in sea-level via polar ice-cap fluctuations, also cause strong climatic changes in equatorial regions, which is where Britain was located in Mid-Carboniferous time. These climatic changes would account for the variations in carbonate productivity and clastic influx that generated the beds and bed-thickness patterns in the Yoredale limestones.

Conclusions

The Yoredale cycles of northern England are a classic example of high-frequency sequences deposited during an icehouse period. The carbonates are the transgressive deposits and the clastics highstand facies. Lowstand facies are represented by palaeosols and coal at the top of the cycles, although periodically substantial forced regressions cut incised valleys into the coastal plain and these supplied lowstand fans and wedges in the Central Pennine Basin to the south. It is postulated that repetition of the

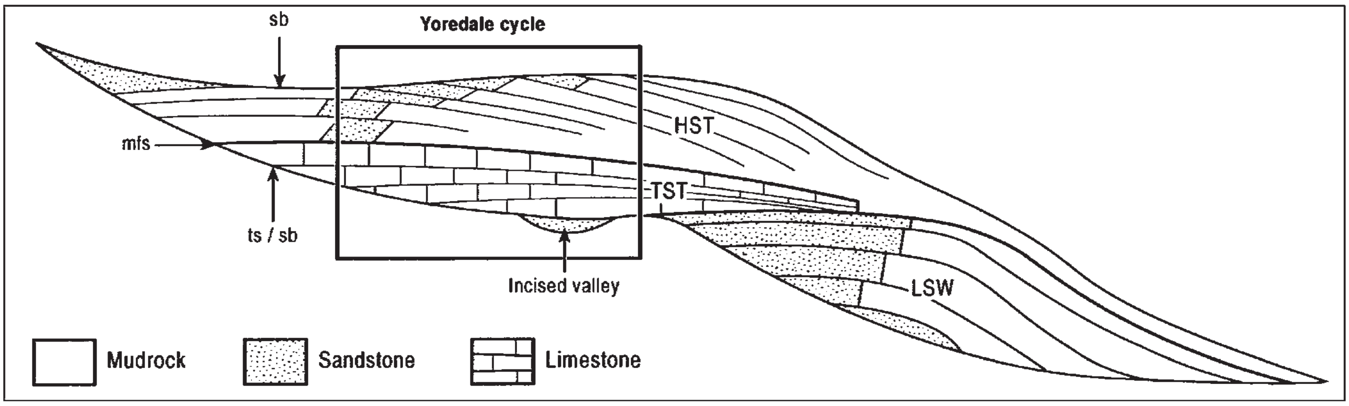

Figure 8. Sequence stratigraphic model for the Yoredale cycles: transgressive carbonates, and highstand fine-to-coarse clastics. Lowstand clastics were mostly deposited in the fans and wedges in the deeper-water Central Pennine Basin to the south (see Figure 2).

Yoredale cycles was brought about by glacioeustatic fluctuations in sea-level driven by the short-eccentricity Milankovitch rhythm. Patterns of bed thickness and oxygen isotope ratios within cycles indicate the effects of higher-frequency precession rhythms and individual beds were the result of millennial-scale environmental changes.

Acknowledgments

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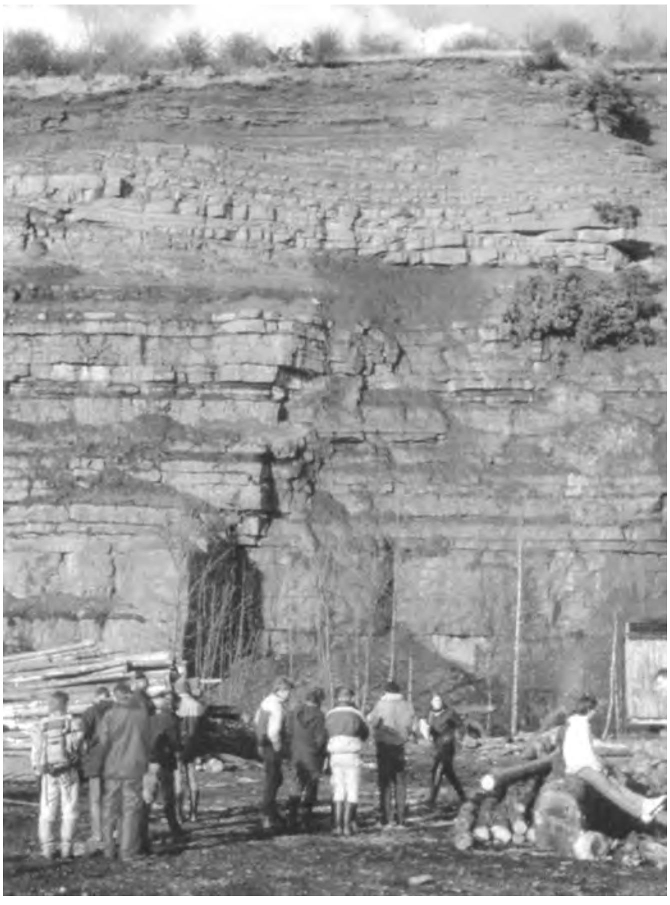

Frosterley Quarry, Weardale showing the well-bedded Great Limestone in the lower part of the exposure, overlain by mudrock into which is cut a major channel sandstone.

The Great Limestone of Teesdale. Note the well-developed stratification; individual beds can be traced over much of northeast England (Fairbairn 1978).

The Caledonian Orogeny in northern Britain – a state of the arc

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Abstract

Here we review the current hypotheses which help explain the nature and timing of events within the Caledonides between the Highland Border and the Solway. We use a variety of fossil, geochemical and stratigraphical arguments to substantiate a mobilistic model for this orogeny. We present a scenario in which the Grampian Orogeny resulted from the collision of two volcanic arc terranes: Novantia collided with the Midland Valley along the line of the Ballantrae Ophiolite and this composite terrane collided with the Laurentian margin. Post-Grampian extension along the Laurentian margin initiated the Highland Border and Northern Belt basins; as marginal basins within the northern Iapetus Ocean. The Highland Border Basin trapped detritus eroded from the newly emergent Grampian Mountains and this was subsequently lost through subduction. The approach of Iapetus volcanic arcs, including the Popelogan-Victoria-Grangegeeth Terrane and Eastern Avalonia, caused the progressive closure of marginal basins. Sediments derived from the Laurentian margin are found in the middle Silurian of the Windermere Group of the English Lake District; the relict Iapetus Ocean must have been closed at this time. The entire Laurentian margin changed into a region of sinistral transpression during the early Silurian. In this mobilistic model the position of the Iapetus suture migrated southwards with the Laurentian margin as new arc terranes were periodically accreted. The closure of the Iapetus Ocean was essentially an Ordovician event.

Introduction

The Iapetus Suture has traditionally been drawn between areas with Laurentian ("North American") and Gondwana faunas; typically as a line trending north-eastwards across northern Britain,

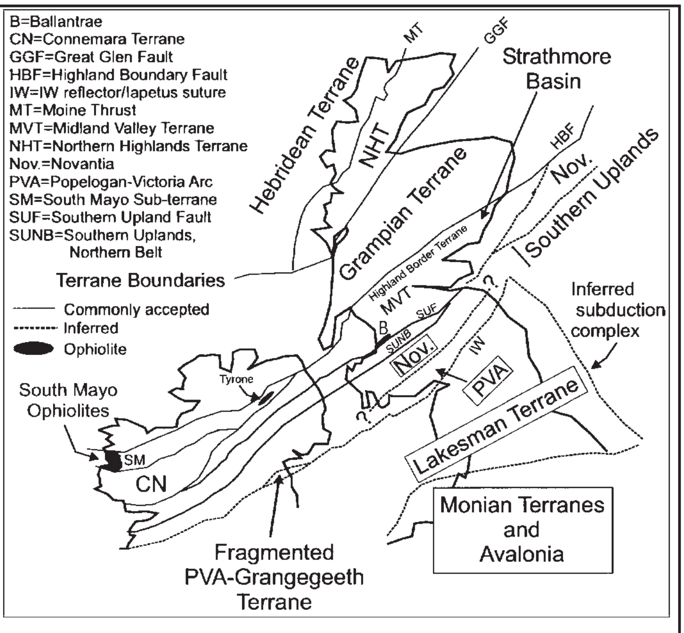

Figure 1. Simplified terrane map of northern Britain and Ireland (after Bluck *et al.* 1992 and Armstrong & Owen 2001). The position of the inferred subduction zone along the northeast coast of England is taken from Cocks *et al.* (1997).

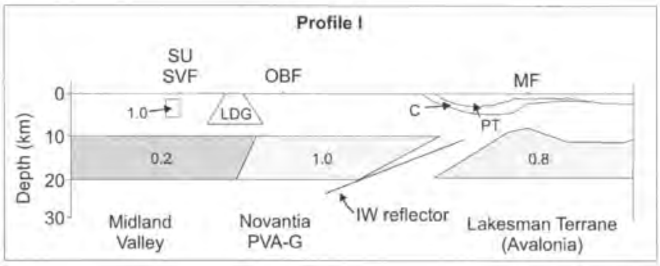

Figure 2. Geophysical profile across the Iapetus Suture Zone constructed by (Kimbell & Stone 1995). Shaded blocks are magnetic, with magnetisations in A/m indicated. A depth migrated line drawing of the central part of WINCH 2 (from Klemperer & Matthews 1987) is superimposed on the central part of the models. Abbreviations, SVF-Stinchar Valley Fault; LDG-Loch Doon Granite; CFG-Cairnsmore of Fleet granite; MF-Maryport Fault; PT-Permo-Triassic of the Solway Basin; C-Carboniferous of the Solway Basin; OBF-Orlock Bridge Fault; IofM-Isle of Man; IW-reflectivity boundary traditionally assumed to identify the Iapetus Suture (e.g. Brewer *et al.* 1983, Hall *et al.* 1984).

separating the English Lake District and the Southern Uplands of Scotland (Figure 1). Geophysical contrasts in the lower crust and the location of the IW reflector in the WINCH deep seismic reflection line (Kimbell & Stone 1995; Figure 2) have tended to reinforce this notion. A notion we consider to be oversimplistic for two fundamental reasons, firstly the margin of Laurentia migrated southwards during the course of the Ordovician as arc terranes, originally derived from Gondwana, were sequentially added from the south. Secondly, modern continental collision zones (e.g. Mediterranean Sea or the S.W. pacific) contain a complex collage of terranes and marginal basins each with its own complex and often short-lived history. If the Eastern Mediterranean Sea is taken as an analogue then arc, ridges and subduction zones can all coexist in a relatively small area. Marginal basins can be opening at the same time others are closing. Strike-slip faults are a dominant component of the structural fabric. Boundaries between faunal provinces in this context do not form neat lines on maps, they move spatially and temporally in response to tectonic and ecological changes. Re-considering the geology of northern Britain, to the south of the Highland Boundary Fault, as part of a "mobile belt" rather than as a zone of orthogonal continental collision provides new insight into the complex geology of the Iapetus Suture Zone.

Whilst the regional tectono-stratigraphical setting of the Caledonian "mobile belt" is reasonably well understood, a number of major questions have hitherto remained outstanding: What was the cause of the obduction of the Ballantrae Ophiolite? Why is there no Dalradian flysch to the south of the Highland Boundary Fault? What is the nature of and what lies beneath the Southern Uplands allochthon? We consider understanding the geological history adjacent to the Southern Uplands Fault provides the key to answering these questions.

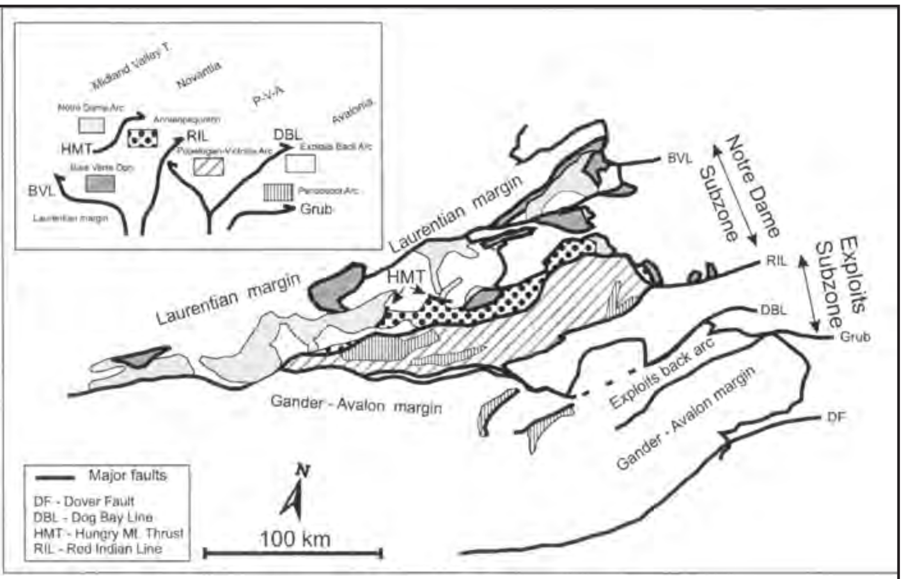

Figure 3. Simplified terrane map of central Newfoundland (reproduced after Armstrong & Owen 2001 with permission of the Geological Society, London). Silurian and Devonian plutons have been removed. The insert shows the structural relationships between the various tectonic elements and our proposed correlation with the Caledonian terranes in Britain. The southern edge of the Midland Valley Terrane, Novantia and the Popelogan-Victoria Arc all lie beneath the Southern Uplands Allochthon in Britain.

Pre-Grampian terranes in the northern Iapetus Ocean

Midland Valley Terrane

Faunal (e.g. Williams 1962; Ingham *et al.* 1986) and palaeomagnetic (Torsvik *et al.* 1996) evidence show the Midland Valley terrane lay close to the Laurentian margin throughout the Ordovician. The Midland Valley Terrane extends along the orogenic strike across Ireland into the Notre Dame Subzone in Newfoundland (Williams *et al.* 1995). In a pre-Grampian context the terrane comprised a complex metamorphic basement possibly including Archean and later Precambrian rocks and a Cambrian ophiolite (Bluck *et al*. 1992).

Novantia

In Newfoundland (Figure 3) the Annieopsquotch Accretionary Tract, the southern part of the Notre Dame Arc, also lies between the Laurentian margin and the Red Indian Line ("Iapetus Suture"). This tract includes an early Arenig (484-473Ma), MORB-like ophiolite, island arc volcanic rocks and an easterly directed thrust wedge, tentatively correlated with the northern part of the Southern Uplands. No comparable island arc terrane is known from the surface geology of northern Britain. However, a marked change in the magnetic properties in the basement beneath the surface expression of the Orlock Bridge Fault (Kimbell & Stone 1995; Figure 2) indicates the presence of a distinct block in the lower crust.

This block was recognised as a potential source of geochemically distinct high-level granite plutons, and may have rifted from Gondwana to supply southerly derived arc-detritus into the Southern Uplands Basin (Stone *et al.* 1997, Armstrong & Owen 2001) Phillips *et al*. (2003) named this terrane Novantia after the Novantae, a tribe who inhabited the south-western part of Scotland when the area was invaded by the Romans. The Midland Valley Terrane is therefore now regarded as composite terrane, extending to the south of the Southern Upland Fault, beneath the northern part of the Southern Uplands (Upton *et al.* 1983; Davidson *et al.* 1984; Armstrong & Owen 2000). Recognition of Novantia as a new terrane now raises the questions what is the geological nature of this terrane and when did it collide with the Midland Valley?

The two hypotheses are currently available to explain the nature of Novantia and are summarised in Figure 4.

Hypothesis 1. Armstrong & Owen (2001) hypothesized that Novantia was an active arc terrane of Gondwanan origin that collided with the Midland Valley Terrane in the mid- Arenig causing the final obduction and emplacement of the Ballantrae Ophiolite Complex. They suggested that the middle Arenig sedimentary rocks and late Cambrian–early Ordovician lavas of the Crawford Group, exposed within the Leadhills Imbricate Zone along the southern edge of the Northern Belt of the Southern Uplands could represent the northern margin of Novantia tectonically exhumed by later faulting. Four lines of evidence support their hypothesis:

1) The Crawford Group contains the Raven Gill and Kirkton formations. Both of these are similar comprising basic volcanic rocks, red cherts and mudstones. Extensive new conodont collections from the Crawford Group support a lower Whitlandian (middle Arenig) age for the Raven Gill Formation and a latest Llanvirn-Caradoc age for the Kirkton Formation (Armstrong *et al.* 2002, see below). There is therefore a significant stratigraphical gap (equivalent to the upper

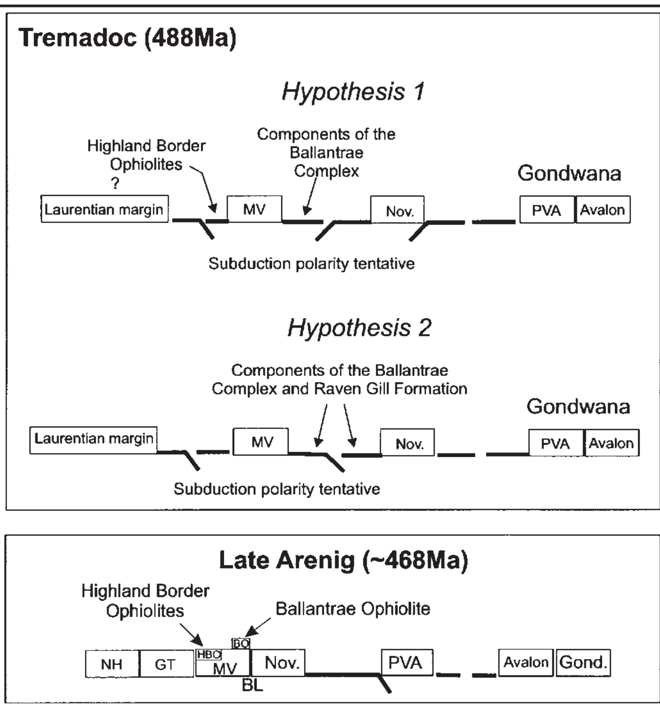

Figure 4. Cartoon illustrating the early Ordovician plate configuration in the northern Iapetus Ocean. See insert on Figure 1 for abbreviations (modified after Armstrong & Owen 2001).

Arenig to upper Llanvirn, approximately 10Myrs) within the Crawford Group. The older deep water succession of the Raven Gill Formation is comparable in age to the Dounans Limestone in the Highland Border Complex and part of the Durness Limestone to the north-west of the Moine thrust zone.

2) Basic lavas within the Raven Gill Formation have been dated at 490±14Ma (Thirwall in McKerrow *et al.* (1985)) indicating a possible late Cambrian-earliest Arenig age; this significantly pre-dates the overlying middle Arenig chert-mudstone succession. Phillips *et al.* (1995) interpreted the MORB-like geochemistry of basalts included within the Raven Gill Formation as island arc tholeiites and volcanic island basalts (influenced by an underlying slab of ocean crust).

3) Cherts within the Raven Gill Formation have a continental margin REE geochemistry (Armstrong *et al.* 1999) indicating Novantia was founded on continental crust.

4) Mid-Arenig conodonts from interbedded mudstones (see Armstrong *et al.* 1990; Armstrong *et al.* 2002) are dominated by *Oepikodus evae*, the eponymous species of the *Oepikodus* Biofacies. This deep water biofacies is typical of lower Ordovician palaeocontinental margins (Stouge & Bagnoli 1990); Novantia was close to the Laurentain margin.

Hypothesis 2. Phillips *et al.* (2003) identified southerly derived detrital-zircon assemblages within the Caradoc Portpatrick Formation in the Northern Belt of the Southern Uplands with mean Neoproterozoic ages of 557, 613 and 1047Ma. They concluded these assemblages were similar to those found in the Gander zone of Newfoundland and were therefore of Avalonian affinity. Difficulties arise however in transporting Avalonian zircons into the Northern Belt during the Caradoc across at least one active subduction zone and through or around the Popelogan-Victoria Arc (see below). They also considered the possibility of Novantia being a potential source of the zircons, in which case this terrane was exclusively Neoproterozoic lacking any Palaeozoic volcanic component. If Novantia was a Neoproterozoic continental fragment rifted from the Gondwana margin during the early opening of the Iapetus Ocean, to become the source of southerly-derived detritus in the Northern Belt Basin during the Caradoc, then the early closure of the Iapetus Ocean must only have occurred along the subduction zone associated with the Ballantrae Complex. The origin of the volcanic rocks in the Raven Gill Formation also has to be re-evaluated. Accepting them as having formed in an island arc setting, they could represent oceanic fragments accreted to Novantia during its collision with the Midland Valley Terrane. This hypothesis is consistent with the view that the Ballantrae Complex is an obducted tectonic melange of slivers of a variety of intra-oceanic crustal blocks (Stone 1984; Bluck in Oliver *et al.* 2003).

Gondwanan terranes of the relict Iapetus Ocean

Popelogan-Victoria Arc (PVA)

In Newfoundland this terrane lies to the south of the Red Indian Line ("Iapetus suture"). This Arenig-Caradoc terrane rifted from the Gondwana margin and drifted northwards from 477-455Ma above a southward dipping subduction zone (Van Staal *et al.* 1991; Van Staal 1994), to collide with the Summerfield Seamount and the Laurentian margin in the Caradoc (Van Staal *et al.* 1991; Prave *et al.* 2000). The PVA terrane has been correlated along strike into the Grangegeeth Terrane of eastern Ireland (Cocks *et al.* 1997). The lower Llanvirn rocks of the Grangegeeth terrane contain graptolites typical of terranes marginal to Gondwana whilst Caradoc rocks contain a shelly fauna rich in Laurentian elements (Harper & Parkes 1989; Owen *et al.* 1992; Romano & Owen 1993, but see also Fortey & Cocks 2003). It is likely that allochthonous masses of basaltic arc-related rocks within the Moffat Shale Group and southerly–derived volcanic arc detritus in the Gala Group were derived from the PVA-Grangegeeth Arc.

Lakesman Terrane

In the late Arenig, Avalonia rifted from the Gondwana margin resulting in the opening of the Rheic Ocean. Until the Llanvirn, sediments were dominated by turbidites (e.g. Skiddaw Group in the English Lake District). These are separated by a regional unconformity from a succession dominated by lower Caradoc volcanic rocks (e.g. Duncannon and Borrowdale groups) that represent the period of climax arc volcanism associated with rapid northwards drift of eastern Avalonia above a southerly dipping subduction zone.

Geology of the post-Grampian Laurentian shelf

Following the Grampian Orogeny, regional extension, possibly along the entire Laurentian margin, caused subsidence accommodating the locally derived, alluvial fan to shallow marine conglomerates (Kirkland and Benan conglomerates) and deeper water Barr Group sediments at Girvan. Armstrong & Owen (2001) suggested the margin was affected by slab pull forces from the incipient subduction zones to the south. They also postulated that as part of this regional extension the composite Midland Valley rifted away from the Laurentian margin to form the Highland Border marginal basin. This hypothesis relied upon cherts, of probable Llanvirn or Caradoc age from Craigeven Bay, near Stonehaven, with a REE profile with a pronounced cerium anomaly characteristic of a mid-ocean ridge setting (Armstrong & Owen 2001).

Southward subduction of the Highland Border Basin beneath the Midland Valley resulted in the formation of the Midland Valley volcanic arc. Magmatic activity in the Midland Valley can be determined from northerly-derived granitic detritus at Girvan. Granite-bearing conglomerates in the Upper Ordovician cover succession at Girvan have ages as young as 451±8Ma (Bluck 1983; Bluck 1984) and are not much older than the sedimentary rocks in which they occur. Subduction towards the north, beneath the Laurentian margin may have been responsible for uplift and granite plutonism in the Grampian Terrane (~460-440Ma, Dempster 1985; Dempster *et al.* 1995). The presence of the Highland Border Basin, with subduction zones along its margins may account for the absence of Grampian flysch in the Southern Uplands Basin.

Ordovician conglomerates in the Northern Belt and Silurian-Devonian successor basins in the Pentland Hills and Midland Valley contain limestone clasts of a similar age to the Stinchar Limestone at Girvan but with a deeper water conodont fauna of the *Pygodus anserinus* Biozone (Armstrong 2000; Armstrong & Owen 2000, Armstrong & Owen 2001). Periodically the distal part of the Midland Valley south of the present Southern Uplands fault was tectonically exhumed to provide a source for the limestone and associated volcanic clasts.

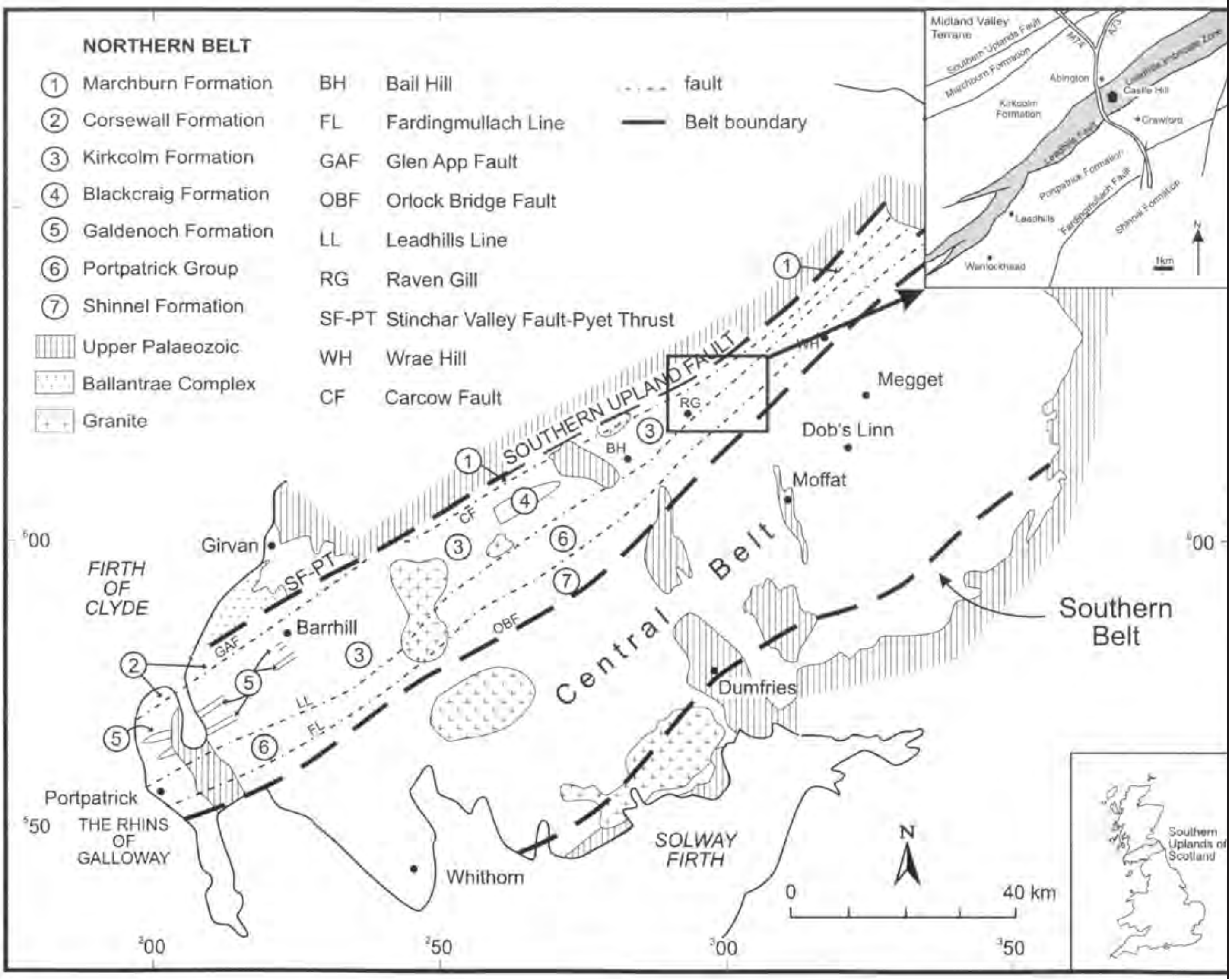

Figure 5. Generalised geological map of the Southern Uplands (reproduced from Armstrong *et al.* 2002, Armstrong *et al*. 1996 with the permision of the Geological Society, London). Inserts show the general location and part of the Northern Belt.

The Southern Uplands as a successor basin

Southern Uplands Terrane

The post-Grampian geology of the Southern Uplands is conveniently subdivided into the Northern, Central and Southern belts, defined by major faults (Figures 1, 5, 6). The strata in any one fault slice generally young to the north-west, but the overall younging direction is towards the south-east. This tectono-stratigraphical relationship and the assumption that the chert succession (Crawford Group: Raven Gill and Kirkton formations) was deposited on ocean crust provided the principal evidence for the Southern Uplands forming part of a fore-arc accretionary prism (McKerrow *et al.* 1977; Leggett *et al*. 1979). This model relies on continuous accretion from the Arenig into the Silurian. Alternative models consider the Northern Belt as a back-arc basin (Hutton & Murphy 1987; Morris 1987; Stone *et al.* 1987) or as an extensional basin adjacent to a continental margin (Armstrong *et al.* 1996). The existence of a large stratigraphical gap within the Crawford Group is inconsistent with the accretionary prism model for the Southern Uplands as this assumes continuous accretion of layer 1 sediments from the Arenig to Silurian (Armstrong *et al.* 2002).

