Published in *Open University Geological Society Journal*, 2012, Volume 33, 29-36

Note that this version of the text does not include the Journal's editorial and proof corrections

The demise of the Iapetus Ocean as recorded in the rocks of southern Scotland

Phil Stone

British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA

ABSTRACT

The late Neoproterozoic to early Palaeozoic Iapetus Ocean attained its maximum size towards the end of the Cambrian Period, separating Laurentia from Baltica to the east and Avalonia to the south. As the ocean began to close, subduction-related volcanic arcs formed at its margins, with vestiges now preserved in the late Cambrian to early Ordovician Ballantrae ophiolite complex. This was obducted in the mid-Ordovician as north-directed subduction of Iapetus oceanic crust was established beneath Laurentia. Thereafter, until the mid Silurian, a supra-subduction accretionary complex built up and now forms the Southern Uplands terrane. The accretionary complex grew through the southward-propagation of an imbricate thrust system that sequentially stripped the sedimentary cover from the subducting oceanic crust. This has produced a distinctive regional geology of linear, fault-bound tracts within which steeply inclined strata strike NE-SW; the oldest tract (Caradoc) forms the NW margin of the terrane whilst the youngest (Wenlock) forms the SE margin. Conversely, each individual tract youngs to the NW with a thin, basal development of graptolitic mudstone at its SE margin, conformably succeeded by a much thicker succession of turbiditic sandstone. As each tract was accreted its strata suffered deformation that was hence diachronous, earlier in the north than in the south. Eventually, in the mid Silurian, the Iapetus Ocean closed and the accretionary complex over-rode and depressed the margin of Avalonia, causing an abrupt increase there in Ludlow sedimentation rates. Deformation of the resulting strata

did not come until the early Devonian, ca. 400 Ma Acadian Orogeny, an event unrelated to the closing of Iapetus. The principal Acadian influence on the Southern Uplands terrane was sinistral transpression, with pre-existing structures re-activated and intensified, and granitic plutons and dyke swarms intruded.

----------ooooooooo----------

This brief account describes the Early Palaeozoic events that shaped the geology of southern Scotland. It is based on the newly prepared and currently ‘in press’, 4^{th} edition of the British Geological Survey’s *South of Scotland* volume in the British Regional Geology series (Stone and others, in press). This volume provides a comprehensive overview of southern Scotland’s geology and is previewed here by permission of the Executive Director, British Geological Survey, NERC.

THE EARLY PALAEOZOIC IAPETUS OCEAN

Scotland’s border with England coincides, more or less, with one of the most fundamental geological boundaries in Britain. This is the Iapetus Suture (Figure 1), the trace of a long-vanished, Early Palaeozoic ocean obliterated by the convergence and ultimate collision of the ancient continents that it once separated. The Iapetus Ocean (as a precursor to the Atlantic Ocean it was named after the father of the eponymous Atlas) was initiated during late Neoproterozoic times and had grown to its maximum width by the end of the Cambrian Period. Thereafter, subduction at its margins wrought its eventual destruction and drove the series of collisional events that built up the Caledonian Orogen, a major tectonic zone that can be traced from Scandinavia, through Britain and Ireland, and on into Greenland and maritime North America. There are particularly clear geological links from southern Scotland, through Ireland, into Newfoundland, Canada (e.g. Colman-Sadd and others, 1992).

Along the northern margin of the Iapetus Ocean at the beginning of Ordovician time, the continent of Laurentia lay in sub-tropical latitudes. The Archaean and Proterozoic crystalline basement rocks of Scotland formed a part of this continent, and subduction of Iapetus oceanic crust beneath its margin led to the sequential accretion of oceanic rock complexes, both volcanic and sedimentary. These now underlie much of southern Scotland. Forming the southern margin of the Iapetus Ocean during Ordovician time, in southern temperate latitudes, lay the northern part of the Gondwanan continent, from which a fragment had broken away early in Palaeozoic times. This continental fragment, Avalonia, drifted north towards Laurentia as the intervening Iapetus Ocean closed; the principal stages in the destruction of the ocean are illustrated in the series of cross-sectional sketches shown in Figure 2.