The Kirkton Formation (Crawford Group) comprises basic volcanics, cherts and mudstones. Lavas within the Kirkton Formation were considered by Lambert *et al.* (1981) to be geochemically similar to basalts from ocean islands or continental rifts. Colman-Sadd *et al.* (1992) reinterpreted this geochemistry to be consistent with a back-arc setting whilst Armstrong *et al.* (1996), using the ESCORT expert system for tectonomagmatic discrimination (Pearce 1987), concluded these rocks were predominantly continental, attenuated within plate lavas. The latter interpretation is consistent with the postulated regional extension of the Laurentian margin.

The Kirkton Formation also contains extensive hemipelagic sediments dominated by red cherts. Extensive historical and new conodont samples contain a *P. anserinus* Biozone fauna indicating the Kirkton Formation is latest Llandeilian-Aurelucian, i.e. latest Llanvirn-earliest Caradoc in age (e.g. Armstrong *et al.* 2002). These cherts also have a REE geochemical signature indicative of a continental margin depositional setting consistent with conodonts typical of deep water (Owen *et al.* 1999).

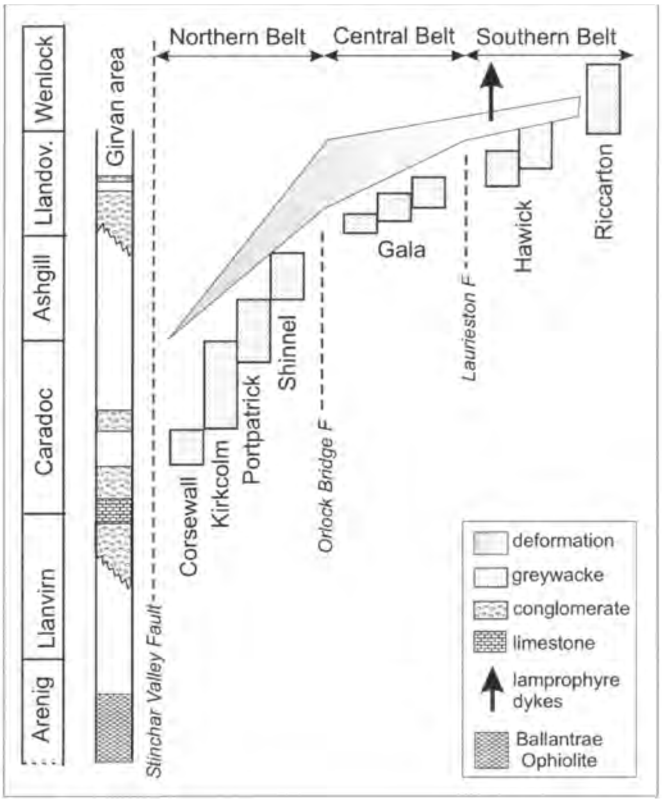

Figure 6. Simplified tectono-stratigraphy of the Southern Uplands showing the onset of greywacke sedimentation (correlated with the shelf succession at Girvan) and deformation. Lamprophyre dykes span the syn- to post tectonic history (modified from Barnes *et al.* 1989; Stone 1996).

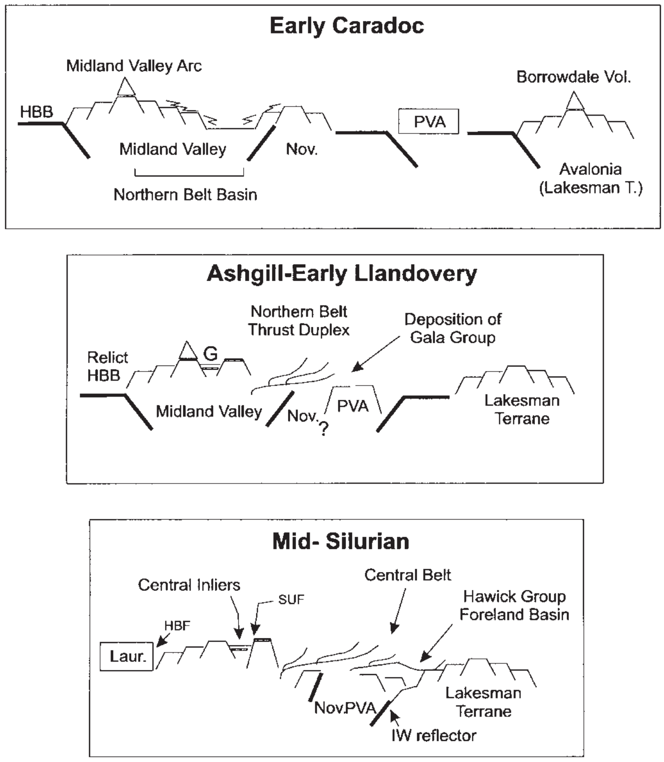

Figure 7. Cartoon illustrating late Ordovician–early Silurian plate configurations in the northern Iapetus Ocean. See insert on Figure 1 for abbreviations (modified after Armstrong & Owen 2001).

The Crawford Group, chert-bearing succession of the Northern Belt, therefore incorporates the juxtaposed sedimentary records of two entirely separate basins, one of middle Arenig (and pre-Grampian Orogeny) and one of Llanvirn–Caradoc age. The youngest, the Northern Belt Basin sensu stricto, entirely post-dates the Grampian Orogeny.

The sedimentary fill of the Northern Belt Basin, to the north of the Leadhills Imbricate Zone comprises greywackes and conglomerates attributed to various formations (Figure 6). The basin received detritus, in the form of deep submarine fan complexes, from both the north and the south during the Caradoc. Northerly sourced detritus had a continental origin including at one horizon bioclasts with a distinctive coralline fauna, including *Kilbuchophyllia*. This genus is only known from here and shelf deposits at Pomeroy in eastern Ireland and indicates the Northern Belt Basin was located to the south-west of its current tectono-stratigraphical position (Scrutton *et al.* 1998). Exposed blocks of the pre-Grampian basement i.e. Novantia and, perhaps, the advancing PVA-Grangegeeth arc were the periodic source of the southerly detritus.

To the south of the Leadhills Imbricate Zone the distal and finer grained equivalents of the Kirkcolm Formation, the Glenkiln Shale and Lower Hartfell formations are dominated by graptolitic shales and provide a complete Caradoc succession. The youngest formations between the Leadhills Imbricate Zone and the southern margin of the Northern Belt, the Orlock Bridge fault are the Portpatrick and Shinnel formations of latest Caradoc and earliest Ashgill age. Limestone clasts in northerly-derived conglomerates within the Shinnel Formation contain shelly fossils (Owen *et al.* 1996) and the distinctive *P. anserinus* Biozone conodont fauna (Armstrong 1997). A similar supply of detritus continued to be provided to late Silurian – early Devonian Old Red Sandstone Conglomerates in the Midland Valley.

Final closure

Oblique collision of the PVA-Grangegeeth Terrane with the Laurentian margin, during the latest Caradoc-Ashgill, initiated inversion and thrusting in the Northern Belt Basin and was responsible for translating the Northern Belt to the north-east from its location to the south of Pomeroy, eastern Ireland. Deformation within the Central and Southern Belts of the Southern Uplands has been shown to be diachronous from the NW to the SE during the Llandovery-Wenlock (Barnes *et al.* 1989; Figure 7). Initial deformation in the Northern Belt was accompanied by thrusting, with sinistral shear becoming important by the late Llandovery (Stone *et al.* 1987) or early Wenlock (Barnes *et al.* 1989).

The southerly progradation of the Southern Uplands thrust duplex from the Llandovery formed the hinterland to a foreland basin that extended to Avalonia (Figure 7). Sediments within the foreland basin (Gala Group) were reworked from the advancing thrust stack. Sedimentary geochemistry indicates a switch in provenance in the mid-Gala Group (Barnes 1998; Williams *et al.* 1996; Barnes & Stone 1999) from an intermittent volcanic source to a source rich in heavy minerals, this may in part represent ophiolitic detritus derived from the Scandian Orogen in Baltica (McCaffery & Kneller 1996). Hawick Group sandstone compositions are uniform, though distinct from the Gala Group and having a carbonate cement matrix. The Hawick and Riccarton group sandstones and those from the Windermere Group in the English Lake

District are similar, consistent with being part of a linked depositional system of late Llandovery to Wenlock age (Stone *et al.* 1999a; Stone *et al.* 1999b; Barnes & Stone 1999) see also references in (Dewey & Strachan 2003; Figure 7).

Traditionally the Eastern Avalonian, arc-subduction complex represented by the volcanic rocks of the Borrowdale Group has been ascribed to the closure of the Iapetus Ocean. Volcanic shutdown in the mid-Caradoc, and hence cessation of subduction is however inconsistent with a final closure of the Iapetus Ocean in the early Silurian (see below). An alternative hypothesis is that this arc may have resulted from the Caradoc closure of the Tornquist Sea between Avalonia and Baltica (Cocks *et al.* 1997). Only the westward extension of this subduction zone resulted in the northward drift of Avalonia towards the Laurentian margin, following the collision of Avalonia with Baltica.

These observations indicate there is no evidence to sustain the accretionary prism model for the Southern Uplands allochthon, at least during its early history. Indeed it is more likely a southerly directed subduction regime followed the Grampian Orogeny, with southerly dipping subduction zones located within the Highland Border Basin to the north of the Midland Valley, and the Iapetus Ocean to the north of the PVA-Grangegeeth Terrane and Avalonia.

The collision of the PVA-Grangegeeth Terrane with the Laurentian margin and the amalgamation of Baltica and Avalonia in the late Caradoc-Ashgill brought southerly subduction to an end. A short period of northerly subduction related to the northwards drift of eastern Avalonia preceded the soft, oblique, docking of Avalonia-Baltica and the Laurentian margin in the early Llandovery (Armstrong & Owen 2001). Northward subduction beneath the Southern Uplands could only have lasted a few million years during the early Llandovery. If this is the case then only the thrusted rocks of the Gala Group represent a possible accretionary complex. The steeply dipping IW reflector-Solway Line represents the suture zone between the PVA-Grangegeeth Terrane and eastern Avalonia.

From the mid-Silurian the Laurentian margin was dominated by sinistral transpression (Dewey & Strachan 2003). Evidence for this lies in the syn-sedimentary strike-slip basins of the Silurian Inliers of the Midland Valley (Soper *et al.* 1992; Smith 1995; Phillips *et al.* 1998), strike-slip reactivation of the Great Glen, Highland Boundary and Strathconan faults (Bluck 1985; Hutton & McEarlean 1991; Stewart *et al*. 2001) and the transtensional setting of the Ayr-Ochil-Sidlaw Ridge (Armstrong & Owen 2001). The Cheviot lavas are Emsian in age (395±3.8Ma, Thirlwall 1988) and lie on vertical and peneplained Wenlock greywackes, essentially all Caledonian deformation had ceased by this time

Implications

This scenario has important implications for the definition of the location of the Iapetus suture. Our thesis envisages the southerly progradation of the Laurentian margin through the Ordovician by the progressive accretion of arc terranes. The northward drift, to lower latitudes of these volcanic islands also led to changes in their faunas to a more Laurentian character. The Highland Boundary Fault marks the southern margin of Laurentia during the early Ordovician. All terranes to the south of this should be considered part of the Caledonian "mobile belt." The Ballantrae Ophiolite (the "Ballantrae Line") marks a terrane boundary within the Midland Valley Terrane and formed just prior to the Grampian Orogeny. If we define the Iapetus suture as dividing terranes of Laurentian affinity from those derived from Gondwana then the origin of Novantia becomes critical. Geophysical, geochemical and dating evidence suggests a greater similarity with Avalonia than the Midland Valley. If this proves to be the case then the Ballantrae Line marks the surface expression of the Iapetus suture and it is a mid-Arenig structure associated with the Grampian Orogeny. The now obscured northern and southern margins of the PVA-Grangegeeth Terrane mark the positions of later sutures as envisaged by Owen *et al. (*1992).

Conclusions

We present a scenario in which the Grampian Orogeny resulted from the collision of two volcanic arcs: Novantia collided with the Midland Valley along the line of the Ballantrae Ophiolite and this composite terrane collided with the Laurentian margin. Extension along the newly formed Llanvirn margin initiated the Highland Border and Northern Belt basins; as marginal basins within the northern Iapetus Ocean. The Highland Border Basin trapped detritus eroded from the newly emergent Grampian Mountains and this was subsequently lost through subduction. The approach of island arcs, including the Popelogan-Victoria-Grangegeeth Terrane and Eastern Avalonia above southerly dipping subduction zones, caused the closure of these basins by the early Silurian. In this mobilistic model the position of the Iapetus suture migrated southwards with the Laurentian margin as new arc terranes were accreted. The closure of the Iapetus Ocean is essentially an Ordovician event.

Acknowledgement

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Book review

Coasts: form, process, and evolution, by Colin D. Woodroffe, 2003, Cambridge, 623 pp, £29.95 (paperback) ISBN 0521912542(hardback) 0521011833 (paperback).

So many existing rocks have been formed on or near coasts – in deltas and estuaries, on volcanic islands and barrier islands, on beaches, reefs, and foreshores – and so many geological processes take place in these areas – erosional, sedimentary, anthropogenic - that any earth science student or teacher must be interested in the forms, processes, and evolution of these features of the globe. What readers of this Journal are likely to want to know is whether Dr. Woodroffe adds materially to the OU texts they will have studied – S236/260, 330, 338, 369 and so on, and if so, whether this a book to buy or to borrow. My opinion is that this is a very useful book to have accessible. It is extremely clearly laid out. The introduction is followed by a most useful chapter on "geological setting and materials" which had a number of points that struck me as ones I hadn't come across (or hadn't taken in). One is the classification of continental coasts as collision (active margins) or trailing-edge (passive mid-plate locations), with "neo-trailing coasts" flanking an active rift such as the Red Sea. They tend to have different forms and processes. A similar division operates with island coasts – but "oceanic crust responds in a simpler way than continental crust." Another point is the section on "materials available to be shaped by coastal processes". Dating coastal landforms, and the extent to which they are Quaternary features, is also helpful. It is a different emphasis, I think, from that to which we are used, and useful as such.

The chapter on coastal processes seemed generally familiar from doing S330, which perhaps even has the edge here. The bulk of the book is divided into the various types of coasts: rocky, reef, beach and barrier, deltas and estuaries, muddy, considered carefully from every possible aspect. The book closes with a chapter on the "morphodynamics of coastal systems" and one on human activities and current and future global environmental change. There are nineteen pages of references, most comprehensive. The examples he chooses through the book are very widely drawn, with a refreshing number from the country where he currently works, Australia, probably not very familiar to most of us and therefore fresh. Many phrases throughout make powerful points – as an example: "The geomorphological significance of an event is governed by the amount of energy it expends on the landscape relative to the resistance of that landscape to change". An impressive work.

Philip Clark, BSc Hons (Open), MA (Oxon)

The Hydrogeology of the Great Northern Coalfield

Professor Paul Younger
School of Civil Engineering & Geosciences, University of Newcastle

Johnny miner, ye were born
Never to see the rising morn
And now it's time that ye were gone,
Farewell Johnny miner…

Farewell Durham,
An' Yorkshire too
Northumberland the same for you
Scotland, South Wales say adieu,
Farewell Johnny miner…

Ye've struggled with the slidin' scale
With blackened lungs and faces pale
And now your body's up for sale
Farewell Johnny miner…

They promised ye the earth sometimes,
To win coal from their stinkin' mines
And now the justice for their crime's
Farewell Johnny miner…

Farewell Durham,
An' Yorkshire too
Northumberland the same for you
Scotland, South Wales say adieu,
Farewell Johnny miner…

And now the colliery's shut for good
And the workings left to flood
The burns run red as pitman's blood,
Farewell Johnny miner…

From Monkton Hall to Silverdale,
From Blenkinsopp to Belvoir Vale
It's New Labour, but the same old tale,
Farewell Johnny miner

Farewell Durham,
An' Yorkshire too
Nottingham the same for you
Scotland, South Wales say adieu,
Farewell Johnny miner…

Well cheer up John, don't take it hard,
Unemployment's not so bad,
They'll treat ye weel in th' knackers yard
Fare well Johnny miner…

Farewell Durham,
An' Yorkshire too
Northumberland the same for you
Scotland, South Wales say adieu,
Farewell Johnny miner…

An opening song[1] which hopefully provides some of the social atmosphere for the more scientific discussion which follows.

Introduction

Everybody thinks of the North-East of England as being finished with respect to coal, but if you look around, coal is still coming from Newcastle. And even when the coal trains stop running (which will be when Ellington and Stobswood stop producing) I do not believe that the history of coal geology in the North East of England will finish with the last train. The resources that remain are many, many times greater than what has already been exploited and my colleagues in the renewable energy sector have yet to come up with anything big enough to replace fossil fuels. I hope they will come up with something, but I shall not hold my breath, and when push comes to shove, I reckon we will be back for carbon in some form or other.

Why should we care about hydrogeology in coalfields? Discharges from abandoned mines can have an utterly devastating impact on watercourses, often wiping them out all the way to the North Sea. Mine drainage may be of neutral or low pH, but irrespective of pH it tends to turn the receiving streams various vivid shades of orange colour, due to precipitation of ochre (ferric hydroxide), which coats the streambed so heavily that no photosynthesis can occur. With no primary production, there is nothing for invertebrates to eat, so there is nothing for fish to eat, so it ends up as a dead stream.

This talk will start with an overview of the geology and patterns of mining of the Carboniferous Coal Measures of north-eastern England, encompassing both the well-known Upper Carboniferous 'Coal Measures' proper, and the the less-often-discussed Lower Carboniferous coalfields (which have posed some of the more interesting problems in recent years). It will then move on to the problems of mine water rebound and pollution prevention that are of prime concern at the moment. I will try to draw some generic insights into what happens when coalfields are allowed to flood. I will finish with a couple of words about our mine drainage remediation research facility, which has been established recently here in the Great Northern Coalfield.

Geology, mineralogy and pollution potential

The Coal Measures of the north-east of England contain significantly more sandstone than the equivalent strata further south. Indeed, in the main Northumberland coalfield, sandstone is the dominant inter-seam lithology. This contrasts markedly with the Midlands coalfields where shale dominates. It is worth remembering that, although the Upper Carboniferous in this part of the UK has a greater total thickness of coal per 100m of stratigraphic sequence than the rest of the Carboniferous, the Lower Carboniferous of the Northumberland Basin actually contains more coal than the main Upper Carboniferous coalfield, because the fewer and thinner seams which it contains are present over a much larger area than that occupied by the main coalfield. This fact, which has long been recognised locally, tends to be forgotten because the seams are generally too thin for underground mining and the areas are too picturesque for open-casting, given our current environmental values. But there is still a huge buried carbon resource up here, which I believe will be needed one day.

[1] Song originally written by Ed Pickford in the 1960s, with more recent additions by the author.

Although everyone knows what coal looks like, it is worth re-examining the odd hand-specimen from time to time (Figure 1).

Figure 1. A typical sample of beautiful vitrinitic coal from Co Durham

The example in Figure 1 is a recently-obtained sample from the Durham Main Seam at Ravensworth Grange Opencast Coal Site. The coal is typical, bright vitrinitic coal with blebs of pyrite on the cleat in the left-hand third of the field of view. The pyrite is the start of the trouble: oxidation of pyrite is the root of all evil in mine water management (Younger *et al.* 2002), as it is responsible for acidification of the water and thus the mobilisation of iron and other problem metals (Al, Mn, Zn etc). As everyone knows, limestone will react to neutralise acidic waters. However, in this region the Upper Carboniferous Coal Measures contain no discrete beds of limestone. However, there are carbonates present, most of which are under-appreciated by sedimentologists. The sedimentologists look at the coal, the mudstones and the sandstones and think, "this is the stuff for a coal sedimentologist!". If they notice the mineralisation on the cleat at all, they are likely to dismiss it as 'late diagenetic gunk'. So cleat mineralisation tends to be overlooked, and the sedimentologists describe the coals, shales and sandstones, coming to the conclusion that the only carbonates in the sequence are siderite ($FeCO_3$) nodules. Now siderite is not especially reactive, and has no net-neutralisation capacity for acidic waters (because every mole of iron released when siderite dissolves in acid water later hydrolyses to release three new hydrogen ions, depressing the pH once more; see Morrison *et al*. 1990). But if you look closely at the cleat of the coal, more important carbonate phases become apparent. Figure 2 is a sample of coal from the same working pit as the example in Figure 1. In Figure 2, the coal itself is a bit duller in lustre than the first example, but more importantly the cleat surface has a substantial spattering of a white mineral phase: this is ankerite ($Ca_2MgFe(CO_3)_4$), which in contrast to siderite definitely does have a strong net-neutralisation potential (Younger in press).

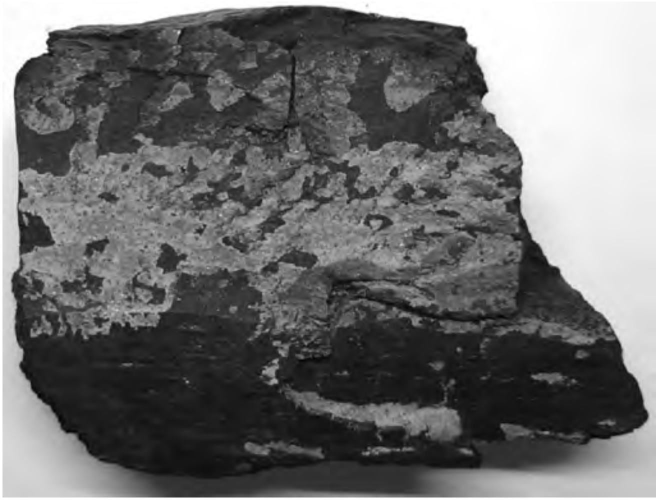

Figure 2. Sample of Durham Main coal seam with abundant ankerite mineralisation on cleat surface.

The overall balance of acidity-generating capacity (principally due to pyrite) and neutralisation potential (due to ankerite and, to a lesser degree, to aluminosilicate minerals; Younger *et al*. 2002) determines the overall acidity/alkalinity balance of waters draining from a given sequence of mined coal measures. However, if you only analyse the mineralogical content and neglect the role of hydrology (in particular time-dependent hydrological behaviour) then you might jump to the wrong conclusions about mine water chemistry. Take a look at Figure 3. This is an open roadway in the High Main Coal at Morrison North Pit, County Durham (exposed by open-casting 100 years after it was first worked). The 100 year old timber-work is not doing so badly, all things considered. On either side of the roadway, the blackness of the coal is evident. But note that floor is light-coloured (actually yellow) due to the growth of ferric and ferrous hydroxysulphates, which are formed by the oxidation of pyrite in a humid but water-scarce environment. These intermediate products of pyrite oxidation are formed above the water table in mined Coal Measures and the real trouble only starts with the dissolution of these minerals when the workings finally flood. Effectively, these minerals store acidity for decades or centuries until the local hydrology changes and they are submerged. Being evaporite minerals, these hydroxysulphates dissolve very quickly once submerged.

At present, the ancient workings of Blenkinsopp Colliery (near Haltwhistle) are flooding and the dissolution of these minerals,

Figure 3. An old open 'bord' in the High Main Seam, Morrison North Pit, Co Durham.
(Photo: Andy Witcomb).

which are abundant in the workings, will undoubtedly acidify the water.

Regional structural framework controls both mining and hydrogeology

The major Upper Carboniferous coalfields of Northumberland and Durham are really one big coalfield, which is delimited:

- on the east by the outer limit of the coastal workings (the last in production being those from Ellington, which stretch 14km out to sea)
- on the west by the outcrop of the lowest seam (usually the Brockwell Seam but sometimes locally the Victoria is the lowest seam of workable thickness)

Internally the coalfield is sub-divided by several major east-west faults (with throws reaching as much as 170m in places) and a number of major WNW-ESE trending 'whin-dykes' (i.e. dolerite dykes). Both the faults and the major dykes represented major obstacles to mining. Where faults had large throws, it was often more economic to proceed to mine the next-deepest seam on the same side of the fault in preference to speculative and costly 'drifting' through bad, steeply-dipping ground either side of the fault plane. In the case of whin-dykes, contact metamorphism was often an issue: depending on the proposed use of the coal, it might be preferable to recover all of the altered coal (as semi-anthracite valuable for metallurgical purposes) or to shun it in favour of more high-volatile coals more suited to the power generation market. Because neither the natural water-bearing strata (mainly the sandstones) nor the mine workings tend to be in continuity across these fault planes or dykes, these features tend also to function as major barriers to the movement of ground water right down to the present-day, long after mine closure.

In the nothernmost part of the Great Northern Coalfield, the major E-W divider is the Stakeford Fault, which ensures that the area where Ellington is working has its own hydrogeological catchment, distinct from the rest of the Northumberland Coalfield. Between the Stakeford Fault and the Ninety Fathom Fault (which approximately defines the Tyne Valley area), a large block of inter-connected Coal Measures have been gradually flooding ever since 1986. At the time of writing (October 2003) pumping is being re-commenced at the former Bates Colliery, Blyth, with a view to collecting all of the mine water north of the Tyne at this one point for treatment and disposal to sea.

The main part of the Durham Coalfield lies between the Ninety Fathom Fault and the Butterknowle Fault (which runs E-W, meeting the coast just north of Hartlepool). We will return to this area later in this paper, as it is an area where lots of changes are underway. To the south of the Butterknowle Faults is the southern Durham Coalfield, from which we have learnt quite a lot about both rebound and mine water quality evolution since pumping was discontinued here in 1975.

Having considered the E-W compartmentalisation of the coalfield, it is worth noting the presence, south of the Tyne, of the Permian Basal Sands and Magnesian Limestones. Together these form a major public supply aquifer, unconformably overlying the mined Coal Measures. (The Permian evaporites also occur some way offshore (on-shore they have dissolved over geological time), where they give rise to some interesting phenomena, such as halite speleothems, as shown in Figure 4). Of more pressing interest from a socio-economic point of view is the process of rebound (i.e. the flooding of mine workings after dewatering ceases) and its possible impacts on both streams and the Permian aquifer onshore.

Predicting rebound

In the early 1990s, when the first pumps were switched off in the eastern part of the Durham Coalfield, we did some preliminary predictive modelling of rebound. Our first finding was that the normal methods used to model groundwater flow are not really suitable for large coalfields, principally because all standard groundwater modelling software assumes that the flow is laminar (because groundwater usually moves very slowly), whereas in a mine there are huge voids which streams can thunder through, with the flow being often highly turbulent. This violates the central assumption of standard ground water modelling software.

Figure 4. Halite speleothems formed from brines seeping into coal workings from the Permian evaporites, Westoe Colliery, South Shields (Photo: A Doyle).

To get around this problem, we developed a new modelling package to simulate really large coalfield systems, and this we baptised GRAM (Groundwater Rebound in Abandoned Mineworkings). In GRAM, the coalfield is divided into discrete ponds (i.e. discrete volumes of highly-interconnected workings which are well-known to mining surveyors). Each pond will be largely separated from an adjoining pond by an unworked pillar of coal (superimposed in successive seams), with only a few inter-pond decant routes. (A lot of these decant routes were deliberately put in during the Second World War when there were fears that there would be bombing raids on the head frames which would have necessitated egress by very distant routes for men who would be trapped underground. The raids never happened (the Nazis being more interested in bombing shipyards at the time), but these old 'emergency exit' roadways have left lasting connections which make for very interesting hydrogeology!). Using GRAM, flow in the ponds is treated simply as a budgeting of water volumes reflected in a gradual rise in water levels, whereas flow along the decant routes is simulated using formulae which describe turbulent pipe-flow.

For more detailed work, we have also developed a more sophisticated model which tries to explicitly model all hydrogeological processes, with a 3-D variably-saturated porous medium model enclosing a 3-D pipe network model (the same sort of pipe network model that is used for simulating water supply networks).

We use this more detailed model (which is called VSS-NET) to represent major mine roadways as a route through the subsurface and play all sorts of games with it; however it needs very high quality mine plan information for its parameterisation and is very data hungry. Very complex models such as VSS-NET are only applied to relatively small systems. If we tried to model the entire Durham Coalfield with it, it would probably take us about 10 years to try to parameterise it and it might well take the computer longer to run the simulation than the water would take to flood the voids in reality!

For further information on GRAM and VSS-NET, a summary paper by Adams and Younger (2001) is recommended reading.

Rebound issues in the Great Northern Coalfield:

When the final closure of all of the Great Northern Coalfield (including Ellington, which was later reprieved) was announced in October 1992, British Coal initially assumed that they would simply implement a complete withdrawal of the pumps. A hue and cry ensued, and when the Coal Authority was formed in 1995, it immediately adopted a more gradual approach than the one that British Coal originally envisaged. Hence in terms of the earlier rebound prediction, we cannot make a like for like comparison. However, where we have been predicting timescales of about 10 to 40 years for northern and eastern areas of the coalfield, we can now say that east Durham is coming in at about the ten-year mark and north-east Durham (South Shields-Sunderland) is coming in at about 20 or 30 years at the moment.

What water resources are we really worried about in terms of the threat from mine water pollution?

I - surface waters

The first big one is the River Wear and its tributaries which forms a wonderful meander around Durham Cathedral, so in campaigning against British Coal's initial plans, myself and colleagues at Durham County Council emotively took that image and made the river red on all the publicity; this definitely attracted the attention of the decision makers. Although the campaign to save the Wear had the desired initial result (i.e. pumping was maintained *pro temp*) later Coal Authority work (which involved suspending pumping at Ushaw Moor) did in fact have the unintended result of producing a bright-orange polluted mine water discharge immediately opposite the Cathedral, emerging out of an old medieval adit driven into the Brass Thill seam. It is just upstream of Framwellgate bridge. Even though it has not turned the whole river red, it certainly caused a few red faces when it came out right opposite the Cathedral!

Residual issues still remain in relation to the Wear, as there is a large public-supply intake from the river near Chester-le-Street, and it is not yet clear whether planned pumping operations on the Durham Coast will be sufficient to prevent some rebound to surface in the Houghton-le-Spring area. This situation is under close monitoring at present.

Second on the list of vulnerable surface water resources are the Northumberland coastal streams, which are in general not very big watercourses (not least because the baseflow they should be receiving has long-since been draining away to the mine workings below). Even if they receive a small amount of mine water discharge these streams will suffer greatly. The new Coal Authority pumping station at Bates should ensure that this never happens.

II - ground waters

Without a shadow of a doubt the most alarming problem currently facing us in the Great Northern Coalfield is the vulnerability of the Permian aquifer in the east Durham area. There are possible problems of leakage across the strata above the shallowest workings through the base of the aquifer. While the Coal Authority and various local government bodies have been vaguely aware of this since our early work flagged this up as a future issue in 1992, the gravity of the threat to the water supply of Sunderland and much of eastern Durham has only recently become clear to the authorities, as a result of a major review which I undertook for Easington District Council. The Coal Authority has discovered that during the working of the coastal mines, British Coal drove roadways into the Magnesian Limestone to obtain water for supply purposes e.g. fire fighting. British Coal apparently did not notify the predecessor agencies of the Environment Agency about this at the time. One of these galleries into the aquifer terminates only 300m from a public supply borehole, so if the water rebounds into that gallery the public supply will be spoilt. While the Coal Authority have flagged this up as a major concern, long before the rebounding water reaches these water drifts the level of water in the mine-workings will be substantially higher than the level of the water in the centres of the cones of depression caused by the public supply boreholes in the Permian aquifer. There is a circular zone around each of the public supply wells in which drawdowns are well below sea level (around -30m in several cases). There is thus a zone in which upflow of polluted water directly into the wells is possible. This is only now being taken fully into account in planning for mine water control, and it is to be hoped that pumping facilities will be in place at Horden and/or Dawdon within the next year to avoid the chance that water supply wells will be permanently contaminated.

Even if the aquifer were allowed to be contaminated, there would still be the issue of Sea Drifts to consider. Sea Drifts were simply horizontal tunnels at sea level, driven from each of the shafts along the coast to save them raising pumped water all the way to the surface of the mine. The North Sea itself would likely go various interesting shades of red if rebound to the Sea Drifts were permitted.

Post-rebound water quality

What do we expect to happen to water quality? In the south Durham Coalfield and parts of the western areas of the main Durham Coalfield, rebounded areas are already overflowing, which provide us with a useful guide. The existence of a phenomenon which we call the ‘first flush’ has been recognised which predicts how water quality will change over time once the mines have finished working (e.g. Younger & Robins 2002; Younger *et al.* 2002). Then there are geological factors, the most important of which is the sulphur content of the strata.

In areas where there is already rebounded mine water, iron is typically in the range 2 to 30mgl^{-1}, these are long-term, settled-down systems, which have already flushed out the acidity that the water picked up when the workings flooded and dissolved all the yellow hydroxysulphate minerals discussed previously (Figure 3). In the actively pumped areas there is less iron because the water is making its way to the sumps by well-washed pathways; it is not picking up much contamination as it is not dissolving the hydroxysulphates which are situated either side of the narrow underground streams. When the water levels rise seasonally in the channels the degree of dissolution rises, but nothing like as much as when wholesale flooding is allowed. In recently flooded areas where the hydroxysulphates have gone into solution there is a lot of iron. Around 400mgl^{-1} is about typical in our coalfield, whilst in Scotland they can get up to around 1500mgl^{-1}. Although it might seem that conditions are relatively benign here compared to parts of Scotland, 400mgl^{-1} is no joke, especially when prior expectations had been around 100mgl^{-1}.

In the south of County Durham there is a very large pollution plume in the Magnesian Limestone aquifer. Fortunately it occurred in a place where there were no existing public supply abstractions. It has wiped out an entire area of the aquifer which could have been used for public supply and is now out of the fresh water inventory forever. The other bad news is that in the 15 years since this plume began to develop, it has migrated down-gradient and is now about to affect one of the Hartlepool Water Company's supply wells. This is very unfortunate, but at least it provides us with knowledge on how the limestone is affected by the rebounding mine waters. Although the mine water is not acidic any more (because dolomite dissolution neutralises the water), and the iron does not travel very far at high concentrations under neutral pH conditions, the water still has a very high sulphate content, far too high for a public drinking water supply, and also very high total of dissolved solids, so it is too saline to drink.

To recap: when the mine first floods to surface it has dissolved all the hydroxysulphates and the water quality is bad at first; then it gradually improves over the years; the timescale for improvement is about four times as long as it took the mine to flood before it settles down. Eventually a residual level of pollution is reached which may not greatly harm the receiving water course, but is still too high to be allowed to discharge without treatment.

The Lower Carboniferous Coalfields

Lest we forget, what about the Lower Carboniferous coalfields? The discharge from the former Bardon Mill Colliery is typical of a long-established discharge from the Lower Carboniferous mine-workings. Even after it has settled-down, long after its 'first-flush' completed, it still has a serious impact on the River Tyne. This reflects the very high pyrite content of the Lower Carboniferous coals, which were almost all affected by marine waters during diagenesis, which has resulted in high sulphur content coals (2 - 4% weight total sulphur). We expect bad water quality where there is such a high sulphur content. The worked Lower Carboniferous coals are almost wholly in Northumberland. There are one or two minor ones on the northern flank of the Alston block (in Cumbria) but there are none in Durham. As mentioned, it is a marine-dominated sedimentary sequence, Fortunately, as this is the Lower Carboniferous, there are also many limestones in the sequence which, if they are present in the material which collapses into the mine as the coal is removed, will help abate the acidity. On the minus side, the limestones in the Lower Carboniferous of Northumberland are not especially thick compared to their southern counterparts.

There have been a couple of recent closures which taught us quite a bit about the Lower Carboniferous. Whittle colliery (closed in April 1997) and Blenkinsopp colliery, near Haltwhistle, which closed just last year (2002) and over which hangs a big question mark.

The problem at Whittle colliery was that uncontrolled rebound threatened the river Coquet, the entire channel of which is a SSSI. If nothing was done there would be severe damage to the river Coquet which would have violated practically every environmental law which has ever been enacted. It also threatened Warkworth water treatment works which supplies very hard-to-replace water to about 150,000 people in south east Northumberland. There was no realistic alternative place to obtain water; a high-pressure main would have to be built very quickly over a distance of tens of kilometres to provide alternative water, so the stakes were very high in this case.

At the time we were working on a project co-funded by the Environment Agency and Northumbrian Water using the computer model VSS-NET. As it was not a huge area of workings we were able to parameterise VSS-NET for the most critical portions of the system and attempt to define the time and volume of water for rebound. We showed that if we ran the model without taking into account the presence of the major roadways, the results showed ludicrously steep gradients developing in the coal workings, but when we included the main roadway the result was a nice flat gradient which agreed with what we saw in the boreholes. This was subsequent to our modelling (the observed rebound). The modelling was all done by July 1998 and then monitoring of rebound continued. It is not often that modellers can compare their predictions with actuality afterwards.

We predicted a coarse rebound discharge rate from the workings at Whittle and predicted that the date that the water would reach 50m below OD as May 2002. Guess when the Coal Authority switched on pumps to maintain the waters at 50m BOD? May 2002! We had a really good fix on when water levels were going to get where within the workings and we worked closely with the Coal Authority. They acquired land, put in a purpose-built borehole, and installed an oxidation and aeration system leading into reed beds. We test-pumped the system on behalf of the Authority in early 2002. The test was a great success: the borehole controlled recovery before an uncontrolled discharge occurred and the treatment system removes 97% of the iron and 96% of the manganese from the mine waters. The water quality leaving the treatment system is so good it actually improves the quality of the water already present in the receiving stream by dilution!

Blenkinsopp colliery worked the Little Limestone coal which is similar to the seam at Whittle. It was the pit in the South Tyne coalfield (not in south Tyneside, but along the south Tyne, way out west in Hadrian's Wall country). It is interesting in that it is the only mine where they have stand-off barriers of coal to avoid affecting Hadrian's Wall! We did a lot of sampling underground. There is a fault plane area underground which has a festoon of drippers precipitating ochre. We sampled all over the pit and obtained unusually good data on what was happening with underground water quality. The water in the workings is locally extremely acidic: we sampled underground on numerous occasions, and in one place repeatedly found a pocket of water which had a pH of 1.9, and iron of 2000 mgl^{-1}, so there are clearly grounds for concern. The pumps were withdrawn in August 2002 when the mining company went into liquidation. The water will overspill from the Smallburn shaft into the Tipalt Burn, which is a major tributary for the Tyne and, if it is not treated, will seriously pollute the Tyne. Before the mine closed we conducted a rebound experiment. We deliberately moved a pump and allowed some shearer panels to flood so we could look at the water quality and see how long it took to flood, so we obtained some reasonable data to play with. We predicted the rebound rate, which is expected to ease off as it rises for two reasons:

i) as the head in the workings rises the inflow from the limestone decreases and

ii) the geometry of the workings changes as you get closer to the surface (changing from collapsed longwall panels to open bord-and-pillar workings).

In summary: the water quality will change during rebound because of the dissolution of hydroxysulphate minerals. It is unfortunate that the seam contains 3% total sulphur by weight and there is no doubt that this will acidify the water dramatically. The pit will also transmit water for a long time to come. The mine roadways which were driven in the 1830s are still in good condition, even though they were already flooded some decades ago and then pumped out again. The pit was shut for about 50 years and given that it has been flooded and pumped out again it is in very good condition. We predict that most areas of this mine will flood by April 2005, the predicted flow rates are going to be around 40% of the total water make during mining. Initially we predict that it will yield very poor water quality, around $300 mgl^{-1}$ iron, but that in the long-term it will settle down quite nicely to closely resemble the waters at Acomb Colliery near Hexham.

Related problems

Rising mine waters are known to aggravate subsidence in some cases. In an old coal mine with bord-and-pillar workings, there is usually a band of seat earth below the seam and fractured roof measures above. As the water comes in it can weaken the seat earth and the and the pillars may begin to "punch" into the floor. Not all the pillars "punch" at the same rate, some go deeper than others, so that bed separation develops above the seam; fractures then develop in the roof and eventually the entire void may collapse, with migration of the void to surface. For a recent review of these and related problems (such as fault reactivation) see Younger (2002).

Mine gas is inextricably linked to mine water. The main problem that we have after closure is not methane, but stythe: oxygen-deficient air. Mine waters release masses of carbon dioxide when they encounter atmospheric pressure; it is a hazard when sampling deep mine waters. The rising water table drives a mantle of oxygen-deficient air ahead of it suffocating anything that becomes engulfed.

There are occasions when rising water pressurises methane which then finds its way under high pressure through cracks. This is a particular hazard when drilling into the old workings to install an observation well; there would sometimes be a rush of gas when you hit a pocket of methane which is caught in a high point in the workings.

CoSTaR

CoSTaR stands for "Coal Mine Sites for Targeted Remediation Research" (see http://www.minewater.net/CoSTaR/CoSTaR.htm). CoSTaR is an outdoor research facility focused on the sustainable remediation of water pollution arising from abandoned mine sites. It is managed by my team at the University of Newcastle. CoSTaR comprises six full-scale passive treatment systems in one small geographical area, with representative examples of the full range of technologies currently applied at full-scale to mine water sites world-wide. Benefiting from substantial routine monitoring data, CoSTaR provides a robust framework of well-characterised systems within which researchers can develop their own top-quality research. In November 2002, CoSTaR was designated as a UK national research facility by the contaminated land 'best practice' organisation CL:AIRE (`www.claire.co.uk`). Anyone who is interested in undertaking research at CoSTaR is encouraged to get in touch (`hero@ncl.ac.uk`) and come take a look at what is on offer.

Conclusion

To conclude; mine water rebound is very complex. It is not just the Upper Carboniferous which presents problems, it is the Lower Carboniferous as well. Prediction of rebound is challenging and, in association with the Coal Authority and others, we are now implementing pollution prevention measures. But incidences of enhanced subsidence and gas emissions linked to water movement, while far less common, are very difficult to prevent.

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Fissuring in the Magnesian Limestone of County Durham

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During many years of underground coal mining beneath the Permian Magnesian Limestone of the concealed portion of the Durham Coalfield, the appearance of open fissures at the surface was generally regarded as an expression of mining subsidence, in some cases several years after mining had ended. (Goulty & Kragh 1989). Despite the ellapse of several decades since the abandonment of mining, open fissures continue to develop, often suddenly and without warning, causing damage to land and structures.

Figure 1. Cracking in surface of A690 road, Houghton Cut, Houghton-le-Spring, City of Sunderland. April 2000.

Attention was focussed upon this phenomenon following the appearance of severe cracking in the surface of the A690 road at Houghton-le-Spring, on the outskirts of the City of Sunderland, early in 2000 (Figure 1). A detailed field survey of several square kilometres around the site revealed active fissuring at a number of locations over a strike length of at least 1km centred upon the damage to the road. The fissuring was found to be concentrated in a narrow linear belt, mainly within the hanging-wall of the Houghton Cut Fault, a major E-W trending fault which cuts both the Magnesian Limestone and underlying Coal Measures. Active fissuring was also identified within the hanging-wall of at least two sub-parallel faults in the neighbourhood (Young & Culshaw 2001).

A major episode of ground movement in the Houghton-le-Spring area early in 2001 resulted in the appearance of new fissures, and the re-opening of pre-existing fissures, over a strike length of at least 0.75km within the hanging-wall of the Houghton Cut Fault (Figure 2) (Young & Lawrence 2002).

Emergency repairs to the A690 road in the summer of 2003, revealed the presence beneath the road surface, of open voids up to 0.66m wide and over 3.0m deep, along the line of the original

Figure 2. New surface fissure. Hillside west of Houghton Cut 2001.

fissure (Figure 3) (Young 2003). Previous geophysical investigations here early in 2002 had indicated no open voids (Cuss & Beamish 2002).

Examination of the Magnesian Limestone outcrop of the Sunderland area and the concealed Durham Coalfield have revealed that exactly similar fissuring is widespread, usually closely associated with known zones of faulting. Whereas in places fis-

Figure 3. Open void exposed in original fissure, beneath surface of A690 road, June 2003.

suring is active in areas long known for such instability, in other areas new fissures have been observed in areas where such fissuring has been hitherto unknown or unrecorded. In all instances underground mining is known to have ended decades ago.

In reviewing possible causative mechanisms, Young & Culshaw (2001) concluded that landslipping, cambering and limestone dissolution did not offer satisfactory explanations for these ground movements. They suggested that the features observed, and the timing of the fissuring events, are consistent with renewed subsidence or fault reactivation, perhaps related to rising groundwater levels within the abandoned coal workings.

Investigations of fissuring, including continued monitoring of movements in the Houghton-le-Spring area, are being continued by BGS and research partners at the universities of Newcastle, Durham, Sunderland and Nottingham Trent, as part of the British Geological Survey's Urban Geosciences and Geological hazards Programme.

This extended abstract is published with the approval of the Executive Director, British Geological Survey (N.E.R.C.).

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Book reviews

Atmospheric Pollution: History, Science and Regulation by Mark Z Jacobson, 2002, Cambridge University Press 399 pages, £29.95 (paperback) ISBN 0521010446.

The author states that the "purpose of this book is to discuss the history and science of major air pollution problems, the consequences of these problems and efforts to control these problems through government intervention" and the book does cover all these aspects well. The book is aimed at students in the environmental Earth and atmospheric sciences and claims to be "detailed enough to be used as a reference text", which it is.

The earlier chapters just cover one area but later chapters discuss the history, science and regulations of a topic. The author states that the problem needs to be severe before action is taken, as it is all political. To quote from the preface "Air is not owned privately, instead it is common property. As a result, air has historically been polluted without limit".

The book makes good use of colour – important names and terms are in blue, examples are in yellow boxes, chemical equations are red etc. It is easy to read, especially the historical sections. Chapter 1 is basic chemistry, I do feel you would need a reasonable understanding of chemistry to understand the book. Chapter 2 should all be familiar, Sun, Earth and evolution of the atmosphere. Chapter 3, Structure and composition of the present day atmosphere – JJ Midgley Junior, who added lead to petrol, had lead poisoning but still concluded it was safe to add lead to petrol! It then has chapters on Urban air pollution, aerosol particles in smog and the global environment, effects of meteorology, effects of pollution on visibility, ultraviolet radiation and atmospheric optics.

Chapter 8 is about regulations of Urban smog, the politics of pollution acts and controls. It looks very briefly at several countries problems and solutions or lack of pollution control. Chapter 9, indoor air pollution is something we do not normally think about. It's a bit worrying that carpets emit 99 different volatile organic compounds!

The last three chapters are what people think pollution is, acid decomposition, ozone reduction, the greenhouse effect and global warming. The author presents the data clearly, with no sensationalism or personal bias, except where Mark Jacobson discusses the regulatory control of global warming and the failure to reduce emissions of black carbon. The book also looks at why other planets don't have global warming and that without the natural greenhouse effect Earth would be too cold to support life. As a textbook I would highly recommend this work and also as a book to read, though perhaps not cover to cover.

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Time-series analysis and cyclostratigraphy: examining stratigraphic records of environmental cycles by G P Weedon, 2003 Cambridge University Press, 267pp £50 (hardback) ISBN 0521620015.

On the back cover, the description of contents describes the book as suitable for senior undergraduate and graduate courses in environmental science, palaeo-oceanography and geology.

In his preface, Weedon says "This book is designed to introduce the main methods used in the examination of qualitative records of ancient environmental changes … explaining concepts, processes and problems, not the details of the mathematics." He has" tried to provide a treatment that is useful to all those interested in time series obtained from a stratigraphic context" and to use diagrams instead of mathematical treatment … to make it available "to non-mathematicians in an accessible form."

However, he assumes the reader's familiarity with concepts of standard deviation, correlation coefficients, moving averages, normal and chi-square distributions and covariance.

There are six chapters of varying lengths, each with its "overview" at the end. The first occurrence of important terms is printed in bold, often together with synonyms " to allow ease of reference to other publications" There is a 30-page list of references and a comprehensive index, but a glossary relating to less familiar and unexpanded terms in bold not otherwise explained, would be helpful. There are plentiful illustrations, one aspect which attracted my attention to the book.

Chapter 1 is introductory and historical; Chapter 2 describes the construction of time series; Chapter 3 considers spectral estimation, methods and processing; Chapter 4 is mainly concerned with techniques for analysing cyclicity as detected in chapter 3; Chapter 5 considers practical matters such as overcoming effects of distortion; Chapter 6 introduces stratigraphic records of various environmental cycles including growth bands (e.g. in shells, ice, trees, sediments) and rocks such as in two records compared for the mean temperature for central England between 1659 and 1996 and the spectra from ice cores. Tidal and Milankovitch cycles are explained at length, also solar cycles and various oscillations.

There is much information relevant to several OU Earth Science courses as diverse as "Oceanography" and "Earth and Life" and the third level soft rocks course, but it would also be useful for more specific studies and for those at a higher level – although despite its excellent presentation on good paper and with robust hard covers, at £50 I think students might well prefer to borrow it rather than buy it!

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The Fossil Collections at the Hancock Museum, Newcastle upon Tyne

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Abstract

The collections at the Hancock Museum have their origins in the private museums of Marmaduke Tunstall (1743-1790), George Allan (1736-1800) and in the collections of the Newcastle Literary and Philosophical Society (Lit. and Phil.) founded in 1793. In 1829 the Natural History Society of Northumberland, Durham and Newcastle upon Tyne (now the Natural History Society of Northumbria, (NHSN)) was formed and took responsibility for the collections. It was prominent members of this society, including John Hancock, who succeeded in raising the funding necessary to build the present Hancock Museum, which opened in 1884.

In the early years of the 19th century, the growth of local mining helped to provide the stimulus for the study of geology and the earliest publications of the NHSN reflect this. It was in this climate of advancing geological thought that many of the most important fossil collections were developed. The distinctive local geology, combined with the interest of local figures such as William Hutton (1797-1860) and Thomas Atthey (1814-1880) allowed major contributions to be made to the developing science of palaeontology, much of which is still of international importance today. This paper aims to provide insights into the palaeontology collections at the Hancock Museum, which are undoubtedly some of the most significant in the UK, with particular emphasis on the Victorian era and the vertebrate collections.

Origins of the Collection

The collections of the Hancock Museum have their origins in the private museum of Marmaduke Tunstall (1743-1790) and in the museum of George Allan (1736-1800) (who acquired part of the Tunstall collection) and in the early collections of the Newcastle Literary and Philosophical Society founded in 1793. These collections, through the formation of the Natural History Society of Northumberland, Durham and Newcastle upon Tyne, (now the Natural History Society of Northumbria), eventually formed the basis of the collections of the Hancock Museum today.

Marmaduke Tunstall, who was actually collecting in London in the mid 18th century, died at his home at Wycliffe, North Yorkshire on 11 October 1790. By the conditions of Marmaduke Tunstall's will, the bulk of his estate, including the Museum and Library, passed to his half-brother William Constable, of Burton Constable Hall, Holderness. However, on the death of William Constable in 1791, the estate passed to his nephew Edward Sheldon (1750-1803). Part of what remained of the Wycliffe estate was sold to Mr George Allan, of Blackwell Grange, Darlington (Jessop 1999).

Allan bought mainly the bird collection, for which he paid £700. What remained of the collection, including the geological material, was sold by auction, by Christies in London in 1742 (Jessop 1999). In 1822, twenty two years after George Allan died, his collection was scheduled to be sold at auction. Through the efforts of George Townshend Fox and others, the collection was bought by private treaty before the auction, by the Literary and Philosophical Society of Newcastle upon Tyne for £400. (Jessop 1999).

Fox published a catalogue and history of the collection in 1827, entitled *Synopsis of the Newcastle Museum* which provided a complete list of the specimens then in the Museum of the Lit. and Phil. The Lit. and Phil. had already acquired a range of material for its own Museum since its foundation in 1793 (Watson 1897; Russell Goddard 1929). For instance, as early as 1794 it received "various curiosities of Nature and Art from the islands in the South Sea, and from China, which may have included items from the Cook voyages."

It had also received a gift of a Wombat, *Vombatus ursimus*, and a duck-billed platypus *Ornithorhynchus anatinus* from Governor Hunter of New South Wales in 1798, both shipped in "a cask of spirits". Fox (1827) notes that "a ludicrous, though somewhat alarming, accident is stated to have occurred on the occasion of …the arrival of the Wombat and Platypus. The woman who was carrying the cask to the Society on here head, burst in the bottom, whilst in that position, when she became almost suffocated, if not drowned, by the discharge of the contents"

The Lit. and Phil. also received two Egyptian Mummies, including *Irt-Irw*, one of the Hancock's most famous objects which was originally one of the mummies collected by Dominique-Vivant Denon (1747-1825), the first director of what is now the Louvre, during the Napoleonic expeditions to Egypt.

It appears, therefore, that none of the original geological collections of Tunstall were purchased by Allan. Fox, in listing the *Minerals or Organic Remains* from the Allan collections in his synopsis of 1827, does not attribute any of the specimens to Tunstall. So what of Allan's geological collection? Unfortunately, at the current time, there has also been no way to identify any geological specimens in the Hancock Museum collections that passed through the hands of George Allan, let alone Marmaduke Tunstall, despite the fact that there is a list of some 253 specimens in the Allan collection (161 minerals and 92 fossils "organic remains"). Fox (1827) describes the situation regarding the geology collections of the Lit. and Phil. at the time:

> "The little attention paid to the subject of Mineralogy sixty years ago, accounts for the small number of Minerals found in this collection. The age and district we live in, are equally favourable for pursuits of this nature, and we are already in possession of an excellent assortment of minerals and geological specimens, by the munificent presents of Mr W. Hutton and Mr. Adamson, and the remains of the once extensive Cabinet of the Philosophical Society of Newcastle, much of which, of late years, has been lost and dispersed, owing to the want of a special Curator".

Clearly, the "little attention" paid to the geological collections of the Lit. and Phil., even before the arrival of the Allan collection, was much to their detriment. The only reference made to fossils in the Allan Museum indicated by Fox is the list of *Organic Remains*. There are no details with this list other than the type of material present, and it is not possible to say with any certainty that these specimens still exist in the collection today, although it is indeed quite possible. The list includes:

“8 Specimens from the Chalk formation, 36 specimens from the Lias formation, 1 specimen from the Magnesian Limestone formation, 7 specimens [of] Vegetable Impressions on Argillaceous Schistus, from the Coal Formation, 25 Specimens of Vegetable Impressions on Clay Iron Stone from the Coal Formation and 15 specimens from the Carboniferous Limestone formation."

Fox (1827) also notes that before the acquisition of the Allan Museum, the Lit. and Phil. already had its own collection of geological specimens. These are listed as:

“A catalogue of the Geological Specimens in the Collection of the Philosophical Society, arranged in the order of Super-position, in four Cabinets in the Committee Room. The greater part of this Collection consists of the extensive donations of Mr Hutton and Mr Adamson, and the whole includes 2667 Specimens…..”

An extensive list of rocks is given, organised according to Conybeare and Philips (1822), of which 1344 were given by William Hutton. At the same time a Mr Harker had donated 88 rock samples, Mr Adamson 606 rock samples and 296 rock samples were identified as belonging to the old Lit. and Phil. collection. In addition there were 71 minerals donated by William Hutton and a further 42 mineral specimens were presented by Hutton and Adamson which were purchased by them in Norway in 1826. In addition to these minerals and rocks, Fox also notes the existence of a further 459 specimens which are described under specific donations. There are also a series of "recent acquisitions" to Fox’s catalogue which describe specimens received by the Lit. and Phil. during the period in which Fox was preparing his synopsis.

Development of the Natural History Society of Northumberland, Durham and Newcastle upon Tyne.

In 1829 the Lit and Phil published a circular "*pointing out the advantages likely to accrue to both sides from the formation of a separate Natural History Society*". In this circular are extensive notes regarding the importance to the region of compiling a representative series of Minerals and Fossils of the district. In terms of the development of a geology collection the arguments were presented as follows:

"A taste for the kindred sciences of Mineralogy and Geology is becoming very general as ornamental and pleasing studies, but their great value is in connection with Mining and Agriculture. Every Overseer and Director of Mines to have sure grounds on which to conduct his operations must understand these sciences to a certain extent. Everyone who has studied the sciences of Mineralogy and Geology will feel, that to attain a knowledge of them without the aid of a Collection of Specimens is impossible. The Society (i.e. the Lit. and Phil.) are in possession of an extensive Collection of Geological Specimens and Fossils, which have been presented by a few individuals, but which are at present totally lost as objects of scientific information.

“The importance of Mineralogical and Geological knowledge, to all persons concerned in mining operations, will be apparent when we consider the immense sums of money which have been lost, even in this district, in a fruitless search for coal and metallic ores, in situations where a slight Geological knowledge would have taught that none was to be expected.

“Placed as we are in the centre of a district where the Remains of Vegetables abound in immense variety and beauty, it has long been felt that a Collection of them ought to exist here, and, although we (i.e. the Lit. and Phil.) could, at a very trifling expense, form one unique as to extent and variety, yet we are stopped at the very threshold by the total impossibility of finding room for them.

“Brongniart, the celebrated French naturalist, when he was preparing materials for his great work on Vegetable Fossils, now in the course of publication, came down to the north in the full expectation of finding a Collection of Vegetable Fossils in Newcastle, and, of course, was much disappointed.”

William Hutton was one of the most ardent supporters of the formation of a Natural History Society. It is clear from the notes above that local scientists found the lack of an organised approach to science in general and the natural sciences in particular, considering its economic importance, intellectually stifling as well as embarrassing (Newman & Chatt-Ramsay 1988). As a consequence of these arguments, the Natural History Society was founded on 19th August 1829 and took responsibility for the running of the Lit and Phil Museum.