One result of the narrowing of the Iapetus Ocean was the convergence through time of the faunal assemblages from the opposing continental margins. The Laurentian and Avalonian shelly fossils such as trilobites and brachiopods, that lived in shallow, coastal marine environments, are quite different in the Ordovician so that distinct ‘faunal provinces’ can be identified, but the fauna then became progressively more cosmopolitan through the Silurian (e.g. Cocks and Fortey, 1982). Whilst distinctive shelly faunas characterise the opposing continental margins, graptolites populated the deeper parts of the ocean. This long-extinct group of colonial animals formed the greater part of the oceanic plankton during Ordovician and Silurian times, and their fossils are of great biostratigraphical importance. They establish age and order in the Ballantrae Complex and its overlying sedimentary cover (the Girvan succession), and are crucial to an understanding of the Southern Uplands. Graptolites are commonly slender and delicate and a few centimeters in length, though the length may range from almost microscopic to a metre or so in extreme cases. During the Early Palaeozoic they evolved an extraordinary variety of shapes (Figure 3), and it is this variety that is key to the biostratigraphical zonation now based on their remains.

Island arcs and obduction

At its northern, Laurentian margin, the first stage in the closure of the Iapetus Ocean was the early Ordovician development of oceanic subduction zones and volcanic island arcs (Figure 2a), one of which contributed to the Ballantrae Complex of south-west Scotland along with volcanic rocks of within-plate character (e.g. Stone and Smellie, 1988). This Tremadoc to Arenig assemblage of oceanic, mostly igneous rocks collided with and was tectonically emplaced (obducted) onto the Laurentian continental margin at about 470 Ma

(Figure 2b) to form an ophiolite complex. Its obduction played a peripheral part in the large-scale collision of a volcanic arc complex (now forming the buried core of the Midland Valley terrane) with Laurentia that instigated the Grampian event of the polyphase Caledonian Orogeny

Within the Ballantrae Complex there is a bewildering array of rock types: ultramafic rock of mantle origin, oceanic lavas erupted in contrasting island arc and within-plate settings, intrusive gabbros and pelagic sedimentary strata (e.g.Thirlwall and Bluck, 1984; Smellie and Stone, 2001). All were tectonically juxtaposed and obducted as the Iapetus Ocean began to close. By early Llanvirn times the complex was in place and had been deeply eroded. Obduction had been accompanied by a switch in the polarity of subduction and as oceanic crust began to be consumed beneath the continental margin a volcanic arc was generated on what is now the basement to the Midland Valley of Scotland. Relative uplift caused by this 'Midland Valley' magmatism was accompanied by extension and relative subsidence of the continental margin to the south (Figure 2c). There, the Ballantrae Complex was progressively buried by a sedimentary cover sequence of shallow to deep marine strata that systematically overstepped northwards from the late Llanvirn to the early Wenlock (c. 460-428Ma). This now forms the Girvan succession. Its northwards transgression was controlled by major faults, with downthrow to the south, stepping back sequentially into the Midland Valley arc zone (e.g. Ince, 1984). The eventual, probably late Silurian deformation of the Girvan succession, involved the reactivation of those originally normal faults as northward directed thrust planes (Williams, 1962).

Subduction and accretion

Whilst the Ballantrae Complex was being buried beneath the thick Ordovician to Silurian, Girvan sedimentary succession, a very different process was operating farther south. As the Iapetus oceanic crust was subducted beneath the margin of Laurentia, sections of the oceanic sequence and its sedimentary cover were intermittently stripped from the subducting plate and thrust beneath a stack of similar stripped-off slices to initiate an accretionary complex (Figure 2c). The Southern Uplands terrane represents the deeply eroded remains of this accretionary complex (Leggett and others, 1979), which developed along the northern fringe of the Iapetus Ocean sequentially from late Llanvirn to mid-Wenlock times. Its outcrop extends across southern Scotland and continues south-westward to underlie a broad swathe of country from County Down in Northern Ireland to County Longford in the Irish Republic.

The sedimentary units incorporated into the accretionary complex (Figure 4) originated as sand and mud carried by turbidity currents from the continental shelf, via submarine canyons, and built up into huge depositional fans (now the Southern Uplands sandstone formations as summarised by Floyd, 2001). The clastic, turbidite deposits filled the supra-subduction-zone trench and encroached onto the oceanic plate, where they covered the sequence of hemipelagic mud (Moffat Shale Group), radiolarian chert and pillow lava (Crawford Group). As the submarine fans built out they overstepped progressively younger oceanic sequences that were continually approaching the continental margin as the oceanic plate was subducted. Then, during the subduction process, discrete sections of the oceanic sequence and its cover of turbidite sandstone were sequentially stripped from the subducting oceanic plate and thrust beneath the stack of similar stripped-off slices that made up the growing accretionary complex. These slices, structurally rotated towards the vertical (and in places even beyond it so that the component beds are inverted), now give rise to the characteristic Southern Uplands lithostratigraphic outcrop pattern of upright beds (Figure 5) contained in elongated and NE-SW-trending, fault-bounded tracts which are defined stratigraphically in terms of groups and formations (Figure 1).