In the early years of the l9th century the development and growing importance of local extractive industries provided a particular impetus for the study of Geology, manifesting itself in the earliest publications of the Natural History Society. As an example, of the 28 papers written in the Transactions from 1829–1831, 19 are geological or relate specifically to mining. It is interesting to note that this was at a time when scientists were developing ground breaking ideas about geology and palaeontology (for example Lyell was publishing his "Principles of Geology" (1830-33) and Agassiz was working on his "Recherches sur les poissons fossiles" (1834-44)). This move toward new ideas about the nature of the Earth is reflected in the thinking of local contributors when one considers papers such as the example presented by Nicholas Wood when he published an article in the early Transactions entitled *Account of some fossil stems of trees found penetrating through the strata above the High Main Coal at Killingworth Colliery at a depth of 48 fathoms*. In this he states that

“Without indulging in any theory as to the origin of the Coal itself, if the forgoing premises be made out, we come to the conclusion that the Coal in this particular district was at one time covered by a layer of matter, in which plants of a nature similar to those existing only in tropical climes vegetated; thus proving an epoch when this was the surface of the earth, and which must have remained so a length of time necessary for the vegetation of these plants, previous to their being enveloped by the sediment forming the beds in which they are found.” (Wood 1830).

It is also interesting to note a paper by Henry Witham on *A description of a fossil tree, discovered in the Quarry of Craigleith, near Edinburgh, in the Month of November, 1830*. Henry Witham (1779-1844), born in Minsteracres, Northumberland, was a founder member of the Natural History Society and was one of the first people to use thin sections for the study of fossils. His work was of great importance in the development of palaeobotanical studies in Britain. His figures in his description of a fossil tree from Craigleith, show a number of "magnified sections of branches of fossil tree", illustrating Witham's interest in the microscopic study of fossil plants and demonstrating the development of his thin section technique which he illustrated to such great effect in his *Observations on Fossil Vegetables* of 1831, and *The Internal Structure of Fossil Vegetables* published in 1833. There are 102 palaeobotanical slides from Witham in the collection and they are amongst the oldest palaeontological specimens known in the Hancock Museum today.

So it appears that most of the traceable specimens begin to come to light from the 1830s onwards. In addition to Witham's material, there are a number of other early specimens including a questionable *Palaeoniscus (sic)*, from the New Red Sandstone of Ireland, a selection of fossil plaster casts donated by the Natural History Museum in Paris in 1834, and a *splendid collection of fossil from Sussex* donated by Gideon Mantell between 1834 and 1836.

Continued Development of The Collection

In the early years the Natural History Society continued to develop the collection, which was housed on the 2nd floor of the Lit. and Phil. building on Westgate Road, Newcastle. By 1831, "*additions to the Society's collections had accumulated to such an extent that it was found necessary to rent a large room over the show-room of John Anderson, cabinet maker, whose premises adjoined the Lit. and Phil. building"* (Goddard 1929). At this time it is noted in the reports that William Hutton deposited, on loan, his private collection of minerals at the Museum for "general use".

As a consequence of the growth of the collection, in 1834, the NHS moved its museum to a new building built on land acquired from the Lit. and Phil. behind the present Lit. and Phil. building. During the first ten years of its existence, the Society continued to be placed at the forefront of the development of geological sciences in the region and in 1838 hosted a special reception for visiting scientists who were attending the British Association meeting in Newcastle that year. They included such eminent geologists as William Buckland, Adam Sedgwick and Roderick Murchison, to name but a few.

It is certainly true that the golden age of palaeontological research and discovery at the Hancock Museum took place in the 19th century, particularly between the mid 1820s and 1900, and indeed by a few key individuals. Our first contributor is William Hutton.

William Hutton (1797-1860)

William Hutton was born near Sunderland on 21st March 1797. He joined the Literary and Philosophical Society of Newcastle upon Tyne sometime between 1818 and 1819. By this date he was probably already building up a comprehensive mineral collection, although the earliest record of this is a letter from a mineral dealer in Bristol to Hutton dated May 1827 which gave a list of minerals and prices (Newman & Chatt-Ramsay 1988).

Hutton was a founder member of the Natural History Society, and Honorary Secretary and Honorary Curator of Geology and Mineralogy, a post he held until his health began to fail him in 1847.

Hutton's first recorded donation to the collections of the Lit. and Phil. was in 1825, when he announced his intention to present a series of 1200 geological specimens to the Society. He had also by this date become one of the honorary Curators of the Allan Museum purchased by the Society in 1822. By 1827 he had donated 1344 rock specimens illustrating most of the then identified stratigraphical divisions present in England.

However, by 1828 or so, Hutton was already beginning to amass a collection of fossil plants from the district, the type of collection that, a year later, the members of the future Natural History Society would indicate a great need for. He even exhibited a small collection of "fossil vegetables" at a meeting of the Geological Society of London in 1828, and presented the specimens at this time to that Society.

Hutton began to work on what were to become his most important publications in 1828 or 1829. *The Fossil Flora of Great Britain; or Figures and Descriptions of the Vegetable Remains found in a Fossil State in this Country* by John Lindley and William Hutton, were published between 1831 and 1837. Hutton's co-author, John Lindley, had been recommended to him through Roderick Murchison in correspondence. Murchison had actively been helping Hutton find a competent collaborator for his work.

It is interesting to note that many of the specimens figured by Hutton were collected by some of his mining associates including John Buddle (head viewer of Jarrow Colliery which accounts for the number of specimens from the Bensham Seam of Jarrow) and William Pearson of Felling Colliery where the Low Main seam was being worked. This was a common situation at the time before industrial mechanisation, and in addition to gifts of this nature, miners throughout Britain would often eke out a poor wage by selling specimens to collectors, demonstrating again the close relationship between the mining industry and the development of the subject of geology and indeed mineralogy and palaeontology.

Most of Hutton's plant collection was purchased by the North of England Institute of Mining and Mechanical Engineers in 1857 after it was presented on the open market by Hutton's trustees after an instruction by Hutton to sell the collection (including his minerals). It was eventually given to the Natural History Society in 1883 and the remaining parts, which had been given to Armstrong College, were donated to the Society in 1980.

The Fossil Flora was written at a time when the study of palaeobotany was in its infancy. One of the first works which dealt with the subject on a scientific basis was Adolphe-Theodore Brongniart's *Sur la Classification et la Distribution des Vegetaux Fossiles* of 1822. The first British work which seriously looked at fossil plants was Edmond Turell Artis's Antediluvian Phytology published in 1825 (Newman 1988).

Development of Vertebrate Palaeontology in the north-east

In the latter part of the 19th century, between about 1865 and 1880 there existed in this area a remarkable group of naturalists who turned their talents to vertebrate palaeontology, and particularly to the study of the rich fauna of fish and amphibia from the coal shales of Northumberland. Their descriptive work was of generally high quality and, while not adequately appreciated at the time, was extraordinarily important in speculations in the early part of the 20th century on the origin of tetrapods and the origin of reptiles (Turner 1975).

William King (1808-1886)

William King was appointed curator of the Natural History Society Museum in 1840. He was the first salaried curator, receiving the sum of £100 per annum. There was, however, some dissension from within the Committee. The honorary geologists, including William Hutton, were not all satisfied with Mr. King, because he was also a dealer in fossils and minerals (Turner 1979).

Numerous arguments occurred between the committee and King over his continued dealing and the apparent conflict which existed between this and his professional position as curator of the Museum. It appears that King was trying to supplement his wages by dealing in fossils, as he felt that he was not being paid enough to cover his expenses. King disputed the fact that the Society claimed they made it perfectly clear that dealing in "objects of natural history" was not permitted. In the end, the committee asked King to give up the keys of the Museum. When he refused, they took the drastic step of having the Museum locks changed (Turner 1979). His Curatorship was terminated on 10 November 1847.

It seems that when he left he took most of the Permian fossils he had been working on with him, clearly considering them his private collection, and, after a short stay in London preparing his Palaeontographical Society Monograph which was published in 1850, moved to the newly founded Queens College Galway where he became the first Chair of Geology and Mineralogy.

King was also involved in a quarrel with Richard Howse. Both were working independently on catalogues of the local Permian fossils and on 17 August 1848 Howse's catalogue was published first but closely followed (on 19 August) by that of King. Naturally there was considerable overlap between the two catalogues but King describing many "new" species in his Monograph (1850), ignored Howse's two day priority and defended his action in the supplement to the Monograph (1850) by stating, "It is well known in Newcastle that this (his own) catalogue although published in 1848 was ready for publication in July 1847". Nevertheless, when the supplement to Howse's catalogue was published in 1857 he bitterly attacked King for claiming priority over some of his species (Pettigrew 1979).

Thomas Atthey (1814-1880)

Thomas Atthey is without doubt one of the most important amateur contributors to the collection at the Hancock Museum. Born in 1814 in Kenton, Newcastle upon Tyne, he spent 30 years as a grocer in Cramlington from 1850-1880 until he died. His main research was concerned with coal-measure fish, reptiles and amphibians. Most of his material came from Newsham Colliery, Blyth, possibly the Hannah pit where the shale above the Low Main Seam yielded an incredible assemblage of fossil vertebrates, most importantly Westphalian tetrapods and fish.

It is said that his interest in coal-measure fossils was sparked by the discovery of fossil fish remains on the pit heaps at Newsham where, "with his usual acuteness of observation, [he] saw upon the pit-heap a piece of shale covered with coprolitic incrustations, which he judged to be the remains of fish. He sent it to a friend for analysis, and was gratified to find that his conjectures were correct. Thenceforward the shale of Newsham pit became the one absorbing object of his investigations. [He] sought the co-operation of the mine owners, officers and miners of the colliery and the officials gave directions that the shale should be deposited in a particular spot where Mr Atthey could always depend upon finding it, and some of the men brought him now and then specimens from below, which they thought likely to gratify him." (Welford 1895).

Many of his publications, 20 in total, were written in collaboration with Albany Hancock as well as J W Kirkby. Atthey clearly had financial difficulties and he was eventually saved from bankruptcy by Lady Armstrong who purchased his collection and eventually presented it to the Society in 1878, two years before Atthey died.

Amongst Atthey's most famous specimens include Atthey's "dawn wriggler", *Eogyrinus attheyi* (now *Pholiderpeton attheyi*) and a very rare vertebral column from the same species. Of the fossil vertebrate material held by the Hancock Museum today, almost 70% of the published specimens were collected by Atthey.

Albany Hancock (1806–1873)

Albany Hancock was born in Newcastle and was the elder brother of John Hancock. When the Society built their new Museum on Barras Bridge in 1884 it was John Hancock, the well-know taxidermist and natural historian, who helped to secure so much of the funding necessary to achieve this. The Museum, known as the Newcastle Museum, was re-named the Hancock Museum in honour of the two brothers who had given their lives to the pursuit of Natural History. Albany wrote a number of papers in collaboration with Richard Howse and Thomas Atthey on fossil fishes, reptiles and amphibians. Albany was a key scientific figure of the time and was in correspondence with many of the most eminent scientists of the day, including Charles Darwin whom he assisted in his work on the Cirripedia. Albany was a co-founder of the Natural History Society.

Goddard (1929) states that:

> "Albany Hancock was of a mild, grave and contemplative disposition and treated everyone with whom he came into contact with the utmost courtesy. He was kind, gentle and sympathetic. Although he never married he was extremely fond of children and was beloved by them."

He died on 24 October 1873.

William Dinning (died 1894)

Whilst we are uncertain about the date of William Dinning's birth, he was born in Newcastle and died in 1894. He was Honorary Curator of Zoology at the Society's Museum from 1872-1879, and Honorary Curator of Geology from 1887-1894. He was a prolific collector of fossil vertebrates, and he donated his collection to the Natural History Society in 1871 (Davis & Brewer 1986).

Dinning collected a wide range of fossil fish including examples of *Xenacanthus, Strepsodus, Sagenodus, Ctenodus, Rhizodus, Gyracanthus* and *Megalichthys*. As a consequence of his prolific collecting the collection of *Xenacanthus* material is the largest in the world. This material demonstrates the type of fossils that the Hancock Museum is best known for. Dinning also contributed significantly to the study of Carboniferous amphibians. It was his specimen, for example, of *Megalocephalus pachycephalus*, which was first described and typed by Barkas in 1873 (originally as *Orthosaurus*)

Richard Howse (1820–1901)

Howse was Honorary Curator in 1848, General Curator from 1866 and salaried Curator from 1882 until 1901. He was primarily concerned with the geology and palaeontology of the Permian system and published his *Catalogue of the Fossils of the Permian System of the Counties of Northumberland and Durham* in 1848. He also published *A Guide to the Collections of the Local Fossils in the Museum of the Natural History Society, Barras Bridge, Newcastle upon Tyne,* in 1889, just five years after the new Museum on Barras Bridge opened (now the Hancock Museum). This publication has proved to be a valuable source of information about the early collections of the Museum.

His main collaborator was Albany Hancock, and together they published their work on numerous Permian vertebrates including *Dorypterus, Protorosaurus, Jannasa* and *Lepidotosaurus* (see Joseph Duff below). Howse's collection at the Museum is not vast, he tended to publish on material collected by others, but he did collect numerous Permian invertebrates and published some of his findings in the Transactions of the Tyneside Naturalist Field Club.

James Walker Kirkby (1834-1901)

Kirkby was born in Sunderland in 1834. He was curator of Sunderland Museum and prior to this, manager of Pirnie Colliery, Fife, Scotland. He was a specialist in Permian and Carboniferous microfossils and fossil fish from the Magnesian Limestone. His collections include a huge selection of the fish *Acentrophorus* mainly from Fulwell, in Sunderland. The collections, which are split between the Hancock and Sunderland Museums, constitute the largest collection of this genus in the world.

Joseph Duff

Duff donated material to the Society in the 1860s. He is perhaps best known for his work on the Marl Slate of Middridge in Co. Durham. This site was made available to him "as a consequence of the Stockton and Darlington Railway Company widening a portion of their line at that place" (Biography in Duff 1885).

He was certainly one of the more fortunate collectors in the region, having found the only two Permian reptiles known from the Marl Slate at that time (which remained true until 1978 when a third example, the gliding reptile *Ceolurosauravus,* was found at Eppleton Quarry in Hutton le Hole, Co. Durham, and a fourth example, *Protorosaurus*, was found at Quarrington Quarry in Co. Durham in 1993). His specimens at the Hancock Museum include the Permian reptiles *Adelosaurus huxleyi* and *Protorosaurus speneri* as well as examples of the rare Permian fish *Dorypterus hoffmani.* Together with Albany Hancock he also described a new labyrinthodont amphibian from the Magnesian Limestone of Middridge which was named *Lepidotosaurus duffi*. This was reputedly the only example of an amphibian from the Permian. Unfortunately it now appears that it may be a large example of the Permian fish *Platysomus* (pers comm Silvano and Brandt 1998).

Thomas Pallister Barkas (1819–1891)

Described as abstainer, vegetarian, hypnotist, astronomer, spiritualist and compulsive lecturer. He was a regular contributor to "Science Gossip" in the 1860s and 1870s. He appears to have been the "odd one out" in the group of friendly vertebrate palaeontologists working in the area in the mid to late 1800s. It has been said that he delivered over 3000 lectures to the people of Newcastle on a huge range of subjects including electricity, Galvanism and magnetism, and "one gets the impression that from around the 1840s it was impossible to venture out of doors without being subjected to a lecture by Thomas Pallister Barkas" (Turner 1975).

He published two major works; *An illustrated guide to the Fish, Amphibia, Reptilia and supposed Mammalian Remains of the Northumberland Carboniferous Strata* published in 1873 and *Outlines of ten years investigations into the phenomenon of modern spiritualism* published in 1862.

Barkas had a major row with Albany Hancock and Thomas Atthey over the identification of a "supposed mammal" described by Barkas in his Illustrated Guide. He was naturally very excited about this find as it seemed to go against everything which was known about the fossil record of mammals. Even some of his family and friends were sceptical and when Thomas Atthey and Albany Hancock presented a paper questioning his identification, he wrote to the *Newcastle Daily Journal* and made some "unfortunate remarks " about Thomas Atthey. "Besides implying that he was of limited education he stated that he merely collected the fossils which Hancock then described, taking no intellectual part in the relationship" (Jeffrey 1998). Barkas eventually sent this specimen to Richard Owen who identified it as a fish.

He amassed a large and important collection of material most of which is now in the Hancock Museum. This includes a fossil trackway from Otterburn, of what he decided was "a quadruped", or more specifically a "small, broad, four-legged mammal" which he named *Platytherium psammobates*.

A New Museum

In 1884, after much planning and a great deal of fund raising, the Society opened its new Museum on Barras Bridge. In 1891, this Museum, still known as the Newcastle Museum, was re-named The Hancock Museum after the brothers John and Albany Hancock, both co-founders of the Natural History Society in 1829.

Undoubtedly a Golden Age of palaeontological discovery at the Museum was over. Nevertheless, over the next century, the collections continued to grow, mainly through donations. Researchers from all over the world began to recognise the importance of the material held by the Museum, and indeed the value of the Victorians' work upon them. For example, the well known vertebrate palaeontologist Professor D.M.S Watson, who made a succession of visits to Newcastle before and after the first World War, recognised the key importance of the Carboniferous fauna in the study of the origin and evolution of tetrapods. In the 1980's Dr Alec Panchen, of the University of Newcastle, worked with a series of PhD students on the Carboniferous amphibian collections and to date over 60 papers have been written on this part of the collection.

Early research into the fossil fish collections never reached the intensity of that enjoyed by the amphibians. In recent times this situation has changed and as a consequence the Hancock collections are receiving more and more attention from workers in Europe, the USA and Australia. Their significance is heightened by the fact that the advanced technology of modern coal-mining seldom gives the opportunities presented in the 19th century to acquire fossil specimens and hence the collection is irreplaceable (Turner 1975).

John Dunn (1865-1937) added significantly to the invertebrate collection through his interest in the Carboniferous invertebrates of Redesdale. A. Logan published his monograph of the Permian Bivalvia of Northern England in 1967 using much of the material in the Hancock collection.

Palaeobotany continued to receive significant attention. Many of the fossil plants in the collection were identified and studied by Robert Kidston (1852-1924) and figured in his *Fossil Plants of the Carboniferous Rocks of Great Britain* published as a memoir of the Geological Survey of Great Britain between 1923 and 1976. It was also the work of Dr Albert Long, deputy curator of the Museum from 1966-1980, on coal balls of Northern England and Southern Scotland, which placed the Museum firmly at the forefront of palaeobotanical research. Long's collection, which is rich in type material, consists of over 15,000 palaeobotanical slides and over 10,000 coal balls.

Some of the more historically interesting specimens which are now held at the Hancock Museum include a nodule containing the fossil of Coccosteus from Cromarty, once owned by Hugh Miller, a large Ichthyosaur from Whitby, and several large fossil trees including one found in a quarry near Stanhope in 1914. It is also worth noting that the Museum holds an extensive archive, which includes original correspondence from a number of eminent geologists and collectors including Owen, Murchison, Sedgwick, Mantell and even Mary Anning.

Most new material now comes to the Museum through donations or through the, often limited, collecting pursuits of staff. The most important new addition to the collections over recent years has been a Carboniferous amphibian skull, discovered by Dr. Dave Martill of Portsmouth University on the coast at Whitley Bay, and described as a new genus (*Kyrinion martilli*) by Jenny Clack (2003). This is one of the very few local Carboniferous amphibian specimens to be added to the collection since 1891 when T P Barkas's collection came to the Museum.

It is undoubtedly true to say that a great deal of important material still awaits discovery, or perhaps even re-discovery. Certainly not all of the published material in the collection has been accounted for. An example of the treasures that lay hidden in the Museum is a collection of Old Red Sandstone fishes from Achanarras in Scotland which had been acquired through Prof. Stanley Westoll of Newcastle University and his association with a collector known as Murray Threipland. This collection lay in the Museum for over 30 years until it was investigated by researchers from Aberdeen University. On examining the contents of over 50 boxes, a new species of fish was uncovered (Newman 2002). There are undoubtedly discoveries still to be made!

Conclusions

In this paper I have really only scratched the surface of the history of the palaeontology collections at the Hancock Museum. There is a huge amount of material, and a large number of collectors that I have made no reference to at all…a consequence only of the limits of space and time. Inevitably, the emphasis has been on the vertebrate fossils at the Museum, the part of the collection that has perhaps been the subject of most research. However, there is still a great deal of work to be done and in order that this is possible we must continue to strive to make the palaeontology collections as accessible as possible to the research community, and indeed the wider community as a whole. By doing this we can, in some small way, achieve part of the objectives that were the driving force for the formation of the Natural History Society. After all, as they enthusiastically stated in their circular of 1829:

> "The study of fossil Organic remains is of great importance ... indeed it is from them and the wonderful views of nature they unfold, that Geology derives its great interest for the general reader."

Acknowledgements

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Book reviews

Igneous Rocks A Classification and Glossary of Terms 2nd Edition by R W Le Maitre (ed), 2002, Cambridge University Press, 236pp £45 (hardback) ISBN 052166215X.

All students of the Earth Sciences will sometimes have grappled with the names given to igneous rocks. The variety of names often teased my tired brain as assessment dates loomed and passed, so it is with some comfort to learn from this book that a group working under the auspices of the Internation Union of Geological Sciences (IUGS), with the help of 456 contributors from 52 countries have taken more than 30 years to come to agreement on a nomenclature for igneous rocks.

There are two main sections: Classification and Nomenclature; and Glossary of Terms. In order to overcome the problems of classification, 9 principles are described and the parameters discussed. There are familiar tables for such measures as the colour index and glass content, but it is in the establishment of root names to which are added qualifier and definitions that the basis of the work has been done. The working group has recognised that one system cannot be used for all igneous rocks, so such groups as pyroclastic rocks and tephra; plutonic rocks and volcanic rocks are dealt with separately. For the last two QAPF (quartz, alkali feldspar, plagioclase, feldspathoid) with provisional field classificaltion is described very clearly. The TAS (total alkali-silica) classification for volcanic rocks is equally well explained. There is fascinating detail here and it is comforting to know that all the hours of pain I endured trying to sort out which rock was which has proved so very difficult even for experts. Painstaking work is evident throughout this section of the book. Altogether, the methods of classifying eleven groups of igneous rocks are included.

The Glossary of Terms takes up just under half the book and it contains 1637 names with each entry containing five types of information. All the root names recommended by the Working Group, together with general adjectival and chemical terms necessary for definition and understanding are listed in bold capitals - some 316 entries. 413 obsolete terms are included but it is hoped that these will not be revived; 312 are local terms. The remainder of terms, 465 of them, are printed in normal type. These consist of terms where the root name might have been used if the rock had be classificed by the IUGS Subcommission but are termed "... a variety of ..." For anyone enthusiastic about the history of igneous rocks there is a wealth of information here.

There is a 46 page Bibliography of Terms with 809 references as well as tables charting the history and origin of new rock names. There are three Appendices: A, is a list of participants: by country in alphametical order and by name and country. The recommended IUGS names are listed in Appendix B and Appendix C contains a description of the IUGSTAS software package and instructions to use it. The C++ program to implement the TAS classification for volcanic rocks and CIPW norm calculations may be downloaded from the Cambridge University Press Website. Both Mac OS and Windows versions are available.

This volume is intended to become a standard reference. It is far from a dry text being full of interesting information and written so well that it is a shame that the price will put it beyond most people's pocket.

Jane Randle BA(Hons) MPhil (Open)

Lithics: Macroscopic Approaches to Analysis by William Andrefsky Jr, 1998, (xxvii + 258 pages, 100 black and white figures, 36 tables, glossary, references, index. Cambridge University Press, £16.95 (paperback) ISBN 0521578159.

This is a comprehensive guide to ancient stone tool studies and analysis. Andrefsky describes in detail how to record, describe, measure, and analyse stone tools and the debris from their production. The book comprises ten chapters. The first five chapters introduce the reader to the fundamentals of lithic studies, raw materials and production techniques, terminology, classification and the basics of standard analysis procedures. The second half of the book addresses various more sophisticated analytical techniques, both for tools and for debitage, and finishes with several detailed case studies of lithic analyses from cultures in several part of the world and of various dates. A concluding chapter sums up the book and describes how the author approaches the teaching of stone tool analysis to students. This book is a welcome manual and overall summary to lithic artefact studies, and its twenty pages of references will serve as a rich source for students and excavators.

Dr David M Jones, OUGS Newsletter Editor

Early Palaeozoic magmatism in northern England

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Igneous rocks contributed very significantly to Early Palaeozoic crustal growth in northern England, and the buoyancy effect of these mainly granitic rocks beneath the Lake District, Cheviots and the Askrigg and Alston areas of the north Pennines was to have a profound effect on the later development of Carboniferous and Permo-Triassic extensional basins in the region. In late Ordovician (Caradoc) times, northern England saw one of the most intense episodes of magmatism in the history of the British Isles when voluminous subduction-related igneous rocks were generated at the margin of Eastern Avalonia as the Iapetus Ocean and Tornquist Sea closed. A chain of volcanoes extended from Ireland through the Lake District and English Midlands to Belgium; magmatism lasted for less than 5Ma. Some 5-10Ma later, in Ashgill times, silicic volcanism was renewed in the Lake District and contiguous areas. By contrast, some 40Ma later, in Early Devonian times igneous rocks were emplaced before, during and after the Acadian Orogeny adjacent to the Iapetus suture (Figure 1).

Caradoc magmatism in the Lake District produced the Eycott (EVG) and Borrowdale (BVG) volcanic groups and components of a large, subvolcanic, granitic batholith (Figure 2). The Wensleydale Granite underpinned the Askrigg Block at this time. Though many of the granites and associated minor intrusions have geochemical affinities with the BVG, the distinctive Eskdale Granite is more typical of granitoids with sedimentary protoliths ('S-type'). The mafic magmas were derived by partial melting of a common lithospheric mantle source enriched to different levels in incompatible elements through subduction-derived aqueous fluids. Subsequent geochemical divergence into suites with tholeiitic, calc-alkaline and transitional affinities resulted from varied amounts of partial melting, crystal fractionation and assimilation of crustal material.

In Early Devonian times sporadic lamprophyre dykes were emplaced throughout northern England and southern Scotland during a period of transtension, and the ensuing high heat-production granites at Shap, Skiddaw, Weardale and Cheviot and their associated microgranite dyke swarms were emplaced towards the end of the Acadian Orogeny. The last of these granites underpins a substantial andesitic volcanic field in the Cheviot Volcanic Formation. The lamprophyric magmas are high melt fractions of depleted oceanic lithosphere metasomatized by aqueous fluids derived from remnants of Iapetus oceanic crust and by

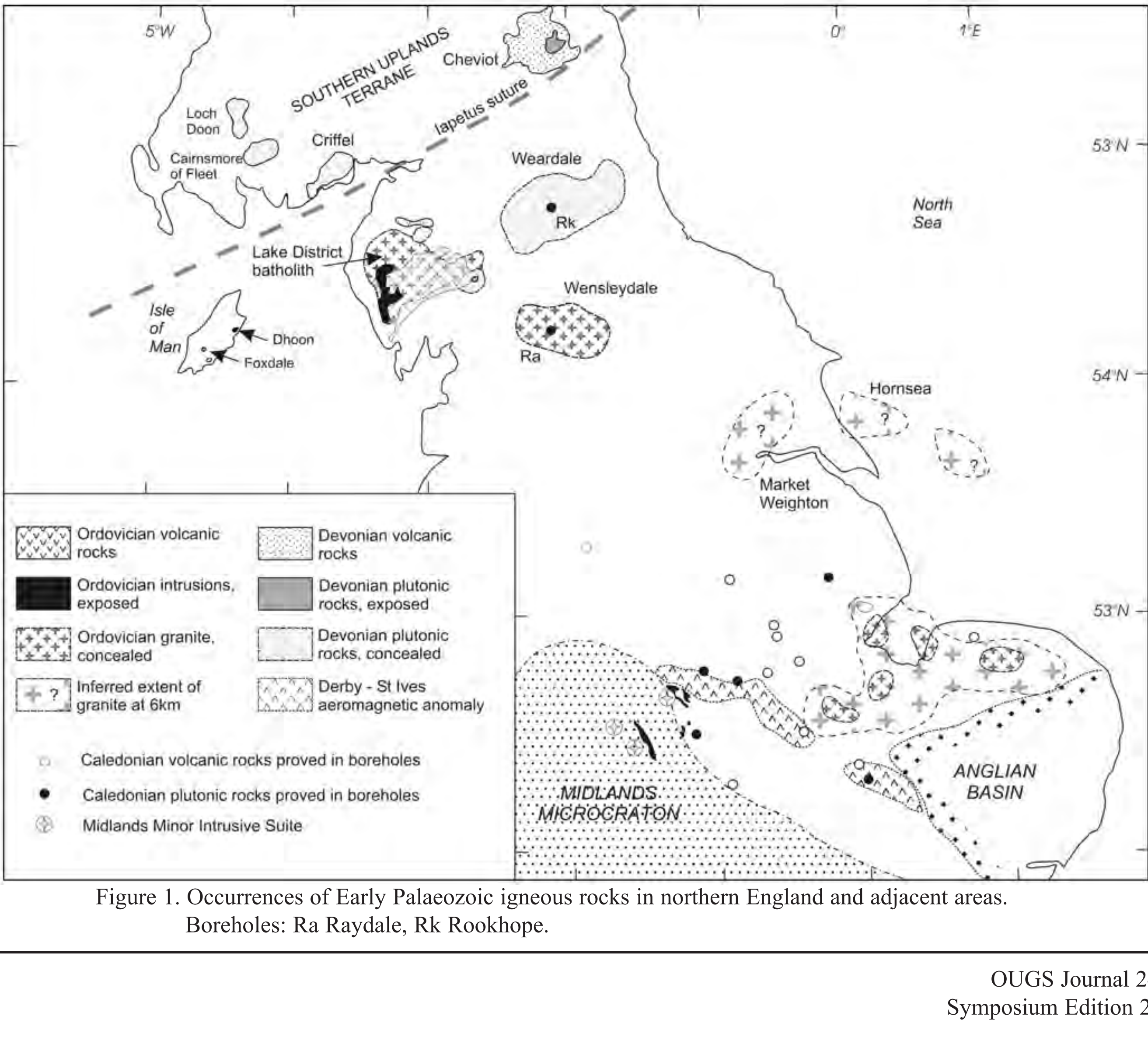

Figure 1. Occurrences of Early Palaeozoic igneous rocks in northern England and adjacent areas. Boreholes: Ra Raydale, Rk Rookhope.

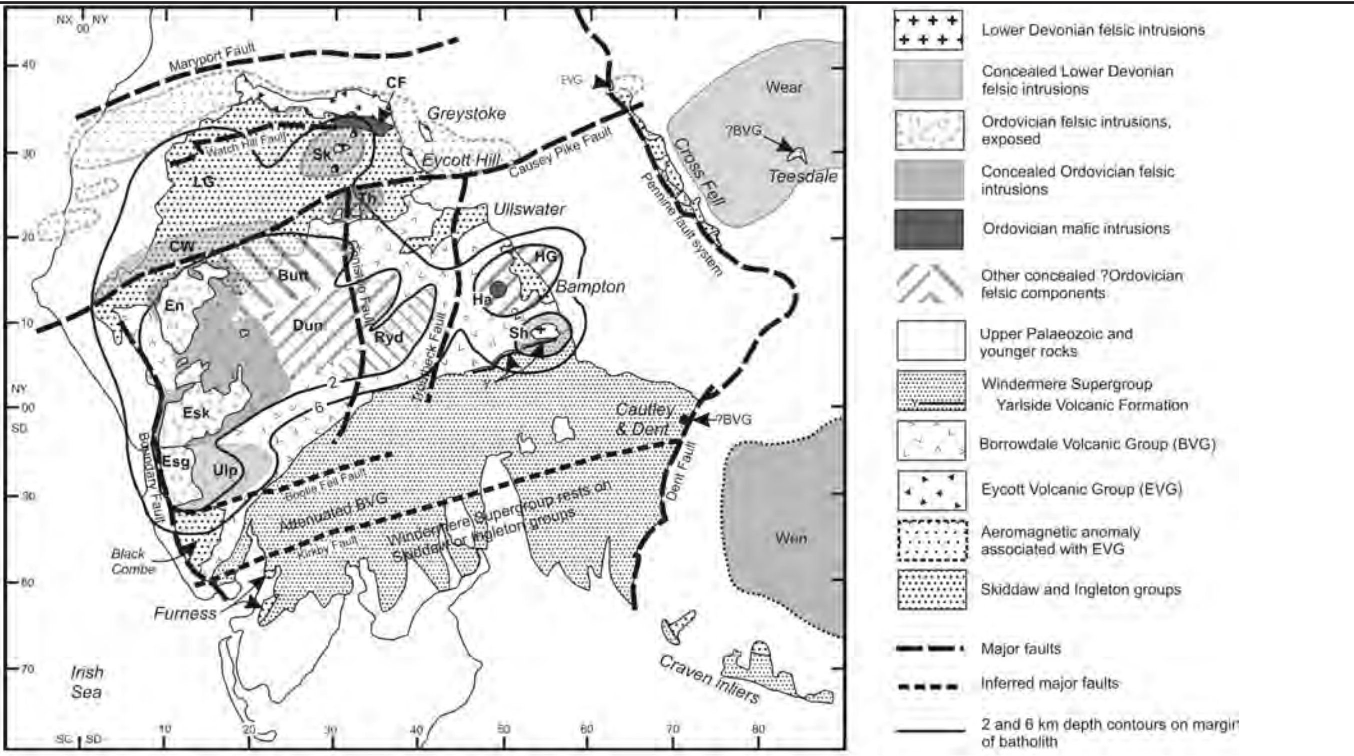

Figure 2. Lower Palaeozoic igneous rocks of the Lake District and adjacent areas. Butt Buttermere Granite, CF Carrock Fell Complex, CW Crummock Water Granite, Dun Dunmail Granite, En Ennerdale Intrusion, Esg Eskdale Granodiorite, Esk Eskdale Granite, Ha Haweswater Intrusions, HG Haweswater Granite, LG Loweswater Granite, Ryd Rydal Granite, Sh Shap Pluton, Sk Skiddaw Pluton, Ulp Ulpha Granite, Wear Weardale Intrusion, Wen Wensleydale Intrusion.

a CO_2-rich phase from deeper in the mantle. By contrast, the evolved calc-alkaline granites were probably derived from a mafic source that contained residual garnet.

During the last twenty years, the British Geological Survey has systematically resurveyed the Lake District Lower Palaeozoic Inlier and has produced the first set of 1:50 000-scale geological maps covering all the igneous rocks in the area since the primary survey more than one hundred years ago. The multidisciplinary investigations have produced new, high-precision U-Pb zircon dates that have clarified the magmatic history of the region (Figure 3).

Eycott (EVG) and Borrowdale (BVG) volcanic groups

The rare preservation of subaerial volcanic successions such as the BVG in the geological record, the superb quality of the glacially sculpted exposures, depth of erosion and relatively low strain, allow a three-dimensional view into this magmatic system rarely seen in modern examples. The BVG is unusual among examples world-wide of subduction-related volcanic suites because it contains high-grade ignimbrites and garnet phenocrysts. Remarkably, trails and trackways attributable to a myriapod-like organism, found at two localities in lacustrine volcaniclastic rocks, are of the earliest known terrestrial arthropods. The importance of these ichnofossils is that they suggest that some terrestrial arthropods emerged on to land from a freshwater, rather than marine, environment. These fossils pre-date the appearance of vascular land plants by more than 20Ma.

The BVG comprises at least 6000m of subaerially erupted basalt, andesite, dacite and rhyolite lavas, sills and pyroclastic rocks, of medium to high-K, continental-margin calc-alkaline affinity. There were two contrasting phases of volcanism. The initial one was dominated by andesite effusions that constructed a lava plateau of low-profile monogenetic volcanoes. The 3200m-thick EVG closely resembles this first phase of the BVG but has geochemical characteristics that are transitional between calc-alkaline and tholeiitic. The ensuing second phase of the BVG was characterized by large-magnitude silicic pyroclastic eruptions, with ignimbrite formation, volcanotectonic faulting and caldera collapse. The largest of these events blanketed the entire BVG sequence with between 150 and 800m of welded ignimbrite. The ignimbrites are intercalated with units of volcaniclastic sedimentary rocks, which are commonly invaded by andesitic intrusions, many of which have peperitic margins.

At least eight depocentres operated during aggradation of the upper BVG and some of these have been identified as calderas (Figure 4). Most of the depocentres are aligned along an ENE trend through the central Lake District and were underpinned by components of the Lake District batholith. To the south, parallel to these, lay two further mixed sedimentary and pyroclastic depocentres. The major phases in development of the BVG are summarized in Table 1.

Volcanotectonic collapse and caldera formation are a fundamental mechanism in preservation of this subaerial sequence. However, it has also been shown that this operated within two larger, intra-arc extensional basins within which the EVG and BVG accumulated. The Maryport and Causey Pike faults mark the boundary of the former, and the Causey Pike and inferred Kirkby faults the boundaries of the latter (Figure 2). Other major basin-forming faults in the region include the northerly trending Lake District Boundary, Troutbeck and Pennine fault systems. The complex history of these large faults implies a significant role for re-activation of fractures in the Avalonian basement. Removal of

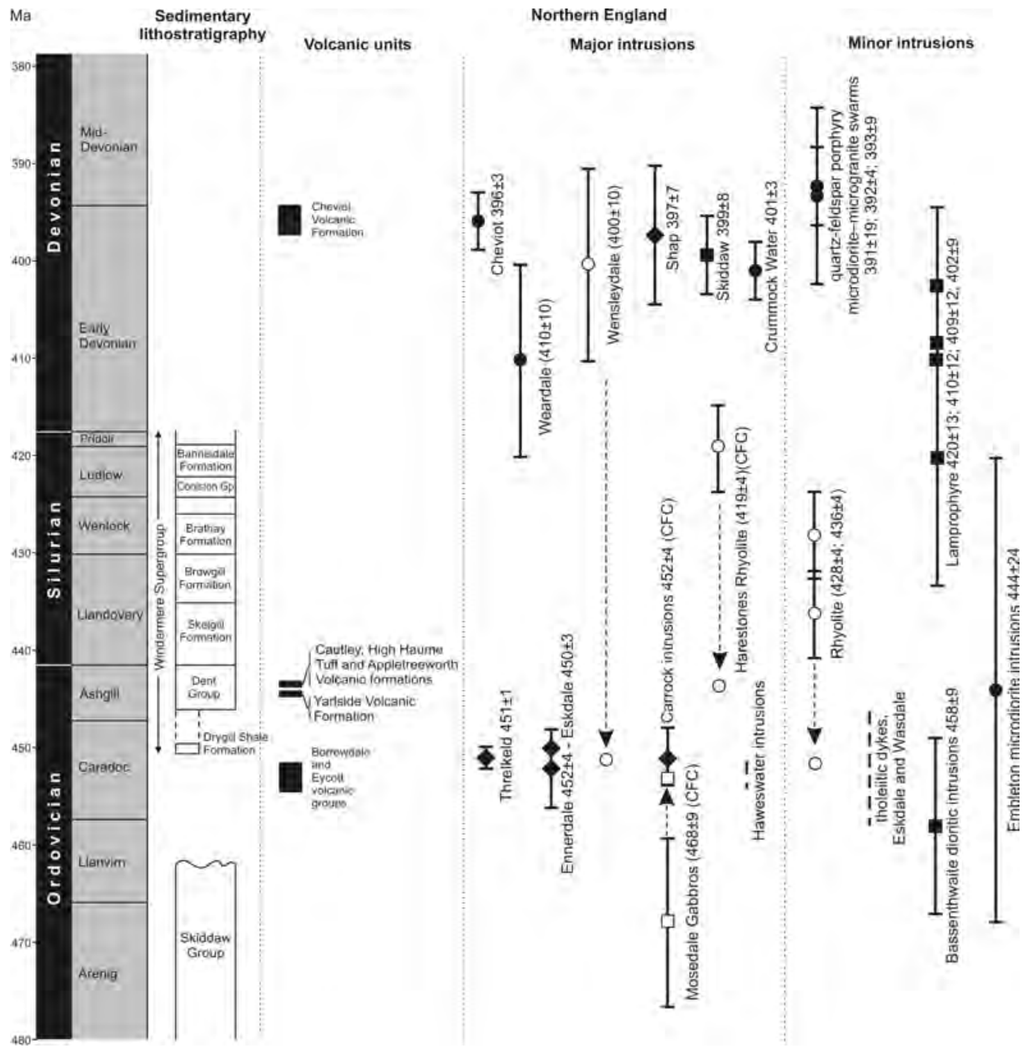

Figure 3. Summary chart showing the stratigraphical distribution and radiometric ages of igneous rocks in northern England. Radiometric dates are in Ma with errors quoted as 2 standard deviations: diamonds U-Pb, circles Rb-Sr, squares K-Ar. Open symbols represent radiometric data for igneous bodies, the ages of which are considered to have been reset; the inferred emplacement age is shown without errors. The ages of the Haweswater Intrusions and the tholeiitic dykes are inferred. CFC Carrock Fell Complex.

Acadian strain shows the original width of the EVG and BVG graben to be 40km and 50km respectively, figures that are not unlikely compared with the currently active Taupo Volcanic Zone of North Island, New Zealand, which is 300km long and up to 60km wide.

Lake District batholith

In the 1960s and 1970s geophysical interpretations linked the outcrops of major intrusive bodies in northern England to large concealed granitic masses. The subsurface extent of the Lake District batholith is more than $1500km^2$ and it comprises numerous components (Figure 2). Seismic reflection profiles across the western margin of the batholith show the western margin to be a tabular sheet complex with a cedar-tree-like form. Exposed components of the batholith, such as the Eskdale and Ennerdale granites have laccolithic forms and Caradoc isotopic ages, suggesting that the concealed tabular components may also have been emplaced during the same event. By contrast, the Early Devonian Shap, Skiddaw and possibly Ulpha granites are steep-sided plutons marginal to the batholith (Figures 2 & 3).

Ordovician intrusions

The *Ennerdale Intrusion* is a tabular body with an outcrop of about $53km^2$. Granophyric granite dominates, but marginal dolerite, dioritic, and hybridized dioritic, granodioritic and melanocratic granitic rocks occur locally. The dolerite possibly represents sidewall cumulates from crystallization of an early dioritic magma, but emplacement of the more voluminous granitic magma whilst the former was still hot and partly crystallized led to the local formation of hybrid rocks. Associated rhyolite dykes are abundant locally.

The *Eskdale Intrusions* are granite and granodiorite bodies with outcrops of $53km^2$ and $23km^2$ respectively. The former is mainly a semi-concordant sheet near the base of the BVG consisting of muscovite granite and varieties of microgranite. Quartz–white mica and quartz–topaz greisens occur locally, the latter associated with quartz–andalusite rock at one site. The Eskdale granodiorite is a discordant mass cutting rocks of the lower and upper parts of the BVG west of the syn-volcanic Ulpha Basin. The rock contains hornblende and, locally, almandine garnet and biotite. In

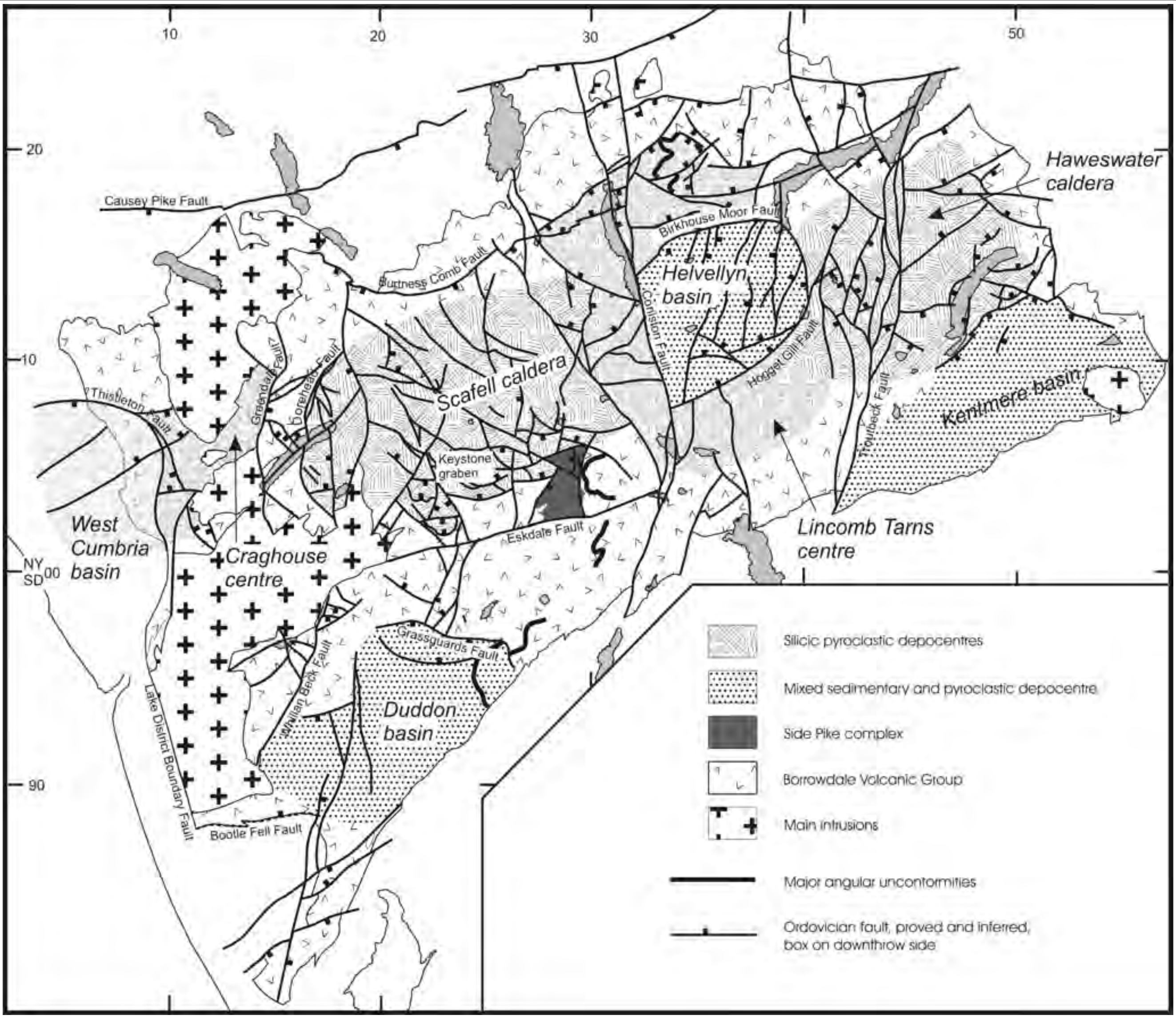

Figure 4. The main depocentres within the upper BVG in the Lake District. The margins of these are approximate and some component formations are more widely distributed. The main faults with inferred Ordovician displacements are shown.

the south, the granodiorite displays strong argillic alteration.

The Caradoc, garnet-bearing *Threlkeld Microgranite* is a largely concealed laccolith, 500-1000m thick, approximately $12 km^2$ in area, that lies above the main part of the batholith.

The *Wensleydale Granite* within the Askrigg Block, is cleaved and, though it has an Early Devonian Rb-Sr isochron age, its heat production value and geochemistry are similar to the Caradoc granites in the Lake District.

Lower Palaeozoic mafic intrusive masses include the gabbro–microgranite complex at Carrock Fell and the Haweswater intrusions (Figure 2). The latter comprise small masses of dolerite and gabbro, with subordinate microdiorite, emplaced contemporaneously within the BVG around Haweswater. Within the Carrock Fell Complex mafic, mafic–felsic and felsic intrusions have distinctive geochemical affinities. The earliest intrusions, the Mosedale Gabbros, are layered cumulate rocks intruded as a sub-horizontal sill at the base of the cogenetic EVG. Cutting the Mosedale Gabbros are the Carrock Intrusions, comprising a main mass of micrographic microgranite, a comagmatic sheet of microgabbro, and a marginal narrow zone of apatite-bearing iron-rich microdioritic rocks. The Carrock Intrusions represent the subsided roof zone of a near-vertical magma chamber in which crystal fractionation of low-Mg tholeiitic basaltic magma had occurred.

Many minor intrusions are also present. Within the Skiddaw Group are dioritic, dolerite and hornblendite masses with geochemical characteristics similar to the BVG. Locally, east of Cockermouth, a group of basalt, andesite and microdiorite intrusions belong to the EVG. Cutting the BVG in the western Lake District are basalt and dolerite dykes, comprising calc-alkaline and high Fe-Ti tholeiitic varieties. A suite of magma-mingled, composite basalt–andesite dykes and minor intrusions were intruded into sediments in the upper part of the BVG between Scafell and Bowfell that were not fully lithified at the time of intrusion. Garnet-bearing dacite dykes in Eskdale and Wasdale are coeval with the Scafell Dacite, a lava dome erupted during the final phase of activity at the Scafell Caldera.

Table 1. Summary of the main stages in the development of the Borrowdale Volcanic Group.

1. Uplift of Skiddaw Group from deep marine to subaerial environment; erosion of 2–5 km of mudrock;
2. Phreatomagmatic basic eruptions forming localized tuff-cone fields;
3. Andesite lava effusion from monogenetic volcanoes, forming low-profile andesite plateaux; one large-volume andesitic-dacitic welded ignimbrite from the Craghouse centre in the west;
4. Large-volume silicic pyroclastic eruptions from the Scafell and Haweswater centres produced stratified ignimbrite successions, associated with volcanotectonic faulting and caldera collapse;
5. Aggradation of mixed successions of volcaniclastic sedimentary and pyroclastic lithofacies and lavas within the caldera basins formed above and in the Duddon and Kentmere basins; final amalgamation of these basins;
6. Large-volume silicic pyroclastic eruptions and resultant caldera collapse to form the widespread Lincomb Tarns ignimbrites;
7. Volcaniclastic sedimentation within caldera basin;
8. Emplacement of major parts of the Lake District batholith causing uplift and erosion whilst marine transgression encroached onto areas contiguous with the Lake District; thermal subsidence of the batholith then allowed complete inundation of the Lake District in Ashgill times.

Ashgill volcanism

Highly silicic volcanic units were erupted into the shallow marine environment of the Dent Group at the base of the Windermere Supergroup, 5–10Ma after cessation of Borrowdale volcanism (Figure 3). In the eastern Lake District, a major eruptive event is recorded by the Cautleyan, Yarlside Volcanic Formation, which is dominated by a widespread felsite, considered by many authors as lava flows, but also interpreted as a high-grade ignimbrite. Events of late Rawtheyan age included the High Haume Tuff and Appletreeworth Volcanic formations in the SW Lake District, the Cautley Volcanic Member in the Cautley and Dent inliers, and the Dam House Bridge Tuff of the Craven inliers.

The Harestones Rhyolite metamorphoses the Longvillian Drygill Shales and crops out within a fault-slice along the northern margin of the Carrock Fell Complex. It is suspected that the rhyolite's late Silurian isotopic age is reset and that the intrusion belongs to the Ashgill magmatic phase.

Early Devonian magmatism

The two main Early Devonian plutons are those of Skiddaw, which is a biotite granite with quartz–white mica greisen, and Shap, comprising biotite monzogranite and containing alkali feldspar megacrysts. There are at least two other masses of this age within the Lake District batholith. Bleached and recrystallized Skiddaw Group rocks, accompanied by locally abundant tourmaline veins, occur in an elongate, ENE-trending zone, 24km long and up to 3km wide adjacent to the Causey Pike Fault. The metasomatic event, dated at 401Ma, is overprinted by a thermal metamorphic event probably associated with the concealed Crummock Water Granite (Figure 2). A similar zone of bleached rocks in the Black Combe Inlier, is possibly of the same age and related to the concealed Ulpha Granite.

Beneath the northern Pennines is the Weardale Granite, a two-mica granite with a shallow-dipping, gneissose-like foliation. The existence of this mass, 60km by 25km in extent, was detected by gravity surveys and proved by the Rookhope Borehole. It has a high heat-flow value, is peraluminous in composition and is geochemically similar to the Skiddaw granite.

The only evidence of volcanism known to have occurred at this time is preserved in north Northumberland, where a subaerial andesite lava field, at least 1500m thick comprises the Cheviot Volcanic Formation. Its outcrop is comparable to that of the BVG in the Lake District. The co-magmatic Cheviot Pluton (outcrop *c.* 62km^2) comprises quartz monzonite, monzogranite and granophyric granite. Situated just north of the inferred trace of the Iapetus Suture, this mass is the easternmost example of the Galloway Suite of granitic intrusions that also includes the Crifell and Fleet plutons.

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Further reading

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The Story of the Weardale Granite

Martin Bott, Emeritus Professor of Geophysics, University of Durham

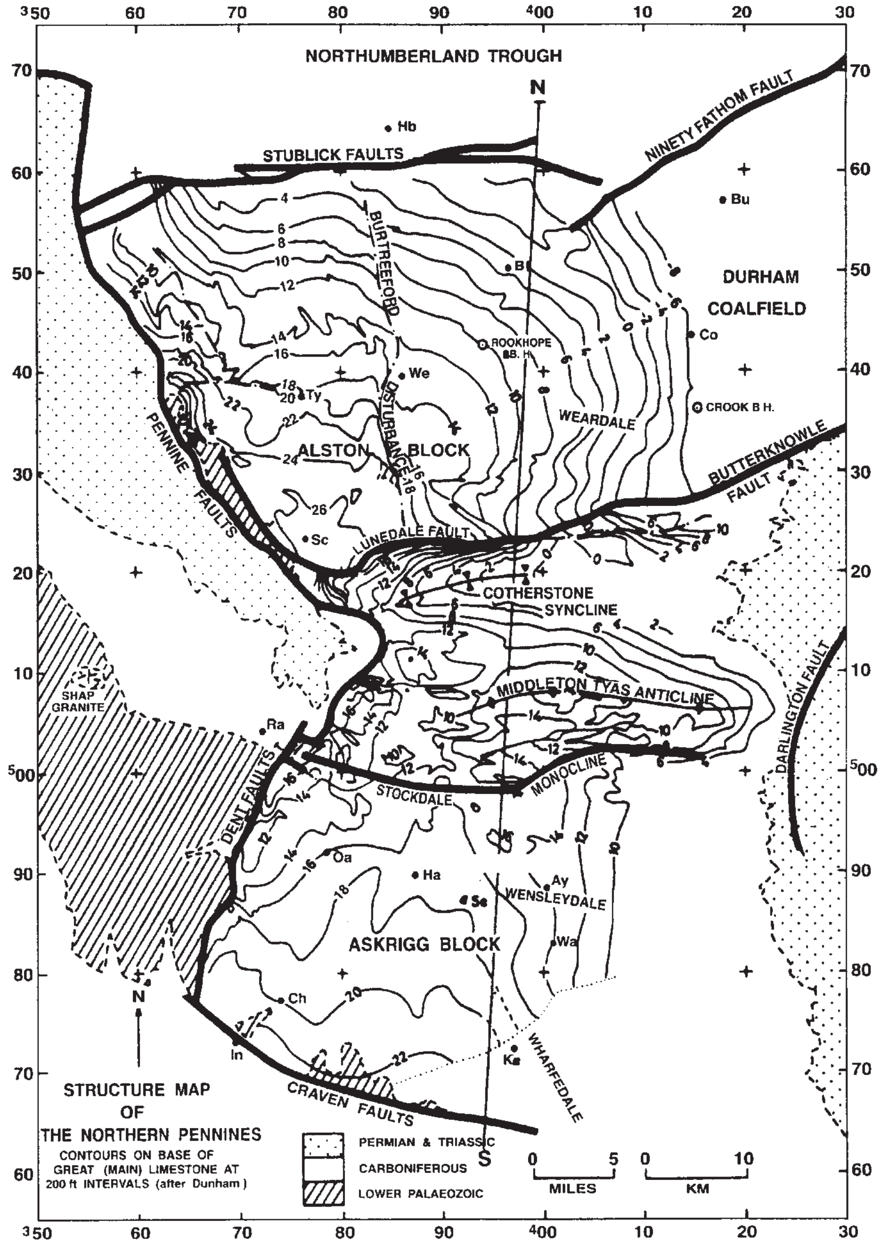

Figure 1. Structure contour map of the Northern Pennines showing the gross vertical uplift of the base of the Great Limestone since deposition near sea level at the onset of the Upper Carboniferous. Boundary faults, main structural units, and locations of the Crook and Rookhope boreholes are shown. The Lower Palaeozoic Teesdale inlier lies just west of the Burtreeford disturbance on the Alston Block.

Introduction

Driving westwards from Durham towards the Lake District one crosses the highest and northernmost region of the Pennines known as the Alston Block. One drives through exquisite scenery along the highest main road in England, passing through Nenthead, the highest village in the country which was once a lead mining centre. One also passes the Killhope Mining Museum which reminds us that this region was once dominated by the mining of lead and zinc, fluorite and barite. Sadly mining is no longer economic here.

Proceeding westwards from Durham, the Upper Carboniferous Coal Measures and then Lower Carboniferous strata are crossed, all dipping gently eastwards. The Carboniferous strata unconformably overlie folded Lower Palaeozoic rocks, which are reached in the Crook borehole (10km west of Durham) at -690m OD and crop out in the Teesdale inlier at about 380m OD. The Carboniferous sequence of the Pennines is truncated by the Pennine faults, which separate it from the Permo-Triassic rocks of the Vale of Eden. Underneath the simple Carboniferous strata of the Alston Block and intruding the Lower Palaeozoic basement there is also an unseen granite, which extends from near Durham to the Pennine escarpment. Most of the Alston Block is underlain by the Weardale granite, as it is now called. The structure of the Northern Pennines, including the northern Alston Block and the southern Askrigg Block is shown in Figure 1.

This contribution discusses the discovery of the unexposed Weardale granite, and its influence on the mineralization of the Alston Block. Also discussed is the influence of the Weardale and twin Wensleydale granites on the structural history of the Northern Pennines. The story of how the granite was discovered is a strange one, which we all got wrong at one stage; but because of this it was especially scientifically productive as it led into new ideas and approaches to the understanding of both lead-zinc mineralization and the influence of a granite on the vertical tectonics of a region subsequent to its emplacement. It is also an example of discovery heavily dependent on cooperative geological and geophysical input.