The sequential incorporation of structural tracts by accretionary underthrusting also explains the long-standing enigma of Southern Uplands stratigraphy: sedimentary structures such as graded bedding and sole marks (Figure 6) show that the upright beds in each tract generally become younger towards the NW, whereas graptolite biostratigraphy shows that the oldest tracts form the NW of the terrane with the youngest tracts at its SE margin (Figure 4). Note that in any single tract, the thin (<30 m) layer of pelagic mudstone at the base (Moffat Shale Group) was deposited over a considerable period of time, but is overlain by a vastly thicker (up to about 1000 m) turbidite sandstone succession that accumulated during the elapse of a single graptolite biozone.

The composition of the turbidite sandstones varies with age, with particularly marked contrasts between some of the Ordovician tracts. Some of the Ordovician sandstones therein are quartzo-feldspathic whereas others are rich in volcanic detritus, the variation reflecting the different sources from which the original sediment was eroded. The fundamental influence of the compositional range, the detail of which is commonly cryptic, is well illustrated by the British Geological Survey's geochemical atlas (1993) based on analyses of stream sediment across the Southern Uplands region. Two examples are shown in Figure 7, the linear distribution of high and low values running parallel to the geological tract structure and demonstrating a close (but not linear) association between the compositions of the bedrock and the modern alluvial sediment eroded from it (e.g. Stone and others, 2003). In Figure 7a, a zone of high chromium (Cr) values spatially corresponds to the older tracts of the Gala Group the sandstones of which contain much chrome spinel as accessory grains. Also note the high level of Cr associated with the mafic-ultramafic Ballantrae Complex. In Figure 7b, strontium (Sr) is markedly partitioned, with high values over the Leadhills Supergroup and Gala Group contrasting with low values over the Ettrick and Hawick groups. One possible explanation may lie in the composition of detrital feldspars eroded from bedrock into the stream sediment: more plagioclase in the older rocks to the north, more K-feldspar in the younger rocks to the south. For reassurance that the regional geochemical patterns accurately reflect the underlying geology, despite the anticipated smearing effects of glaciation, note the correlations across the outcrops of the Galloway granite plutons; even the details of compositional zoning are reflected in the stream sediments.

A model of the Southern Uplands as a forearc, supra-subduction-zone accretionary complex is now generally accepted, following much discussion of possible alternatives that arose, in part, from the provenance contrasts evident between different sandstone tracts. In particular, sedimentary palaeocurrent indicators (Figure 6) show that introduction of the volcanic detritus was apparently from the south, i.e. from the oceanic plate rather than the continental margin, a circumstance that has been cited in support of a back-arc origin for all or some of the terrane (Morris, 1987; Stone and others, 1987). There has also been some discussion of the possible extension of the Girvan depositional setting, an extending and subsiding continental margin, into the northern part of the Southern Uplands terrane (Armstrong and Owen, 2001). Analyses of basin thermal history have now ruled out the back-arc possibility (Stone and Merriman, 2004), whilst dating of detrital zircon grains has shown the volcanic detritus to be mostly Neoproterozoic and so unrelated to volcanism contemporary with the depositional setting of the host sandstone (Phillips and others, 2003).

Polyphase folding was imposed on the strata as the accretionary complex built up (e.g. Barnes and others, 1989). Early folds were formed in association with thrusting during the subduction process and so of course the earliest deformation was diachronous, older in the north than in the south. Subsequent folds developed as accommodation structures when the early-formed part of the accretionary complex adjusted to continued subduction at its leading edge and responded to intervals of strike-slip movement rather than orthogonal compression. There is however one important difference between the early and late stages in the development of the accretionary complex. The older tracts were accreted from subducting oceanic crust, but by mid Wenlock times the Iapetus Ocean had effectively closed and the complex, at the leading edge of Laurentia, over-rode the margin of Avalonia (Figure 2d). The meeting of the two continental masses did not produce a deformational climax and instead the accretionary complex continued to advance through the foreland basin that formed ahead of it, above Avalonian continental crust depressed by the encroaching mass of Laurentia. In somewhat pedantic terms, the accretionary complex had become a foreland fold and thrust belt. Thereafter, convergence of the two continental plates probably ceased in Ludlow times, to be replaced by intermittent lateral movement between them.