Hypothesis of granite beneath the Alston Block

Arthur Holmes was Professor of Geology at Durham University in 1928. An exceptional student had obtained a first-class degree that year and wanted to stay on to do research. The student's name was Kingsley Dunham, later to become Professor of Geology himself at Durham and in 1966 Director of the British Geological Survey, subsequently being knighted. His research problem was to investigate the mineral deposits of the Alston Block, by mapping them and investigating how they originated.

The mineral veins most prominently carry lead and zinc (as galena and sphalerite) accompanied by the gangue minerals fluorite or barite. These veins cut vertically or nearly vertically through the Carboniferous succession and the Whin Sill. In the limestones, the veins tend to flow out horizontally and form flats. The minerals originated by crystallization from upward rising hot hydrothermal fluids postdating the Whin Sill.

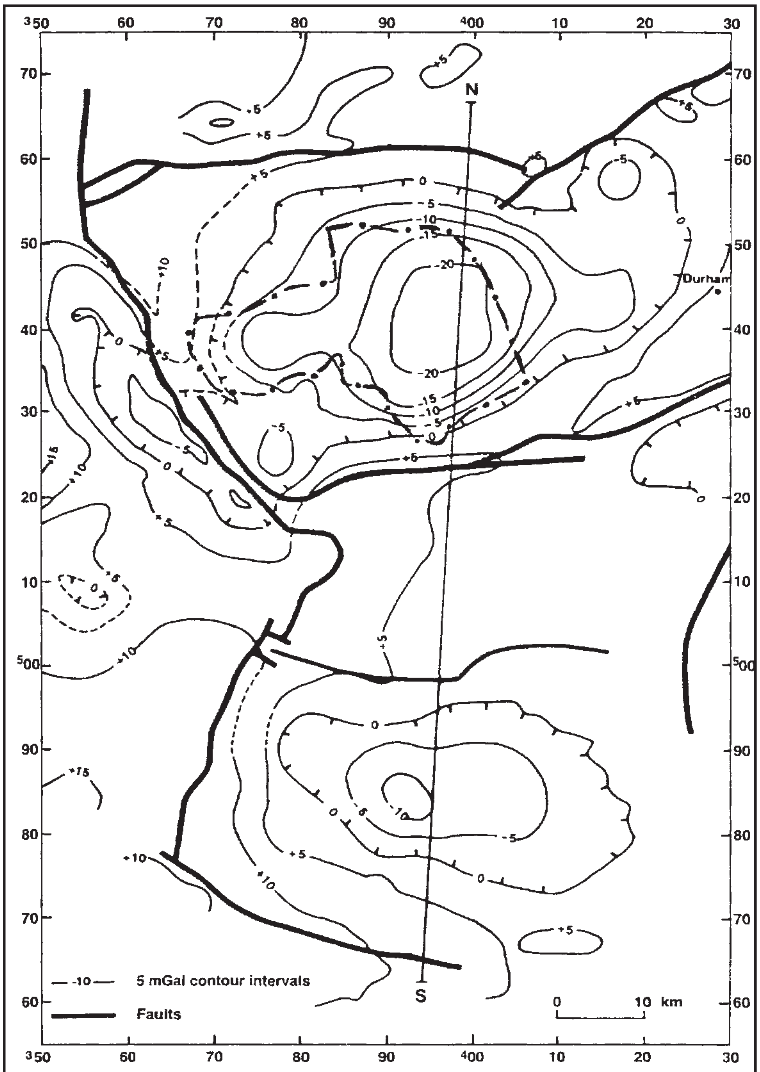

Figure 2. Bouguer gravity anomaly map of the Northern Pennines showing negative anomalies over the Alston and Askrigg Blocks. Gravity contours are at 5mGal interval (1mGal = $10^{-5}m/s^2$). The outer margin of the fluorite zone of the Alston Block is marked by a dot-dash line.

Dunham (1934) located, identified and mapped the mineral veins of the Pennines, which mostly have a south-west/north-east or north-west/south-east orientation probably controlled by the weaknesses in the Lower Palaeozoic basement. When mapped, the mineral veins show a zonal pattern, with a central zone where the gangue mineral fluorite accompanies the lead and zinc minerals (Figure 2) surrounded by a peripheral zone where the gangue mineral is barite.

The zonal pattern of the Alston Block mineralization suggested to Dunham (1934) that its origin may be analogous to that of the mineral deposits of Cornwall, which are of the same age as the Armorican granites which dominate the peninsula of Devon and Cornwall. Dewey had postulated that the minerals originated from the late stage of cooling of the granite; hydrothermal fluids were expelled and migrated upwards into the rocks above, depositing the sulphide minerals as they cooled. Dunham adopted this interpretation for the Northern Pennines and used it to suggest a granite beneath the Northern Pennines which had given rise to the mineralization. As the mineralization postdated the Carboniferous rocks, on this hypothesis the postulated granite must have been later than the local Carboniferous succession. He suggested a Hercynian (Permian) age.

Support for the granite hypothesis from geophysics

The idea of granite beneath the Northern Pennines lay fallow for about twenty-five years. I was a second-year undergraduate at Cambridge in 1949/50 when Percy Allen, my supervisor in geology and later Professor of Geology at Reading, first brought to my attention that Dunham had suggested a granite beneath the Northern Pennines. I was interested in applying geophysical methods to investigate geological problems. When the opportunity occurred in 1951, David Masson-Smith and myself, as new research students, set about investigating this granite hypothesis using geophysical methods.

At this time two other research students, Jan Hospers and Pat Willmore, at the invitation of Professor Westoll of Newcastle University, had just carried out a gravity traverse across the Stublick Fault which separates the thick Carboniferous succession of the Northumberland Trough from the thinner deposits of the Alston Block to the south (Figure 1). They found that gravity decreased southwards onto the Alston Block and not northwards onto the thicker sediments as expected (Hospers & Willmore 1953). We picked up on this and followed up their work because we realized from gravity surveys elsewhere that large granite bodies are usually associated with low gravity. So we mapped the gravity values over the whole of the Alston Block and into adjacent regions (Figure 2), and demonstrated that the Alston Block is dominated by low Bouguer anomalies which extend from near Durham in the east to the Pennine fault in the west. The gravity contours correlate closely with the fluorite zone of mineralization (Bott & Masson-Smith 1953, 1957). The minimum Bouguer anomaly is more than 30mGal (i.e. about thirty millionths of g) below that of the surrounding regions, which is a substantial local negative anomaly of the amplitude normally associated with sizeable sedimentary basins or granite batholiths.

At that time, the origin of low gravity over granites was controversial. There had been suggestions that similar anomalies elsewhere were caused by a thickened continental crust beneath. However, the gravity gradients indicate a much shallower origin for the negative anomalies than the base of the crust. It is now well established that the cause of the negative anomalies is the low density of the granite relative to the denser invaded country rock. This is because granites are richer in the light minerals quartz and feldspar and poorer in dense ferromagnesian minerals than normal basement rocks.

We next needed to demonstrate that the negative anomaly was caused by a granite, and not by a deep sedimentary basin, which was the other realistic possibility. Such a basin would need to be Devonian in age. However, folded Lower Palaeozoic rocks crop out in the Teesdale inlier, overlain unconformably by the local Carboniferous succession. This inlier is in the central part of the negative anomaly, thus ruling out the possibility of thick Devonian rocks as source. A few years later, an objective criterion for distinguishing gravity profiles across granites and basins was found (Bott 1962). The contacts of granites normally slope outwards so that the most rapid change in gradient occurs near the central part of the anomaly rather than near the edge. In contrast

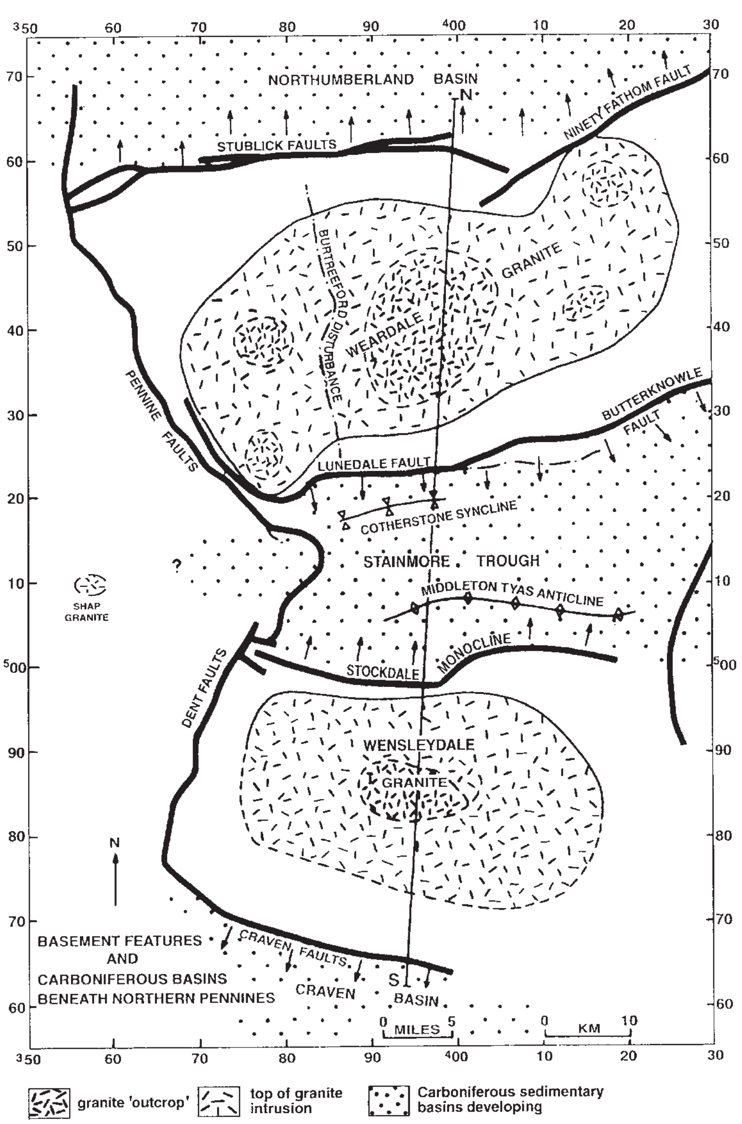

Figure 3. Basement granites and Lower Carboniferous basins/troughs beneath the Northern Pennines, shown in relation to the boundary faults.

a sedimentary basin shows the opposite pattern as the boundaries of the basin almost invariably slope inwards, so that the most rapid change in gradient occurs near the edge. Our Bouguer anomaly profiles were characteristic of a granite, so our confidence that a granite would eventually be found, and not low density Devonian sediments underlying the Carboniferous, was strengthened prior to later drilling.

Simple limiting depth criteria showed that the top of the granite could not be more than about 1400m deep. Subsequently more sophisticated criteria showed that the top was not more than 600 m deep in some locations. Drilling to such depths was readily feasible, so the way was opened to test the granite hypothesis by drilling. The estimate of depth to base of the low density granite depends on the average contrast in density between the low density granite and the denser country rocks of Lower Palaeozoic and older age. A reasonable estimate is –130kg/m^3, which gives a depth to base of nearly 9km. This is about a third of the depth to the local Moho. The shape of the gravity profiles indicates that the contacts of the inferred granite slope steeply outwards. The gravity anomalies also indicate that there are five cupolas where the inferred granite reaches closest to the surface, with the largest of these centred on Rookhope and the adjacent smaller cupola to the west over Tynehead (Figure 2). The overall size of the batholith is 60km long (WSW-ENE) and 25km wide.

The geophysical results do not yield an age for the granite. But the close correlation between the fluorite mineral zone and the gravity lows over the inferred Rookhope and Tynehead cupolas (Figure 2), and the occurrence of semi-anthracites in the Carboniferous in the same region, confirmed to us that the granite was likely to be post-Carboniferous and probably Hercynian as originally suggested by Dunham. Following publication of the gravity results in the Geological Magazine in 1953, there was a correspondence mainly supporting a Hercynian or later age, but Arthur Holmes wrote to suggest that a Caledonian age would be more in line with the tectonic setting, with the granite thus pre-dating the mineralization by about 100Ma.

Gravity surveys also led to postulation of the smaller Wensleydale granite beneath the Askrigg Block; in contrast to Weardale, the mineral veins here are not obviously related to the gravity anomaly. Furthermore, a combination of geological and geophysical observations has outlined a Lower Carboniferous block and trough structure of the Northern Pennines. A relatively thin Lower Carboniferous succession (400-600m) underlies the Great Limestone (Figure 1) of the Alston and Askrigg Blocks. The succession thickens to about 3-5km across hinge-lines near the present faults, into the east-west Northumberland and Craven basins and intervening Stainmore trough (Figure 3). The geophysical results over the Northern Pennines are summarized by Bott (1967) and illustrated in Figures 3 and 4.

Proving the Weardale granite by drilling at Rookhope

After I finished at Cambridge in 1954 I joined the geology staff at Durham where Kingsley Dunham was Professor of Geology. Both of us were keen to test the granite hypothesis now that the predicted depth to the top was within realistic drilling range. In 1958 the opportunity occurred when new money for large university research projects became available. In 1958 Dunham was in committee with Professor (later Lord) Blackett, Chairman of the Government Grants Committee, who encouraged Dunham to apply for a grant to drill down to the Weardale granite at Rookhope. A grant to drill was successfully obtained in 1958.

What did we expect to find? The Carboniferous succession including the Whin Sill would be about 400m thick. As there are no signs of sediment metamorphism (apart from coal devolatilization), we expected the borehole to pass out of the almost horizontal Carboniferous into strongly folded Skiddaw Slates which would be at least 500m thick above the granite. The granite would thus be reached at about 1000m depth below the surface.

The Rookhope borehole was drilled in 1960-61 (Dunham *et al.* 1961, 1965). To our great surprise, the hole passed through a thin basal Carboniferous conglomerate including granite pebbles into the weathered upper surface of granite at 391m depth. The granite was penetrated for a further 417m, the borehole bottoming at 808m depth. The granite core was subsequently dated as 410±10Ma (Lower Devonian), proving Arthur Holmes' suggestion of a Caledonian granite to be correct.

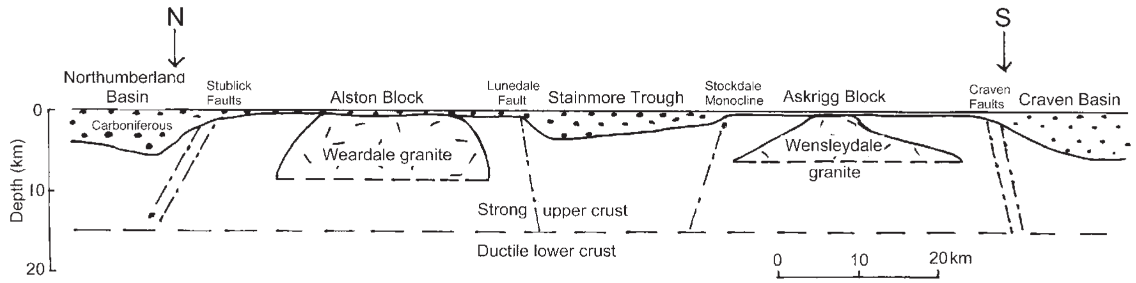

Figure 4. True scale upper crustal section along line N-S (Figures 1 to 3) showing the Bouguer anomaly profile and the inferred subsurface shape of the Weardale and Wensleydale granites, the Lower Carboniferous troughs, and the main faults.

The Rookhope borehole proved that the hypothesis of granite beneath the northernmost Pennines was right, but all of us (except Holmes) got the age wrong. However, the new insight into the age of the granite turned out to be highly productive scientifically, as it gave us important new insights into the origin of the lead-zinc mineralization and to the structural control that can be exerted by a low-density granite batholith subsequent to its emplacement. The borehole gave a complete cored section of the Carboniferous and 400m of granite beneath which proved invaluable for research. Heat flow was also measured in the open borehole. A decade later, the Wensleydale anomaly was drilled, and also proved to be Caledonian of equivalent or slightly younger age than the Weardale granite (Dunham 1974). Granite underlies both the Alston and Askrigg Blocks (Figures 3 and 4).

The origin of the lead-zinc mineralization

The original suggestion that the mineralization of the Alston Block came directly from the cooling Weardale granite had to be abandoned, since the granite had cooled over 100Ma prior to emplacement of the mineral veins. Nevertheless the strong correlation between the zone of fluorite mineralization and the position of the Rookhope and Tynehead cupolas (Figure 2) is unlikely to be fortuitous. It was concluded that the granite had provided structural passageways for the rising mineralizing fluids. The new evidence led to a radical reappraisal of the origin of the mineralization by Dunham and his co-workers, summarized by Dunham (1990).

Uranium-lead dating gave a Hercynian age of 292±20Ma for a mineral vein, implying the minerals were emplaced just after intrusion of the Whin Sill which they cut across. Fluid inclusion studies showed that mineralizing fluids were hypersaline chloride brines at temperatures up to at least 220˚C in the middle of the fluorite zone. On isotopic evidence, the brines were inferred to originate as trapped formation waters in adjacent deep Carboniferous basins. Dunham realized that the high heat flow in the Weardale granite would give rise to convection of the trapped brines which sank laterally to depths of 4 to 8km. The hot brines took up elements such as lead and zinc into solution as chloride complexes, and then rose through vertical passageways through the granite. As the fluids cooled, they deposited galena, sphalerite, fluorite etc near the top of the granite and especially as veins and flats in the overlying Carboniferous succession. As the cooling solutions migrated outwards they reacted with shallow sulphate waters to precipitate barite near and beyond the margins of the granite batholith.

Post-emplacement tectonic influence of the Weardale and other granites

Prior to the drilling of the Rookhope borehole, it had been recognized by Bott and Masson-Smith (1957) that the underlying postulated granite corresponded to the highest topography of the Pennines, and it was inferred that the low density of the granite isostatically supported the excess topographic load, which approximately equaled the upper crustal mass deficiency of the granite.

Deeper insight into the influence of the Weardale and Wensleydale granites on the post-Lower Carboniferous structural history of the Northern Pennines comes from comparison of the uplift since the Great Limestone was deposited in a shallow sea (Figure 1) with the location of the granites (Figure 3). The stable Alston and Askrigg Blocks are half domes truncated by major faults and there is very little local faulting and folding in comparison with the adjacent trough regions to north, west and south. This suggests that the granites have exerted a controlling influence on the post-Lower Carboniferous structural history by stabilizing the blocks and causing isostatic uplift.

By far the greatest differential vertical movement affecting the Northern Pennines since the Caledonian orogeny was the differential subsidence of up to 5km along hinge lines during the Lower Carboniferous. These hinge lines occur along the Stublick–Ninety Fathom fault line forming the southern faulted boundary of the Northumberland basin which is a half graben, the Lunedale–Butterknowle line bounding the Stainmore half graben on the north and the Craven fault line bounding the basin to the south of it. Prior to drilling, the close relationship between the inferred Weardale and Wensleydale granites and the adjacent east-west orientated Lower Carboniferous troughs (Figure 3) remained unexplained. The discovery that the Weardale (and Wensleydale) granites pre-date the Lower Carboniferous gave new understanding to the relationship between the granite cores of the Alston and Askrigg Blocks and the adjacent deep Carboniferous troughs (Bott, 1967). It now appears that the low-density granites resisted strong subsidence during the Lower Carboniferous, and that the Northumberland Trough, Stainmore Trough and Craven Basin subsided along hinge lines which correspond to the major east-west fault lines (Figure 3). Thus the low-density granites dominating the upper crust of the Northern Pennines exerted a dominant control on the location of these deep half grabens formed under north-south orientated regional tension.

A problem in understanding the differential vertical movements affecting the block and trough structure of the Northern Pennines is that they are on a much smaller scale than would be expected for flexural deformation of a 100km thick continental lithosphere. The explanation appears to be that, when the vertical movements occurred, the underlying lower crust has been hot enough to be ductile, deforming with power law viscous rheology and allowing the much shorter wavelength flexure to affect the ~15km thick brittle upper crust than could result from bending of the whole lithosphere. The relatively high heat flow measured in the Rookhope borehole indicates a relatively warm lower crust at the present time (and during the Tertiary?), and we assume such a situation also applied during the Carboniferous. Flexural uplift assisted by faulting of the upper crust can then produce vertical movements on the scale of the blocks and troughs. Uplift of the blocks and formation of half grabens would be driven by north-south regional horizontal tensions assisted by the isostatic upthrust of the low-density granites. With the improvement in geodynamic modeling techniques in recent years, it has been possible to model this situation and demonstrate its feasibility using finite element methods with a realistic rheological structure for the lithosphere (Bott 1999).

The above mechanism can explain the local uplifts of about 300m caused by the low-density granites, but it does not explain the general Tertiary uplift of the Pennines and of mainland Britain upon which the local uplifts are superposed. We have most recently attempted to model this with some success in terms of the isostatic effect of a hot, low-density upper mantle which has recently been postulated from results of seismic tomography (Bott & Bott 2004).

Summary

The story of the Weardale granite unfolded as follows:

1. The story began over seventy years ago when Kingsley Dunham suggested that the zoned mineral veins of the Alston Block originated from late stage cooling of a Hercynian or later granite beneath Weardale, by analogy with association between mineralization and granite in Devon and Cornwall.
2. Fifty years ago, a gravity survey over the Alston Block, made to test this hypothesis, revealed a substantial negative gravity anomaly which gave compelling evidence of an underlying Weardale granite batholith with its roof less than 1.5 km deep (Figure 2). Gravity surveys also suggested a twin Wensleydale granite beneath the Askrigg Block (Figure 2).
3. Forty three years ago, the Weardale granite was drilled at Rookhope and surprisingly found to be a Caledonian granite directly underlying the Lower Carboniferous strata. A few years later, the postulated Wensleydale granite, also of Caledonian age, was proved by drilling.
4. The discovery that the Weardale granite preceded the mineral veins by 100Ma led to a re-evaluation of their origin by Dunham and colleagues. The mineralizing fluids are now believed to originate as hypersaline brines in adjacent deep Carboniferous basins. These convected laterally and downwards into the warm granite, dissolving Pb, Zn, Ba and F as chloride complexes as they heated up. They were then expelled upwards through passageways in the granite, depositing vein minerals as they cooled and flowed into the Carboniferous.
5. The Northern Pennines now provides a unique example of the influence of pre-existing granites on local tectonics, due to their strength and low density favouring stability and the tendency to rise isostatically. The Weardale and Wensleydale granites exerted master control of the development of fault-bounded block and trough structure during the Lower Carboniferous, when differential subsidence of up to 5km occurred along hinge lines parallel to the granite margins under regional tension (Figure 3). These granites have also influenced the subsequent less spectacular but well-documented faulting, folding and vertical movements displayed in Figure 1.
6. During the last few years, we have been able to model the fault-controlled vertical isostatic uplift caused by low density granite, as in the Northern Pennines, in terms of a relatively warm lower crust in which ductile flow can occur. This provides a mechanism.

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Northumberland Rocks - a story that has to be told

Dr Stuart Monro, Scientific Director, Our Dynamic Earth, Edinburgh

All earth science is about reading the story in the rocks, the unfortunate aspect is that more than 90% of the pages of this book are missing. So earth science is very much a forensic science, piecing together a larger picture from small bits of evidence. It is therefore a subject that can capture the imagination of the public but only if the geological community is prepared to tell the stories that are there to be told. This concept is not new. Hutton, in the abstract of his Theory of the Earth paper, says "In this manner, there is opened to our view a subject interesting to man who thinks and one which may afford the human mind both information and entertainment." However, geologists have long been renown as poor communicators to the world beyond their discipline. The saying, "Geologists are good company – especially for other geologists" exemplifies this. But things are changing and communicating the earth science behind the landscape is now an expanding area of interest. It is important primarily because earth science is relevant to people's lives, but there are also secondary reasons:

1) Need for science education

2) Earth science can contribute to the tourist industry; it has a role in the rural economy

This symposium should leave a legacy about how better to communicate the rich diversity of stories embedded in the rocks of Northumberland and the north of England and also an understanding as to why this is an important activity.

Science education

The need to stimulate science education in the UK has been recognised within the education community. There is real concern about how the UK science base is to be promoted in the future when children seem to be abandoning all interest in scientific disciplines. In Scottish universities, applications for science, engineering and technology places have fallen by ~3% per year since 1997, UK oil industry needs to replace ~40% of geoscience staff in 8-10 years, only ~30 schools teach Higher Still Geology, only ~50 candidates per year for Higher Geology. These statistics indicate that the demographic time bomb is ticking …

The National Debate on Education in Scotland throws up some interesting quotes from children;

"I love science but I want more"

"I want to find out more about the world, what makes things work, how things grow, about volcanoes, earthquakes, space, everything!"

And also from teachers;

"I love teaching science, but……"

"I need support in delivering earth science topics"

The overriding message from the National Debate is that science must be perceived in the classroom as relevant. This is a real strength of earth science as a gateway to other science disciplines. Many of the issues facing Society are underpinned by a knowledge of how the Earth works … use of resources, availability of energy, nuclear waste management, climate change, ozone depletion, earthquake hazard, flooding, landslips, availability of water, deforestation, desertification – the list is virtually endless. All of these issues are seen as relevant, each affects the quality of life in UK Society and the solutions lie in scientific understanding.

The Northumberland rocks can contribute to education and the generation of an earth science literate Society who can address the issues of the day. Supporting teachers in the delivery of earth science in the classroom is the way that our future may become a little bit more secure.

Earth science can contribute to the tourist industry

As the industrial infrastructure of north-east England declines there is a need to bring in new sources of revenue. The tourism industry is becoming increasingly important in this area. For the people living in Northumberland and the many visitors to this area, the landscape is its main attraction. Underpinning this landscape is a rich diversity of stories told in its rocks. These stories give added value to the appreciation of the Northumberland landscape. There are many exciting initiatives going on just now, many stimulated by the RIGS groups. But there is a need for the contribution that earth science can make to the tourism industry to be more widely recognised and incorporated in regional strategies.

The Scottish experience that can be applied to Nothumberland is that visitors come for culture, heritage and landscape. Earth Science relates to all three. Science is part of our culture and heritage but we sometimes take for granted the great advances that have been made on our doorstep. In Scotland we boast Siccar Point, the most important geological locality in the world, yet to date there has been no attempt to exploit the site and to interpret the significance of the location for visitors. Fortunately that is not true everywhere. Knockan Crag in the North-West Highlands was the location of the great Highland Controversy where discussion on the nature of what we now know as the Moine Thrust raged on for many years before being finally resolved and demonstrated by Peach and Horne. The site is now beautifully interpreted using a wide range of techniques in Scottish Natural Heritage's Knockan Visitor Centre. Here the added value of interpretation of the landscape has been well demonstrated.

Over 80% of visitors say that the environment is what they like the most about Scotland and it is undoubtedly one of the most important resources to the Scottish tourism industry. Similarly, the character of the Northumberland landscape underpins the attraction of the area to the tourist. It is important for the earth science community to recognise the contribution it can make by giving added value to the landscape through its interpretation. This is something that can be achieved at the local, regional and national scales.

There is a lot that all of us who are interested in earth science can do to tell the stories that are in the rocks. The leaflets which are now becoming common place for a variety of localities around the country, explaining the significance of the landscape features, are produced by people like the membership of OUGS. They are spreading the stories in the rocks.

A Taste of Namibia

Chris Crivelli

Sunday 8th June 2003, GMT 0700 + 1.00, Windhoek International Airport, Air Namibia jumbo jet decants its payload, half cargo, half passengers onto the sun drenched tarmac. Heathrow it is not! One runway - flanked by scrubby desert - and a terminal building smaller than Bristol's. Apart from the 747 and a handful of private aircraft, the tarmac is deserted. Among the passengers are fifteen OU geologists bleary eyed, having been travelling and waiting at airports for eighteen hours since they collected their flight tickets from Elizabeth Maddocks at Heathrow. Elizabeth met us as husband David, trip organiser and leader, had stayed in Windhoek (Figure 1) after seeing the previous group off two days earlier and we were about to meet up with him.

Figure 1. Windhoek Airport.

Having collected David and the vehicles we drove off into Namibia. A couple of km from the airport along the desert road we were stopped at a security point where we were wished a good day by one guard, another smiled at us from his chair, a few metres away. On route to a supermarket to collect water and lunch we visited the Meteorite Fountain, 33 of the Gibeon Meteorites. 77 were originally recovered at Gibeon 200km south of their present position in Windhoek. 600Ma old, they are part of the largest ever discovered meteorite shower with an average mass of 348kg (the largest is 556kg). They comprise over 90% iron, the rest is nickel plus trace elements (Figure 2)

Once out of the capital we drove 550km south on Namibia's main road, B1 through desert all the way, seeing only a few dozen vehicles; we arrived at the Quiver Tree Forest Rest Camp at sunset.