THE IAPETUS SUTURE

By late Silurian time the Iapetus Ocean had all but disappeared (Figure 2c), though the ultimate continental collision was something of a tectonic anticlimax. It was not a mountain-building event of orogenic proportions and the results are hard to identify in the tectonic record preserved on either the Laurentian or Avalonian margins. The metamorphic grade of the Southern Uplands strata is invariably low, with some rocks only showing diagenetic effects. There was instead something of a tectonic continuum, as the Southern Uplands accretionary thrust terrane over-rode Avalonia and continued southwards as a foreland fold and thrust belt (Figure 2d). Initially, a load-induced, flexural foreland basin advanced ahead of the thrust front and was an influential control on sedimentation during the accumulation of the mid- to late Silurian parts of the Windermere Supergroup in the south of the English Lake District (Kneller and others, 1993). This situation did not last, and by the end of Ludlow times convergence between Laurentia and Avalonia had ceased, the foreland basin failed to migrate farther southwards, and isostatic adjustments reversed the earlier effects of loading.

The tectonic effects seen within the exposed rock sequence, though created by collision-related processes, give little indication of the deeper structure of the suture zone. This is more usefully modelled from geophysical data. A number of seismic lines have traversed the Iapetus Suture Zone and have generally been interpreted in terms of a north-west-dipping, reflective zone projecting to the surface close to the northern coast of the Isle of Man and thence striking north-east beneath northern England. When the seismic results are integrated with regional interpretations of gravity and magnetic data (Figure 8) a rather more complicated picture emerges in which Avalonian-type crust is caught up in a compound suture zone that extends well to the north beneath the Southern Uplands terrane (Kimbell and Stone 1995).

It is something of a geological paradox that the Lower Palaeozoic rocks of the Laurentian margin did not experience substantial deformation as a result of the collision with Avalonia. One possible effect is seen in the Girvan district, where the normal faults that had controlled deposition of the Ordovician to Silurian forearc basin succession were reactivated as north-directed thrusts late in the Silurian. Another possible tectonic outcome of the collision is implicit in Figure 8, wherein Laurentian-type crystalline basement extends from the Midland Valley terrane beneath the northern part of the Southern Uplands. Perhaps large-scale northward thrusting of the accretionary complex onto the Laurentian margin accompanied the demonstrable north-directed thrusting of the Girvan succession (Bluck 1984). The considerable horizontal shortening of the accretionary complex that would have been likely in such circumstances could have been accommodated by the widespread rotation of bedding to the vertical, an attitude hard to attain only by accretionary activity.

Despite the uncertainties, it is clear that the continental collision between Laurentia and Avalonia was not an orthogonal event. A wealth of evidence shows that a sinistral stress regime was important during the later stages of convergence, and indeed may have been the dominant final effect. With a sinistral shear sense applied to the major north-east-trending strike faults, a conjugate pattern of smaller, cross-cutting, late Caledonian strike-slip faults was established across both the Southern Uplands terrane and the Lower Palaeozoic outcrop in northern England. The conjugate fault system comprises strike-slip faults trending either generally north-west with a dextral sense of displacement, or generally east-north-east with sinistral displacement. Though individually minor, these faults were to have a profound structural influence during subsequent episodes of extensional tectonism when their re-activation controlled late Palaeozoic basin development and geometry. More immediately, in the transtensional tectonic regime pertaining during latest Silurian to early Devonian times, strike-slip basins opened across the region and were filled with the clastic, terrestrial sediments of the Old Red Sandstone lithofacies. The transtensional regime may also have been an important factor in the intrusion of the early Devonian granite plutons.

AFTER IAPETUS

In the aftermath of the final closure of the Iapetus Ocean a range of igneous rocks were intruded into the Ordovician and Silurian strata of the accretionary complex: a regional swarm of late Caledonian (Silurian–Devonian) calc-alkaline felsic and lamprophyre dykes; several large, early Devonian granitic plutons (Figure 1), and a number of smaller diorite-granodiorite-granite intrusions. Radiometric dating has confirmed that the first to be intruded were microdiorite and lamprophyre dykes, with ages ranging from 418±10 Ma to 400±9 Ma (Rock and others, 1986). The age of the larger, granitic intrusions varies across the Southern Uplands (Thirlwall, 1988) with the northern plutons, such as Loch Doon, giving ages around 410 Ma (earliest Devonian) and proving to be older than the southern plutons that were intruded closer to the Iapetus Suture, such as Cairnsmore of Fleet and Criffel, which give ages of around 397 Ma (early to middle Devonian). The southern plutons were coeval with the Skiddaw and Shap granites, intruded to the south of the suture (Figure 1).