* * * * *

Geological background

More than 2100Ma ago there were the Congo and Kalahari Cratons, the former to the east and the latter to the north of modern southern Africa. Between 2100 and 1800Ma the Vaalian and Lower Mokolian formations occurred and are the oldest surface rocks showing in the Epupa, Huab and Grootfontein Metamorphic Complexes in the far north west of Namibia today. Grootfontein is on top of the Kalahari Craton, the earlier two complexes are on the Congo Craton.

Figure 2. Section through Gibeon Meteorite

Between 1800 and 1000Ma erosion material from the earlier metamorphics and cratons formed huge mountains which constitute the modern subsurface, the Namaqualand Metamorphic Complex of Upper Mokolian age cut through by granitic and doleritic intrusions.

From 900Ma a third orogeny started when the two cratons and their overlying mountains were further eroded and transported into the ocean basin between them. Deep beneath these oceanic sediments tectonic forces were driving the cratons together. The oceanic crust, followed by the Kalahari Craton, was subducted under the Congo Craton until the erosion sediments were forced upwards between the cratons. Between 750 and 460Ma the Damara Sequence of metamorphic rocks was formed and towards the end of this upfolding, deep molten crust intruded into the sedimentary pile. Concurrently a shallow sea intruded over the southern part of the area and deposited sea shelf sediments which formed the Nama Sequence between 650 and 570Ma.

At about 560Ma global tectonic forces welded what are now the southern continents, India and Madagascar into Gondwana, in the southern central part of which lay what is now Namibia. In the following 200Ma the Damara rocks were weathered and eroded.

At about 300Ma Namibia was close to the south pole and largely glaciated, as was most of the southern region of Gondwana. From 280Ma the super continent drifted northwards, away from the polar region, and the melting ice sheets extensively deposited their moraines into ridges which contained glacial meltwater lakes. These lakes collected further sediments. Rivers draining the highlands deposited more material in huge and numerous deltas. These are the Karoo sediments.

Within 100Ma the climate changed dramatically from glaciation to a massive continental desert with endless dune fields, the relics of which formed the impressive red Etjo Sandstones.

At about 130Ma extensive rift systems appeared over dozens of kilometres in north-west Namibia. This was the start of the breaking up of Gondwana. The Atlantic Ocean slowly formed from icy water rushing in from the south as Africa and South America were driven apart and Namibia's western seaboard started to form. From the initial rifting lava welled up and flooded over north western Namibia. This was followed by Karoo volcanics as volcanic craters, lava sheets, granite bodies and dykes occurred throughout western Namibia.

The Great Escarpment in central Namibia dates from the break up of Gondwana when isostatic forces pushed up the western side of Southern Africa to form the edge of a basin to the east which is today the Kalahari desert.

The Tertiary brought the beginning of the period of erosion and transportation. The gargantuan Karoo layers were eroded down to the Precambrian basement. Erosion debris was moved westwards and deposited in the Atlantic or, at times at the base of the Great Escarpment, where it shows today, e.g., as the Tsondab Sandstone Sequence (30Ma). Later huge gravel deposits and river terraces formed and from about 5Ma the modern arid climatic conditions in the area started. Evaporation of surface water left thin calcrete layers on the surface in many parts. The Namib Desert started to form 2Ma years ago and gave its name to the country on independence in 1990. At the same time the North Polar ice sheet extended southwards leading to a substantial fall in global sea levels, which increased the land/sea gradient and intensified the erosional power of rivers which cut deeper into the gravel deposits and even into basement rocks. (e.g., Ugab Terrace).

* * * * *

To resume .. for the last 100km of our journey to the south we had travelled at the base of the Weissrand Escarpment, the eastern part of the Great Escarpment (Figure 3). The junction of the sand and shale of the Nama Sequence and the overlying white Karoo calcrete that gave the structure its name (white cliff).

Figure 3.The Weissrand (with communications tower).

The road follows the valley incised by the Fish River 15Ma ago. To the west we observed, from 40km away, the Brukkaros crater towering over 600m above the surrounding plains and 3km across at the base looking, for all the world like a volcano, but magma, which never reached the surface, superheated circulating groundwaters and the resulting steam pressure led to an enormous explosion at the surface 80Ma ago and Brukkaros was formed from rock debris from as deep as 1000m underground. The crater floor is 350m below the rim.

Aloe dichotoma, the kokerboom or quiver tree normally grows singly but can be found near Keetmanshoop in clusters of dozens and even hundreds. They easily tolerate the harsh arid climate, their stems and branches having a fibrous pulp at the centre for storing water and which used to be hollowed out by San (Kalahari) bushmen for use as quivers. The kokerboom survives among the numerous dolerite outcrops in this area. We scrambled over the dolerite and watched the sunrise behind the trees, which can grow to over 6m (Figure 4). This midwinter dawn (at 6.30!) was also experienced by weavers and other small birds, who flew in and out of the foliage collecting rich nectar and insects of the quiver tree, locals strolling to work, wild cheetahs and the caged goats that had attracted them to the camp and the semi tame cheetah, meerkats, warthogs and a love bird that lived at the camp.

Figure 4.Quiver tree dawn.

Nearby, 'The Giant's Playground' is all that remains of basaltic intrusions into Karoo sediments about 180 Ma ago. The sediments have been eroded and the weaker dolerite rocks weathered to leave stacks and piles of boulders – as if left by a giant (Figure 5).

Figure 5. Giant's Playground.

Fish River Canyon, the world's second largest canyon, is, for many people, the jewel in Namibia's geological crown. It is, at its extremes, 549m deep, 160km long and 40km wide. Its basement is of the Namaqualand Metamorphic Complex which 800Ma ago was penetrated by dolerite dykes, but the Canyon, itself, started to form at 350Ma when a large graben subsided 380m between two wide spread fault zones and formed the broad ancient valley of the Fish river, the bed of which was 300m higher than it is today. The top of the graben comprised the grey-brown quartzites, black limestones and schists of the Nama Sequence. These extremely hard layers initially prevented deep incision of the Fish River and instead facilitated sideways erosion, which levelled a wide plain, the Hums Plateau. The river subsequently meandered slowly over the plateau forming ox bow lakes and cut off hills and today has incised the newest and deepest part of the Canyon, the modern riverbed. These distinct features of the Canyon are all clearly visible today (Figure 6).

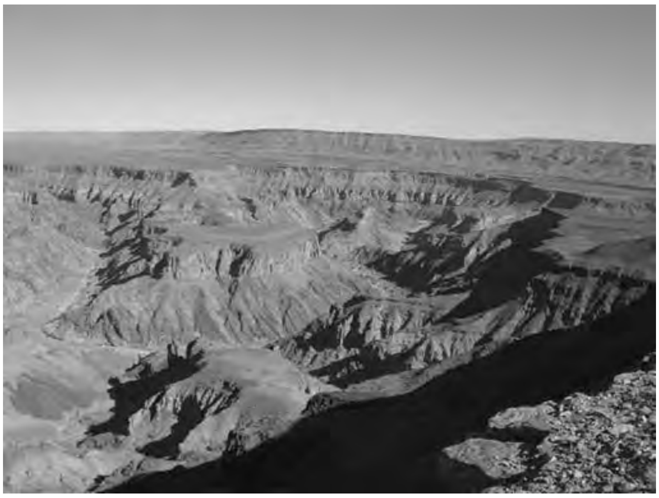

Figure 6. Fish River Canyon

The piles of granite boulders, hugh inselbergs or *kopje*, that abound in this area are home to the rock hyrax or dassie, a gregarious and agile cat sized mammal that can scale almost vertical rock faces. *Kopje* are smooth, rounded rust coloured granite blocks, some as big as houses amongst which thatched lodges have been built as tourist dwellings. Some lodges are built around the inselberg leaving a 1.5m rock intruding into the sleeping area.

Travelling to the north-west we pass to the west of the Schwarzrand Escarpment, which is part of the Nama Sequence and the west side of the Great Escarpment. The older sandstone and shales have been eroded and transported by the Konkiep River. The overlying hard black-green quartzitic layers are more durable. The plain between the road and the escarpment is vegetated with small shrubs, more like savannah than true desert. This is a truly African landscape. Again, during the 550km drive we have the road to ourselves.

The red dunes of Sossusvlei are my favourite of all Namibia's geological wonders (Figure 7). The area is the remnant of a lake at the end of the Tsauchab River. It is a complex of clay pans of different sizes and ages, which when exposed at the surface form scorched and cracked calcretes. The pans are separated by the enormous red sand dunes. During rainy periods, which may be several years apart (1997 was the last time), the river will break through into some of the areas contained by dunes (vleis), but not others which are so blocked up with sand masses and get no water, for example Dead Vlei, in which the small trees are now nothing more than eerie grey sculptures of former trunks and branches rising from the cracked calcrete floor of the vlei.

The dunes here are, at 350m, the highest dunes on Earth. The lower 60m comprise the 30Ma Tsondab Sandstones, petrified dunes of ancient Namibia, the top 300m less than 2Ma old, two deserts separated by millions of years and an intervening humid climate.

As we traverse the dunes, the wind gently blows the perfectly spherical grains of red sand off the sharp crest of the dune and the edges of our footprints in the sand are quickly softened as wind and gravity nudge the tiny grains to replace what we have disturbed.

The midwinter sun casts long shadows of people and scarce shrubs and enhances the ephemeral patterns of the sandy slopes.

Figure 7. Three of many faces of Sossusvlei.

Nearby, Sesriem Canyon got its name from early settlers who connected six leather thongs (*ses rieme* in Afrikaans) in order to get their water from the canyon, which was cut through the Tsondab Sandstones 30Ma ago. The Canyon is up to 40m deep and 3km long. 'Not much of a canyon compared with Fish River…' our driver said. True, but it does demonstrate the change to the less arid conditions when river gravels (erosion debris and dissolved carbonates from the Naukluft and Zaris Mountains nearby) formed terraces which were eroded by rivers crisscrossing the plains and, unlike today, reached the Atlantic.

We took a midday walk through the cool canyon and saw the sequence of river deposits, trees and some water at the bottom and evidence of bird inhabitation with guano deposits formed below nesting sites way above the canyon floor.

We travelled north stopping at Solitaire, a small town with a garage, motor workshop and a general store unchanged for decades and feeling like something from a western movie! Having replenished fuel, food and water we continued to the Kuiseb Canyon. It is really a canyon within a canyon formed 20Ma ago when the ancient Kuiseb River course was silted up by its own sediment and was forced to cut a new valley. Today it is a spectacular landscape of rugged dipping black glittering mica schists. We continued through the Canyon then into the Namib Desert, the harsh midwinter sun measuring 40°C at times. We arrived at Walvis Bay. Lying on a lagoon and hemmed in between the Atlantic Ocean and the Namib Desert, it is the centre of the country's fishing industry, rich from the fruits of the Benguela Current (remember S330?). Our leader promised flamingos and a cool breeze. We got dead jellyfish and an almost icy blast from the Atlantic. What a contrast from what we had felt in the desert less than an hour before! We stayed at Swakopmund just round the bay. It is an old German colonial style resort. Three or four metre Atlantic rollers crash onto the beach. Nearby the so-called Moon Landscape flanks the Swakop River Valley. This area is made up of Damara Granites from 500Ma ago and subsequently eroded (about 125Ma ago) and cut by dark dolerite dykes that meander for up to several kilometres over the softer granite and stand out above it (Figure 8). The dykes are up to several metres wide and clearly show chilled margins. Another feature of this area is the *Welwitschia* plant (Figure 9), a large striking plant that has only two leaves that split as they grow up to several metres across and for up to 2000 years. This unusual species grows only in a narrow belt 30–40km inland from Namibia's Atlantic coast. This is the Welwitscia Drive. As well as scorching desert, Moon Landscape, dykes and the so called fossil plant that gives the excursion its name, we saw desert chameleon as well as the remains of armour, rusty cans and broken bottles abandoned by South African troops in 1915

Figure 9. *Welwitschia mirabilis.*

Our drive to Twyfelfontein takes us to the Cape Cross seal colony where a quarter of a million South African fur seals live on a stretch of less than a kilometre of the coast and play in the gigantic Atlantic waves. A gentle offshore breeze ensured our visit there was not as smelly as we had expected! The coast road we drove over was made of salt, a smooth natural surface that continuously repaired itself. Our drive took us through a sandstorm that engulfed our vehicles for a few minutes - disappearing as quickly as it had come.

Twyfelfontein is an area of Karoo aged permeable red Etjo Sandstone on top of relatively impermeable shale, such that after substantial rains water seeps from the junction of the two rocks, but this is so rare that it is known as *doubtful spring* – 'Twyfelfontein' in Afrikaans. These smooth red sandstones are the site of 2400 rock engravings, of mid to late stone age, up to 5000 years old (Figure 10). Some painstakingly carved with bone, many painted, these images are of the local animals and some show exaggerated feet and tails suggesting the importance of the footprints and tail trails that the tribesmen of the area used to track their prey.

Only discovered in the 1940s, the petrified forest is the fossilised remains of 240Ma trees growing on the margins of the tundra

Figure 8. Dolerite dyke.

Figure 10. Rock engravings - mid to late Stone Age

from the late Gondwana ice age. The glacial meltwaters gushed sufficiently to uproot and transport trees tens of metres tall and over a metre in diameter. This much is clear from the alignment of the trunks. The fifty or so surviving trees have their bark, cells and concentric rings perfectly preserved as crystalline quartz, which was glinting rich red, green and yellow in the sun. The local Damara people are rightly proud of their geological gem, a national monument since the 1950s and have learned many western languages to provide a splendid guided tour of the site (the only way groups are allowed to visit and collecting is strictly forbidden) (Figure 11). The trees belong to the Cordaites, ancient ancestors of today's firs and pines and which later formed enormous coal deposits all over Europe.

Figure 11. Damara guide shows off a fossil tree

Burnt Mountain is a 20 m flat-topped mound formed 125Ma ago. It comprises former lake deposits, shales rich in organic floral and faunal remains, which were vaporised as basaltic magmas of the Karoo Volcanism, hotter than 1000°C, metamorphosed the shales into the black rocks with red and purple of iron and manganese oxides weathered from the remnants of the intruded dolerites. The structure was never ablaze only scorched by the contact metamorphism.

Just a short walk away in a dolerite dyke, also intruded in Karoo times in a small gorge a few hundred metres long, there are masses of hexagonal columns, the so-called Organ Pipes (Figure 12).

Figure 12. Valley of the Organ Pipes

We drove to Etosha across the Ugab Terraces, the remains of gravel and sand deposited over millions of years after the Ugab River's erosive energy was firstly increased when western Namibia was uplifted as Gondwana broke apart and the land/sea gradient increased. Then the river's flow rate fell and the huge volumes of erosion materials were deposited on the river bed to a depth of over 100m. As the North Polar ice cap migrated south 2Ma ago, sea levels fell and the Ugab's flow increased and started to cut deep and wide into its own bed to leave the river terrace that we see today.

Figure 13. Etosha.

The Etosha National Park is 22570km^2, a quarter of its size before 1963 when the Government took 72,000km^2, with total disregard for ecological considerations, for its homeland policy.

Today, Namibia is much more environmentally aware, as is borne out by the checkpoint at the gate to the reserve. The size of the Park becomes obvious as we drive for 17km to Okaukeujo, our base for two days. The drive is across flat dry scrubby desert. Just north and east of Okaukeujo lies the Etosha Pan. It is a seemingly endless salt pan of 4600 km^2 which was originally scoured flat by glaciers 200Ma ago at the time of the Gondwana Ice Ages. It is fed by seasonal and sporadic rainwater which quickly evaporates away in the scorching desert sun leaving just the hard, barren salt crust. Little vegetation survives and any fine soil or dust is swiftly removed by the wind. All that remains is spectacular flat nothingness. Etosha means *large white place of dry water*.

The rest of the Park is a haven of wildlife. At Okaukeujo there is a waterhole right on the edge of the rest camp and separated from it by a small stone wall. Late afternoon - and two adult elephants come to the waterhole.

They were playful between long drinks using their trunks to touch each other as if showing off to the visitors assembled behind the wall, and they soon leave. Soon only an eagle owl sat hidden on the branch of a large tree, overlooking the otherwise deserted oasis, awaiting prey. Later, a murmur buzzed amongst the human visitors as in the distance there appeared a line of elephants of all sizes backlit by the red glow of sunset. The line slowly approached the waterhole (Figure 14). The herd drank. As well as drinking there was more touching of trunks and a baby took to chasing some birds waving ears and trunk about to assert its superior size, though it hardly needed to. I was minded of a toddler chasing pigeons. Then, seemingly on a signal from one of the

Figure 14. Elephants at the Okaukeujo water hole

herd, the drinkers slowly turned away from the water and reformed the orderly line which moved silently back from whence it came. After only a few minutes, now completely dark save the spotlights, erected by and for humans, the hole is once again deserted. People are quiet and I'm left almost wondering if the visit had really happened. It is a magical place.

I woke at about four in the morning and walked the few hundred metres to the still illuminated waterhole. The camp was deserted except for a jackal scavenging the remains of a braai (southern African barbeque). The water hole was also deserted but I had the pleasure of sharing the next hour or so with jackal, springbok, kudu, elephant and astonishingly, nine white rhino, of which there are only 300 left in Namibia (Figure 15)

Figure 15.White rhino by night.

Waterberg Plateau was our last stop. It stands 200m above and in stark contrast to the surrounding acacia plain and savannah. The plateau is a lush, green, vegetated place and home to many rare game species and other animals. Geologically it is an erosion relic. As Gondwana was moving away from the South Pole over millions of years climate change brought ice sheets that scoured the Damara basement rocks and left moraines which were subsequently covered with glacial meltwater and for 60Ma collected sandstones, shales and conglomerate eroded from the Damara Mountains to a depth of hundreds of metres. A subsequent desert climate in the area left petrified desert sand – the Etjo Sandstones

Figure 16. View from the top of Waterberg Plateau.

that cover the Plateau today. The Plateau is the relic uplift associated with thrust faulting as the Kalahari basin pushed westwards. The junction of the permeable sandstone and the underlying shales results in a spring line facilitating the woodlands at the base of the plateau. Walking there was not unlike a walk in English woods. It was, in the past, a plantation. A half hour dawn scramble up the fragmented red sandstone cliffs was rewarded with magnificent views of the surrounding plain (Figure 16).

Our last stop before the airport was Dusternbrook, in earlier times a splendid colonial farm, now a restaurant and big cat reserve. The 17km drive through the estate to the restaurant is testament to both the wide, open spaces of Namibia and the isolation of plantation life. After lunch we took an open top safari to see leopard and cheetah fed by our hosts - a circus, maybe, but a great chance to see semi-wild cats from a few feet away.

Namibia is different, special. It is a land of cloud free sunsets (normally experienced in the middle of nowhere with a 'sundowner' to hand) where abundant and varied rocks change from pale yellow through a range of reds and oranges to a gentle brown glow … and sunrises. I will never forget breakfast at Canyon Lodge, eating home-grown bacon, sausage and egg whilst watching first the sun peek over a distant mountain then the shadow speed towards us. Within minutes we were engulfed by daylight. The temperature rose in an instant to take the winter chill from the air. Nor will I forget the proud indigenous people, who variously served meals and road fuel, begged and bartered with us, waited patiently outside our rooms to change beds, guided us through their splendid country and not least the caterers who came from the kitchens to entertain us at dinner with their tribal songs and dances.

The geology's not bad, either.

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Seven unconformaties and a thrust fault: north west Highlands excursion 4-11 May 2002, led by Iain Allison of Glasgow University

Margaret Donnelly, Lynn Everson, Stuart Fairley, Margaret Kennedy, compiled by Jane Hickman

The NW Highlands offer a wealth of geological experience. The rocks exposed along the western margin of the Caledonian orogenic belt cover the age range from Archaean to Pleistocene and the rock record is as notable for the long time gaps as it is for the rock units which bound these gaps. The theme running through this week-long excursion was the identification of unconformities, seven in all. Some we were able to observe at exposures and some were inferred from the rocks.

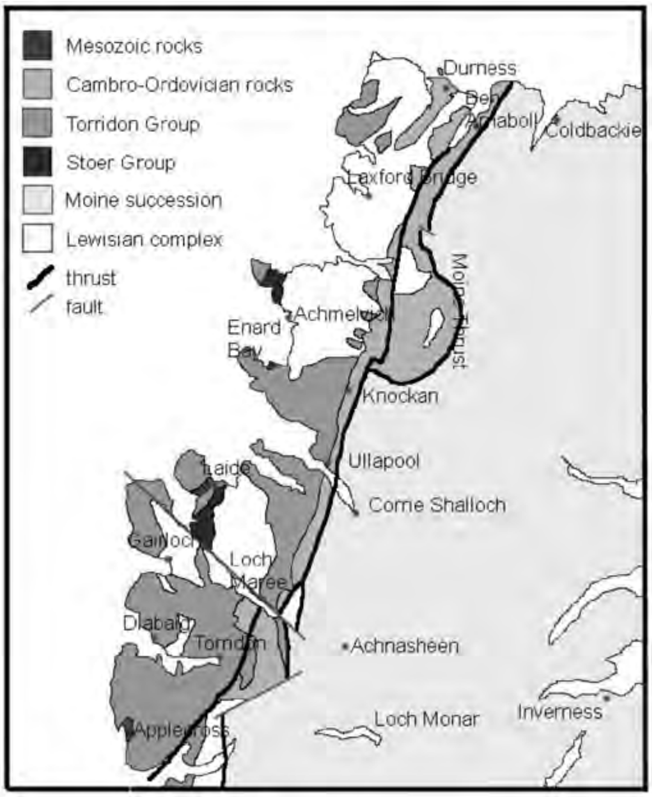

Figure 1. Generalized distribution map of main rock types.

Saturday

The group assembled in Inverness on the evening of Friday 3rd May. Saturday night was to be in the Torridon youth hostel so, as we had to traverse the Moine outcrop, the opportunity was taken to examine some well exposed rock surfaces on the shore of Loch Monar at the end of the scenic Glen Strathfarrar [NH 197388]. Here, the dominantly psammitic Moine metasedimentary rocks display refolded folds where the geometry of refolding can be easily seen. Hook-like and 'egg-box' refolds are common, (Figure 2).

Formed from the deposition of quartz rich sediment in an offshore marine environment, they had lithified as sandstones before being metamorphosed to psammites by burial to a depth of some 13 to 14km where temperatures reach 400ºC–500ºC. The high metamorphic grade of these rocks precludes the development of a strong axial-planar schistosity. Overall the entire package had been shortened in a SE–NW direction but two periods of extension, at least, had occurred as evidenced by the quartz stringers (infilled extension cracks) cutting across the fabric. Ptygmatic folding was also seen.

Figure 2. Interference patterns within Moine psammites, Loch Monar, Inverness-shire.

A mica rich layer was folded gently (i.e. with a long wavelength) but the thin quartz layer, which it contained, was tightly folded within it (i.e. short wavelength Figure 3). How could this have

Figure 3. Differential fold wavelengths between psammitic and pelitic layers, Loch Monar, Inverness-shire.

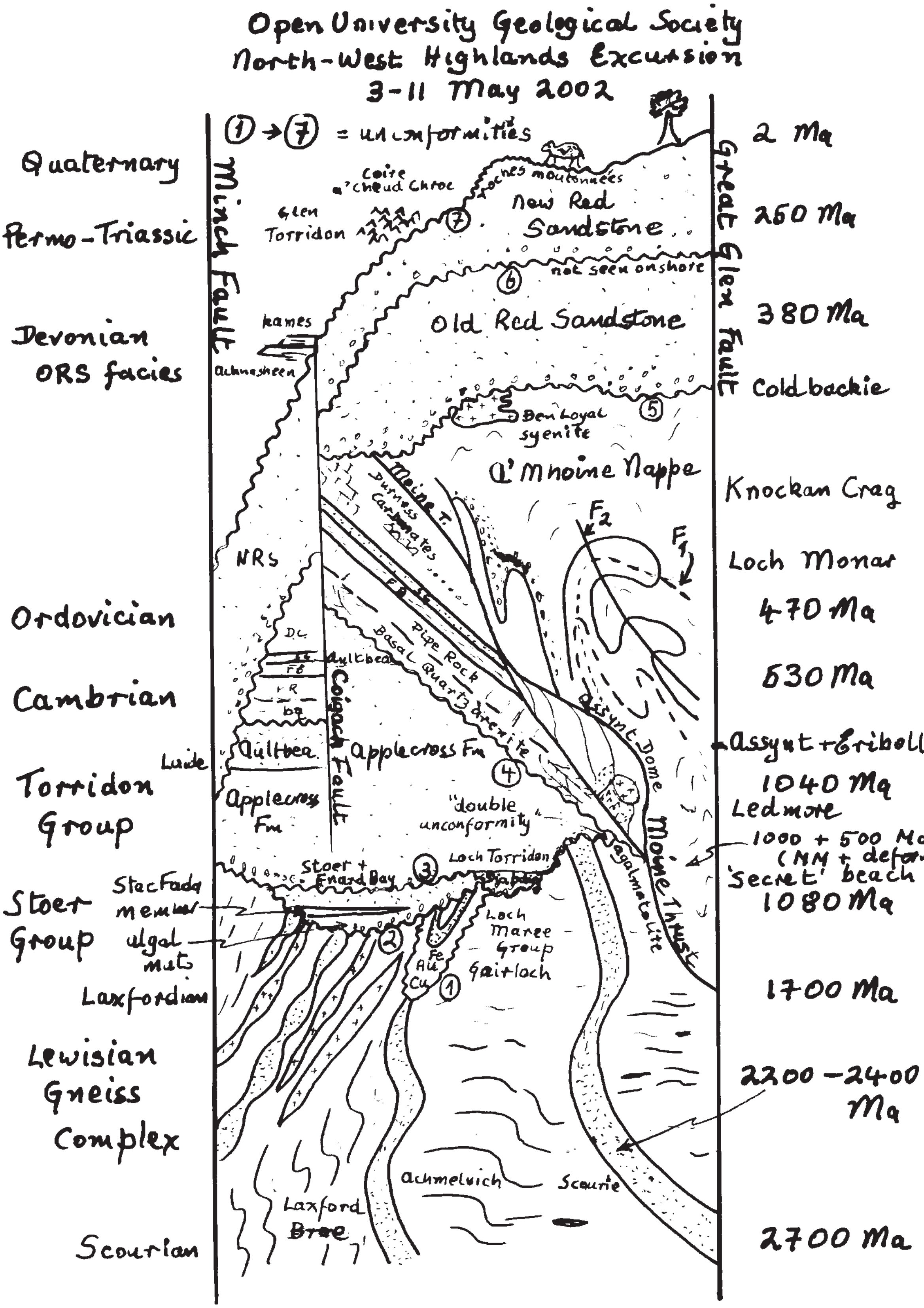

Figure 4. Synopsis of the excursion produced by Iain Allison. © Iain Allison 2002.

happened when the layers had been subjected to the same SE-NW shortening? Biot's buckling equation states that wavelength is proportional to layer thickness and contrast in competence. If both the quartz vein and the mica rich schist layer were to be unfolded then the quartz would stretch much further indicating that the mica must have thickened considerably during shortening.

On leaving the glen a brief stop was made at Aigas Dam [NH474438] to see a conglomerate of Old Red Sandstone (ORS) age consisting of a structureless mixture of large (0.5m) and small (10mm), rounded and angular clasts which unconformably overly the Moine rocks: our first unconformity (Figure 4 No 5). The time gap between cessation of movement on the Moine Thrust and deposition of the ORS rocks is relatively short. However, if uplift rates like those of the present Southern Alps of New Zealand prevailed, i.e. 1km in 10,000 years, then time is not a problem to get rocks from 15km depth to the surface.

One further stop was made at Achnasheen [NH1658] to look at the Pleistocene kame terraces which are so well developed there (Figure 4 No 7). Then we had a quick freshen-up at the youth hostel before heading up one of the highest roads in the UK over the Bealach na Ba in the Applecross hills for dinner at Applecross Inn with views of the sun setting over Raasay and, later, 5 planets visible to the naked eye.

Sunday

Sunday dawned clear and bright as we headed west towards Diabaig with the inselberg of Beinn Alligin to our right, a mountain carved out of Applecross Formation (Torridon Group) red sandstones and just one of many such mountains from here to the north coast. Our first stop [NG823598] was above Loch Diabaig's Airde where the basement Lewisian gneisses (Scourian complex) display cross-cutting metadolerite dykes of the Scourie dyke suite. These show small shear zones in which a strong fabric has developed during Laxfordian deformation. Outside the shear zones there is a relict igneous texture although the minerals are of metamorphic origin. We clambered up the gneiss hillside and were greeted with a puzzle, what looked like sandstone dykes cutting through the gneissic country rock. These are interpreted as fissure infills from the overlying Applecross Formation sandstones even though the original unconformity must have been many tens of metres above.

Having driven down to Diabaig, we saw the lowest member of the Torridon Group, the Diabaig Formation, which immediately underlies the Applecross Formation. The Diabaig Formation here [NG797603)] comprises siltstones, fine sandstones and laminated mudstones, which were probably lacustrine. Rain pits, desiccation cracks and ripples were all seen on the surfaces, which dipped 20ºW. Further to the NW we could see the overlying Applecross Formation.

En route to our next locality on the south side of Loch Torridon we stopped to look across to Beinn Alligin (985m). The sun was casting a shadow showing up the gap where a large section of the mountain had slid off during an earthquake about 6000 years ago.

The Applecross Formation could be seen resting on the exhumed Lewisian landscape and in the low road cutting at Ob Mheallaidh [NG835537] we examined the unconformity of Applecross Formation on Lewisian Gneiss (Figure 4 No 3) and then took a short traverse down section to find mudstones and siltstones with ripples and fine lamination similar to those seen at Diabaig.

Figure 5. Group photograph on shores of Loch Maree, Ross-shire, with a backdrop of Slioch and the undulating Lewisian/ Applecross Formation unconformity.

Driving towards Gairloch we stopped on the shore of Loch Maree [NH001650] for a good view of the undulating unconformity at the base of the Applecross Formation (Figure 5) on Slioch (980m).

Looking east we saw the edge of the thrust belt with a layer of Lewisian overlying the pale Cambrian quartzarenites.

We then headed for the shore at Gairloch [NG805760] to examine a conglomerate comprising gneiss, quartzite, schist, jasper and some bits of magnetite. We deduced from the clasts that it had not travelled far and contouring round the outcrop we saw the contact with the underlying Lewisian basement. It was a locally derived basal conglomerate of the Applecross Formation .

Monday

Today was the day we had to travel the 200km between the Torridon Youth Hostel and the Inchnadamph Field Centre at Assynt and pack in all the geology along the way. Luckily the sun was shining and the air was clear, so we set off enthusiastically. We drove up past Beinn Eighe again, with its capping of snow, and from the minibus we could see the glacial scenery including Coire a'Cheud Chnoc [NG955558] (the Corrie of the Hundred Hills), pointed hillocks of moraine from a stationary glacier.

The first stop [NG822732] was a bog stop (no, not a comfort stop) south of Kerrysdale, near Gairloch. Here we saw a rusty-weathering quartz vein, a gossan, the surface indication of copper/iron (plus some gold) deposited in quartz vein systems into the schistose metasedimentary rocks. The leaching of iron from the pyrite gave rise to iridescent films of iron oxy-hydroxide (FeOOH) on the pools of stagnant water. While our boots sank gently into the bog, the difference was demonstrated between the round globules that form when a film of oil is disturbed and broken up, and the angular polygonal plates that form from a film of iron oxy-hydroxide. The fluids carrying iron in reduced state precipitate out when exposed to the air as the insoluble oxidised Fe^{3+}. The area is peppered with boreholes where Consolidated Gold Fields plc had searched and found gold. The area is still used for training in geophysical exploration methods.

The next stop was near Flowerdale Mains Farm. Walking up behind the New Inn we saw hornblende schists and a gully where marble had been mined out for use as lime in the fields. A little further on we came to a locality where our compass needles swung away from magnetic north, revealing the presence of magnetite of the banded iron formation (BIF) that had formed on an early Precambrian sea floor. This was the probable source of the magnetite within the conglomerate seen yesterday. The schists had once been mud and the marble had once been limestone; we were within the late Archaean/early Proterozoic supracrustal sequence of the Loch Maree Group. Hence at the base of this sequence, where the Loch Maree metasediments rest upon the gneissic basement, was the earliest unconformity that we were to encounter on our trip. This unconformity (Figure 4 No 1) was some 1500Ma older than the one we saw the day before. The BIF's have been dated to about 2,500Ma. The sequence has been preserved in a tectonic syncline and metamorphosed to medium grade (low amphibolite facies) during the Laxfordian (2200–1600Ma), so the sedimentary sequence is a time marker at some point in the early Proterozoic. This sequence is not seen elsewhere in the Lewisian rocks of the mainland.

Another unconformity was seen at Laide, a coastal stop on the way north to Ullapool. Here [NG901929] a red bed conglomerate, regarded as Triassic (New Red Sandstone) containing clasts of limestone from the Cambro-Ordovician Durness Carbonate Formation, overlaid the Precambrian Applecross Formation of the Torridon Group (Figure 4 No 6). There is much more of this NRS conglomerate out to sea in the Minch as shown by drilling over the past 30 years. What is seen onshore is the proximal feather edge of an offshore Mesozoic basin.

From Little Loch Broom we drove along Destitution Road (so called because it was built by Irish workers who had emigrated at the time of the 1840's potato famine) to the Corrie Shalloch (Ugly Corrie) Gorge and the Falls of Measach. The gorge was a spectacular deep ravine eroded along a fault in the Moine Rocks. We had seen so much already, but it was only lunchtime. We ate under the trees here and it was sunny and peaceful.

We continued north through Ullapool and spent the rest of the day at the new Knockan Crag visitor centre [NC188091] which has been laid out as a series of geological trails with explanatory sculptures and works of art as well as interactive audio-visual exhibits . It is a lot of fun and very well put together.

Figure 6. The Knockan Puzzle.

At the base of the trail, there is a sculpture called 'The Knockan Puzzle', which shows the geological succession at Knockan using polished slabs of the actual rocks (Figure 6). The succession is not stratigraphic and the visitor is invited to puzzle over why there are old, metamorphosed strata lying over what look to be unmetamorphosed sedimentary beds. It gave us a great opportunity to inspect both the polished and the weathered surfaces of the rocks that we were to walk over as we followed the trail to the top of the crag. This exhibit had been prepared by the Orcadian Stone Company of Golspie, founded by Don Shelley who had set up a museum that displays rocks from the northern Highlands as well as from all over the world. Sadly, he had died shortly before our trip.

The weather was still wonderful and from the top of the crag we could see a great panorama to the north over part of the Assynt window. This window formed by erosion of an up-domed thrust allowing the rocks below the thrust sheet to be exposed. At Knockan there is no thrust zone, the metamorphic rocks of the hinterland rest directly on the rocks of the foreland, whereas in the window the thrust zone is up to 12km wide. The Moine Thrust is essentially sub-horizontal on the large scale but the Assynt window resulted from the Moine Thrust coming up against a resistant igneous block causing the propagation of lower thrusts which produced local updoming. And so it was, that whilst up upon Knockan Crag, the group participated in a Moine Thrust Hand Dance, choreographed by Iain, to explain how this would have worked.

Knockan is also one of the very few places where it is possible to place one's hands either side of the thrust fault at the base of the Moine sheet. Estimates suggest that here it has travelled some 75km from the ESE.

We had superb views of the mountains to the west, Suilven, Canisp, Stac Pollaidh and south to Ben More Coigach and, in the distance, An Teallach. It had been a tremendous day and we drove on for our first night at Inchnadamph Lodge.

Tuesday

The day dawned with signs of another glorious sunny day. The morning was spent climbing Meall Mor [NH140945] on the outskirts of Ullapool from where we had a good view south, across Loch Broom, of the angular unconformity between the grey Cambrian quartzarenites (Figure 4 No 4), dipping about 15°E, and the brown Applecross Formation sandstones. During our ascent we were to note whether the succession of outcrops was what we would expect.

After a steep climb over the Torridon sandstones of the Applecross Formation we came across the Cambrian basal quartzarenite member. This is mineralogically a very mature sedimentary rock in which the individual quartz clasts have quartz overgrowths which has effectively eliminated all pore space. Hence these rocks have been referred to as quartzites but it was explained that the term quartzite implied metamorphism to most geologists so the term quartzarenite is to be preferred.

After the cross-bedded quartzarenites, we were expecting to find the next Cambrian unit, the PipeRock, in which the vertical burrows, the trace fossil Skolithos, were probably formed by filter feeding worms. However, instead we found Lewisian quartzofeldspathic gneiss which is older than the quartzarenites indicating that we had crossed a thrust. The next exposure was also a gneiss but a dark basic one in which the amphibole had now been changed to chlorite, an indication that the rock had been retrogressed by the effects of the thrusting. This was followed by flaggy mylonites, siliceous, fine grained, pale grey rocks, of the Moine Series indicating that we had crossed the Moine Thrust.

Apparently there are only two major thrusts here, the Moine Thrust and the lower Loch Broom thrust which carried the Moine Thrust, piggy-back style towards the WNW. Within the mylonites on the hill top there is a rock which has caused much debate and confusion. It looked igneous, of a granitic sort, with large crystals of K-feldspar, some quartz, but no fabric, and may be an intrusion which occurred at some late stage towards the end of the thrusting. This may be the Logan Rock referred to in Oldroyd's "Highland Controversy" (Oldroyd, 1990).

At the top of the hill glacial action has smoothed and rounded the rocks to produce bullet shaped landforms called roche moutonnée and we could see at the blunt end where the rock had been plucked out by the ice.

We now made the long climb down the hill and observed dolostones of the Cambro-Ordovician Durness Carbonate Formation within the wall of the quarry at the valley bottom. These dolostones, which exhibited some large scale recumbent folds, had been cut by two large extensional faults which dipped in the opposite direction to the thrusts observed higher in the succession. This appears not to make sense but may be explained by the collapse that follows when a period of mountain building comes to an end.

After a well-earned lunch break at Ullapool we set off for Enard Bay where we were to spend the afternoon looking at rocks of the Stoer Group (lower Torridonian). This started with a 2km walk across the bog which, luckily, was reasonably dry.

First we came to a fissure within the Lewisian rocks which had subsequently been filled with a coarse conglomerate. Nearer the sea [NC027147] we found a very coarse deposit at the base of the Stoer Group containing clasts of Lewisian (Figure 4 No 2), which could obviously not have travelled very far. This has long been regarded as scree debris but some think that it might have been generated by glaciers about 1200Ma ago.

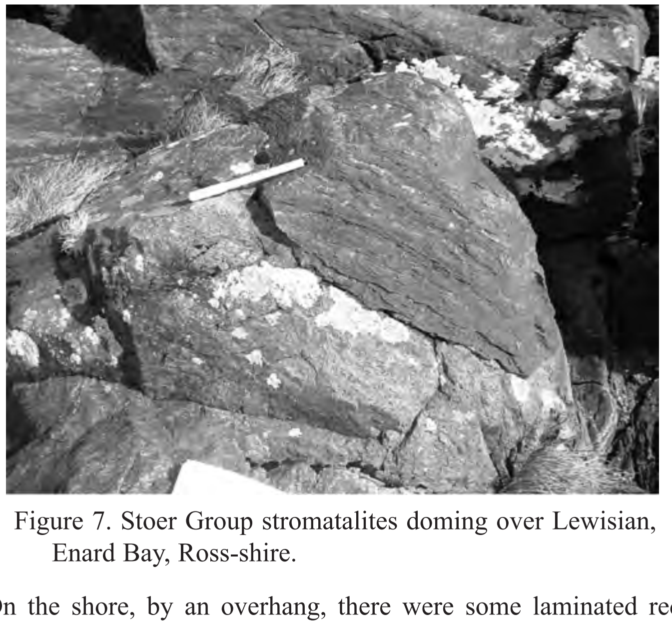

Figure 7. Stoer Group stromatalites doming over Lewisian, Enard Bay, Ross-shire.

On the shore, by an overhang, there were some laminated red rocks which effervesced with dilute HCl so proving to be carbonates. These domed upwards and appeared to be mantling the underlying Lewisian basement (Figure 7). They are stromatolites and there is some debate as to how these algal mats formed: either in a cold environment (they are forming today in lakes in Antarctica) or in a marine environment in a hot climate and there is some evidence for both of these theories.

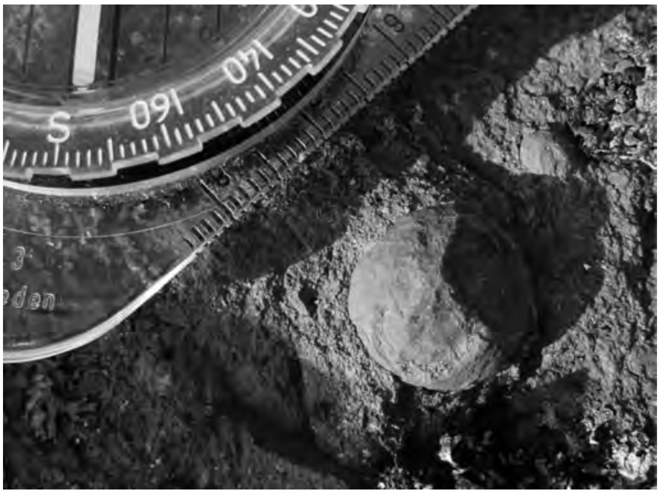

Figure 8. Accretionary lapilli, Stac Fada member, Enard Bay, Rosshire.

Further round the bay we reached a dark red clastic sedimentary rock which has been interpreted as a volcanic mud flow. On the top surface we could just see small (up to 10mm), smooth, rounded lumps which were formed when fine ash gathered in concentric layers round a nucleus on falling through the volcanic ash cloud. These were accretionary lapilli (Figure 8) and this rock unit is the Stac Fada member of the Stoer Group. From here we could see rocks of the Applecross Formation, distinctly different, paler and well bedded, a short way across the bay; an unconformity (Figure 4 No 3) between the two was inferred which represented a time gap of some 140Ma.

Wednesday

At Allt a' Mhuillin Quarry [NC288098] we examined borolanite within an intrusive sheet, part of the Borralan Complex. Sub-spherical aggregates of light coloured minerals have been termed pseudoleucites from their shape and the assumption that they were originally leucite and have now been replaced with nepheline and K-feldspar. The rock was injected towards the end of movements on the Moine thrust at about 440Ma. Minerals included zeolites, biotite from alteration, garnets, and sulphite was present in the form of pyritisation. The sub-spherical pseudoleucite 'crystals' make good strain markers and are, in places, flattened and elongate indicating deformation in shear zones implying that the sheet had been emplaced during ongoing thrusting.

A few miles to the NW we stopped at the Loch Awe quarry [NC250157] in the Cambrian Fucoid Beds, a member of the An t-Sron Formation. The rocks here included dolostones, shaley dolostones, dolomitic shales, and argillites which are predominantly of adularia, a form of K-feldspar. Trilobites are present in the shales. This rock has been used as an organic fertilizer due to its high potassium content of up to 12% K_2O. There were vugs in the dolostones containing anhydrite and celestine, the presence of which is indicative of a vanished evaporite. The most likely setting for original sedimentation was lagoonal.

We stopped to view a small reverse fault in a road cutting through the Salterella Grit and overlying carbonates near Ardvreck castle [NC245232]. One particular *Salterella* specimen, which had expired in just the right orientation, provided us with a perfect subject.

At Achmelvich [NC058247] a 15m wide metadolerite Scourie dyke through the Lewisian loomed over the track way down to the beach. The Scourie dyke swarm, which was emplaced 2200-2400Ma and covers a minimum area of 120x250km, was one of the most remarkable events in the evolution of the Lewisian. The trend of this specimen was roughly NW-SE.

Our last call of the day was Ledmore marble quarry [NC251137]. This was a white to greenish marble which had formed by thermal metamorphism of the Durness carbonates by part of the underlying Borralan complex (seen earlier today). The carbonates had been raised to temperatures of up to 900ºC. Unfortunately the quarry owners had used high explosive to remove the top cover prior to production and, although an attempt was made to produce blocks for facing stone, the resultant fine fracturing throughout had rendered it useless for this purpose – a pity!

Thursday

The first locality of the day [NC195262], a road-cutting about 2km west of Skiag Bridge on the A837, took us again to the Applecross Formation sandstones in unconformable contact with the Lewisian gneisses (Figure 4 No 3). Here the unconformity is flat and has only a slight undulation. The gneisses below are fresh with no indication of weathering, recent or ancient. The sandstones above are pebbly rather than conglomeratic. The sandstones, well-bedded with clasts up to 10mm, continue up the hill in a series of steep cliffs, 2-3m high, with flat benches between, interpreted as layers of mudstone which erode more readily than the sandstone. These are interpreted as the individual channel infills of a big braided river system in huge alluvial fans. Cross bedding indicates a current flowing from the NW. The Applecross Formation has been dated using radiometric methods as well as palaeomagnetism and, although these give different values, they both distinguish the older Stoer Group from the younger Torridon Group.

Looking south across Loch Assynt the Applecross Formation can be seen lying horizontally on the Lewisian, here with a hilly topography on the unconformity. The base of the Cambrian quartzarenite forms a planar unconformity (Figure 4 No 4) and dips gently to the east where, near the eastern end of the loch, it is seen to transgress the Appecross Formation to lie directly on the Lewisian beyond: the 'double unconformity'. This is a line in space along which the base of the Applecross Formation and the base of the Cambrian meet the Lewisian.

The planar unconformity at the base of the Cambrian can be traced all the way from Denmark to Wisconsin in the USA and everywhere a similar stratigraphic succession is seen, quartzarenites overlain by carbonates.

From Skiag Bridge we drove north on A894 to Loch Glencoul. The road crosses up through the Pipe Rock member of the Eriboll Sandstone Formation, Fucoid Beds, Salterella Grit (of the An t-Sron Formation), then follows the line of the lowest thrust. To the east, in stream sections, an imbricate zone with many repeated, tectonically-emplaced, units of Fucoid Beds, Salterella Grit and Ghrudaidh Dolomite can be identified. The road then descends down the succession finally crossing Torridon sandstones and on to the Lewisian as Loch Glencoul is approached.

On both sides of Loch Glencoul, the Lewisian is unconformably overlain by the Basal Quartzarenite and Pipe-Rock of the foreland with, above, a tectonic sheet of Lewisian, also carrying Basal Quartzarenite and Pipe-Rock, thrust over them on the Glencoul Thrust. From a viewpoint on the SW shore, the Glencoul Thrust is clearly seen with, in the distance, the Stack of Glencoul, composed of thick Moine mylonites lying above the Moine Thrust.

At the viewpoint, just north of the bridge at Kylesku, gneiss is seen in the road-cuts. Looking south to Quinag, different angles of bedding are seen in the Applecross Formation sandstones. These dips could be due either to late Precambrian deformation causing gentle folds or to deposition in enormous alluvial fans interfingering with each other such as seen in the alluvial fans of Death Valley, USA.

Continuing north, we passed many road cuttings in gneisses and finally stopped at one near Badcall [NC165428]. Here pyroxene granulites of the Scourian Lewisian are exposed. These rocks have no hydrated phase such as amphibole or biotite. This is an anhydrous Lewisian gneiss with plagioclase, green pyroxene and occasional garnets, formed at very high temperatures in the deep crust. With the metamorphism having been dated 2700Ma these were the oldest rocks of the trip.

The Scourie Dyke crops out on the shore just north of Scourie pier [NC149455] and is the type locality for the Scourie dyke suite. This can be traced inland as a depression in the surrounding gneisses. It appears to have an igneous texture but the igneous minerals have been replaced by metamorphic equivalents. Shear zones with well developed planar and linear fabrics occur in both the dyke and country rock and the sense of shear indicates that the north block has moved up relative to the south.

The 'Multi-coloured Rock Stop', a road-cut just north of Laxford Bridge [NC233487] on the A894, gives an excellent view of the different rock types and their structural relationships within the Laxfordian Lewisian. Grey gneisses have been cut by almost black Scourie dykes of various compositions and both have been deformed by the Laxfordian events. The whole complex was subsequently cut at different angles by granitic pegmatites at late stages of the Laxfordian deformation (*ca* 1700Ma). This locality lies close to the Laxford-Stack Line (Loch Laxford to Ben Stack), a zone of intruded sheets of granite. Although the gneissic foliation appears fairly uniform in attitude large scale folds can be mapped north of the Laxford Stack Line.

The road north rises up to about the top of the Lewisian peneplain. To the south the landscape appears very dissected producing a rugged topography; to the north the landscape is very smooth with Applecross Formation sandstones infilling the palaeovalleys of the Lewisian. To the south we are looking at an exhumed eroded Lewisian landscape which is what the topography would have been like as the sandstones buried it some 1100Ma ago.

The afternoon was spent on the east-west coastal section on the south shore of Balnakiel Bay which is the type area for the Cambro-Ordovician Durness Carbonate Formation. The present day topography is karstic with deep fissures and a large blowhole or 'geodha' which the sea enters via a tunnel producing a spout through a hole in the cliff-top. Our traverse started in the west [NC376688] with the second lowest member, the Eilean Dubh member, and we worked east. These are fine-grained, flaggy, dolostones. The beds are extensive and thin (~20-30mm) and are interpreted as having been deposited on a shelf as lime muds by turbidity currents. Some horizons contain frosted, very rounded, quartz grains (millet-seed sand which look like oolites); these must have been blown in from a nearby desert during intermittent violent storms. Slightly higher in the succession, gutter casts, narrow erosive channels produced by rip currents, occur. Further up section, a flake breccia occurs immediately below a metre-thick layer of stromatolites whose domed surfaces have a honeycomb structure, indicative of the cell structure. These tidal deposits are inconsistent with the surrounding shelf sedimentary rocks and may have slid as a slab out onto the shelf generating the flake breccia below.

Figure 9. Chert nodules with the Sailmhor member, Durness Carbonate Group, near Balnakiel, Sutherland.

The overlying member, the Sailmhor, comprises mainly massive, mottled, crystalline, granular dolostones which contain large spheroidal chert nodules (Figure 9). The chert nodules have nucleated at points between stromatolites and have grown to replace the algal mat. Comparison of the thickness of layering within and outwith the nodules implies that they formed early in the diagenetic history of the rock. There are zones of fracturing nearby related to the east-west fault in the adjacent bay which has brought down the Moine and Lewisian rocks of Faraid Head on the other side of the bay.

The overlying Sangomore member consists of fine, granular, non-fossiliferous dolomites with layers of white chert. The boundary between the Sailmhor and Sangomore members is marked by a small cliff. The top surface of the former contains numerous karst-like fissures and breccias and it has been suggested that these formed before the latter was deposited indicating a major time break between the Cambrian and Early Ordovician. However, this weathering appears not to extend beneath the latter and so they are likely to be of recent origin.

The final member on this section, the Balnakiel member, has alternating dark and light grey dolomites, some limestone layers and layers with chert nodules. Some layers have a tectonic fabric where the angle between cleavage and bedding can be measured. These layers act as shear zones in which the top has moved towards the WNW, the same direction as the overlying thrust movements, as deduced from the cleavage-bedding relationship. Although these rocks lie hundreds of metres beneath the lowest thrust the shearing is the result of late Caledonian deformation within what is regarded as the foreland.

Friday

The light drizzle sweeping across the Durness headland, our first taste of true highland weather in a week, confirmed the suspicions created by the 'watery moon' last night as we boarded the minibus for our final day of geology. We headed east and our first stop was Traigh na h-Uamhag, the Beach of the Little Cave [NC440660] where the Cambrian lay directly on the Lewisian. What we saw on the floor of the little cave was a big block of agalmatolite, a beautiful pale green rock, composed mainly of a type of muscovite. This muscovite is very fine grained with all the crystals arranged in random orientation. In the Moine Thrust belt certain stratigraphic horizons are preferred for the thrusts to propagate along. This may be one such 'easy slip' horizon. Several theories for its formation have been put forward including hydrothermal alteration of the gneisses by waters constrained to flow along the unconformity during burial at 8-10km and temperatures of about 250°C at the peak of the Caledonian orogeny. However, in keeping with the interpretation of Peach and Horne, the favoured origin is extreme Precambrian chemical weathering, and what we see is a paleosaprolite (the 'fossilised' base of a deep tropical weathering profile). The fact that little is left may be due to glacial erosion during possible Snowball Earth times. Interestingly the surrounding gneiss and amphibolites become softer and greener in colour as the unconformity is approached, another indication of over-all surficial chemical weathering.

Figure 10. Iain and Jane sitting on Arnaboll Thrust plane, Ben Arnaboll, Sutherland.

We drove round the head of Loch Eriboll to the next locality, the Ben Arnaboll Thrust (Figure 10) and associated imbricate zone [NC 453603]. It was time to apply the knowledge of the foreland succession we had gained over the past few days, and identify the rock types in this zone ourselves. So: Salterella Grit, Applecross sandstones, Basal Quartzarenites, Fucoid Beds, Quartzarenite, Salterella Grit, Applecross sandstones, and Pipe Rock topped off above the thrust plane by Lewisian gneiss. The sequence was due to movement on the main thrusts causing multiple stacking of the Torridon and Cambrian beds, with a large thrust sheet of Lewisian emplaced over them. Peach and Horne surveyed this area extensively in the mid 1880's, and Lapworth researched the area about the same time. It was he who coined the term mylonite, from the

Greek for a mill, after studying specimens taken from the gneisses close to the thrust plane on Ben Arnaboll (Figure 11). The connotation of a mill suggests crushing and grinding, however, modern studies have shown that these rocks are the products of plastic rather than cataclastic deformation. The individual crystals change shape internally and 'flow' and recrystallise rather than break into smaller pieces. "How fast was the thrust moving?" asked our leader. The familiar OUGS minute's silence followed, "about a mile-a-night," he said, answering his own question!

After lunch we walked to the coast to examine an imbricate zone beneath the Arnaboll Thrust. Each thrust slice is only metres to tens of metres thick. The bedding in these Cambrian rocks starts off with a very steep dip in the middle of the imbricate zone and the dip decreases as they approach the flat-lying roof thrust.

Our final destination was Coldbackie, [NC605601] north of Tongue and back within the Moine outcrop. Here we looked at fold mullion structures in the Moine. A plunging anticline-syncline fold pair has a strong lineation parallel to the fold hinge, with the limbs of the folds having this strong mullion-like appearance. On the way down to the beach we were surprised to find an exposure of clast supported, poorly-sorted conglomerate comprising vein quartz, metamorphic, and syenite clasts with a crude imbrication indicating water flow to the NW. A small knoll closer to the beach consisted of Moine schists overlain unconformably by this conglomerate interpreted as of ORS age. However, the current BGS view from published maps is that it is Permian in age. From here we could see Watch Hill far above consisting of this same coarse conglomerate. It seemed that we were seeing a palaeo-hanging valley which had filled with conglomerate during unroofing of the Caledonian mountains and which had then flowed down many hundreds of metres forming the isolated exposures we had seen on the beach.

The exertions of the week had taken its toll on many of us, what with all the tourist style geology, long lie-ins and early nights!! We therefore headed for the local hostelry for our final dinner. In appreciation of Iain having survived a week in our company we presented him with a ceramic fish platter designed and crafted by Lotti Globb, a renowned local artist. The weather had been fantastic, the geology superb and our leader unparalleled, a most memorable trip. Thanks Iain.

Acknowledgement

I would like to thank Iain for all the patient help he gave me during the compilation of this excursion write-up and acknowledge his contribution to the editing process. In other words, if there's something wrong I'll blame him!

Photographs kindly contributed by Lynn Everson, Elizabeth d'Eyrames, Chris Preece and Jane Randle.

Reference

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Book review

Islands of the Arctic by Julian Dowdeswell and Michael Hambrey, Cambridge University Press, 2002, 280pp, £25.00 hardback, ISBN 0521813336.

At a first glance this is an attractive coffee table book with superb pictures on almost every page but it is much more than just a beautifully illustrated book. Julian Dowdeswell is Director of the Scott Polar Research Institute and Professor of Physical Geography at Cambridge University, and Michael Hambrey is Director of the Centre for Glaciology and Professor of Glaciology at Aberystwyth University and between them they have spent over forty seasons undertaking field work in the Canadian Arctic, Greenland, Svalbard and the Russian islands.

The first chapter sets the scene by describing the principal topographic and physical features of each major island or archipelago. Chapter 2 explores how tectonic, sedimentary, igneous and metamorphic processes have shaped the Arctic over nearly 4,000 Ma. Weather and climate and the changes over the last 100,000 years are the topics of Chapter 3, including an account of meteorological observations going back to the early records obtained by the British Admiralty between 1820 and 1850. Chapter 4 deals with glaciers and ice sheets, past and present, and there are very clear explanations of the difference between ice sheets and ice caps, the different types of glacier and the erosional and depositional landforms produced by them. Chapter 5 moves on to icebergs and sea ice and how they serv as indicators of environmental change. Chapter 6 covers frozen ground and frost activity and the building and engineering difficulties encountered: heated buildings resting directly on permafrost can become structurally unstable fairly quickly, so buildings are constructed on wooden piles to prevent transfer of heat to the ground. Coasts, rivers and lakes are the subject of Chapter 7: the distinctive landscape features are described and the environmental record found in sediments. The Arctic islands support specially adapted plant and animal populations and their interactions with the environment are described in Chapter 8. Chapter 9 deals with the indigenous people who have lived in harmony with nature for centuries and the damage done by others in the exploration and exploitation of the last three centuries; tourism is growing but there is an increased awareness of the fragility of the Arctic ecosystem. Chapter 10 is headed Postscript: the future of the Arctic islands and looks at predictions of climatic change as well as the future of human activity.

This book will appeal to students of geology and also to the general reader who is interested in learning about one of the Earth's last true wilderness areas. The final words are "It is our hope that this book will enhance the enjoyment of those who come to the islands of the Arctic, and to awaken the interest of those who have yet to appreciate its unique landscape, wildlife and peoples."

The authors have certainly achieved this objective and at the modest price of £25.00 this is a book I should love to have on my bookshelf.

Elizabeth Maddocks BA (Open)