Broadly coincident with the c. 400 Ma magmatism in southern Scotland and northern England, but focussed farther to the south, was a major deformation event caused by the collision of another Gondwanan continental microplate (Armorica?) at the southern margin of Avalonia. This is commonly described as the Acadian event of the polyphase Caledonian Orogeny, but since it has no connection with closure of the Iapetus Ocean it has also been thought of as a separate orogeny in its own right. In northern Britain the most widespread Acadian effects seen are the folding and cleavage developed in the Lower Palaeozoic rocks of the English Lake District. In the Southern Uplands of Scotland the Acadian, sinistral-strike-slip tectonic regime reactivated some of the dominant NE-SW Caledonian faults, with a particularly intense effect seen along the boundary between the Leadhills Supergroup and the Gala Group (Figure 1), a boundary marked by the Moniaive Shear Zone (Phillips and others, 1995). This tectonic feature interacts with the thermal aureole around the Cairnsmore of Fleet granitic pluton (Figure 1) with early-formed metamorphic cordierite porphyroblasts wrapped by the tectonic fabric, whereas late-formed biotites cross-cut the fabric. The U-Pb radiometric age of the pluton is about 397 Ma, coincident with the age range established for the Acadian Orogeny farther south in Wales and northern England (e.g. Merriman et al. 1995). Elsewhere in southern Scotland, the Lower Devonian strata were tilted and disturbed during the Acadian Orogeny so that when alluvial basins were re-established, the Upper Devonian strata deposited therein were laid down unconformably on their predecessors, both Lower Palaeozoic and Lower Devonian. Most of the Upper Devonian deposits, red sandstone and siltstone with some conglomerate, were fluvial in origin though some also show an aeolian influence. By this time, the southern Scotland region formed an inland part of Laurussia, a 'supercontinent' formed by the amalgamation of Laurentia, Avalonia, Baltica and terranes of Asiatic Russia. The Iapetus Ocean was ancient history.

Acknowledgements

The ideas explored within this paper owe much to the insights of many colleagues, as discussed with and demonstrated to the author over a number of years. Particular thanks are due to Drs D. J. Fettes and S. D. Campbell for their astute and helpful reviews, to C. Woodward for assistance with the production of figures, and to N. Breward for the processing of the regional geochemical data. Publication is by permission of the Executive Director, British Geological Survey (NERC).

References

Armstrong, H. A. and Owen, A. W. 2001. Terrane evolution of the paratectonic Caledonides of northern Britain. *Journal of the Geological Society, London*, Vol. 158, 475-486.

Barnes, R. P., Lintern, B. C. and Stone, P. 1989. Timing and regional implications of deformation in the Southern Uplands of Scotland. *Journal of the Geological Society, London*, Vol. 146, 905-908.

Bluck, B. J. 1984. Pre-Carboniferous history of the Midland Valley of Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 75, 275-295.

Cocks, L. R. M. and Fortey, R. A. 1982. Faunal evidence for oceanic separations in the Palaeozoic of Britain. *Journal of the Geological Society, London*, Vol. 139, 465-478.

Colman-Sadd, S. P., Stone, P., Swinden, H. S. and Barnes, R. P. 1992. Parallel geological development in the Dunnage Zone of Newfoundland and the Lower Palaeozoic terranes of southern Scotland: an assessment. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 83, 571-594.

Floyd, J. D. 2001. The Southern Uplands Terrane: a stratigraphical review. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 91, 349-362.

Ince, D. 1984. Sedimentation and tectonism in the Middle Ordovician of the Girvan district, SW Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 75, 225-237.

Kimbell, G. S. and Stone, P. 1995. Crustal magnetisation variations across the Iapetus Suture Zone. *Geological Magazine*, Vol. 132, 599-609.

Kneller, B. C., King, L. M. and Bell, A. M. 1993. Foreland basin development and tectonics on the northwest margin of eastern Avalonia. *Geological Magazine*, Vol. 130, 691-697.

Leggett, J. K., McKerrow, W. S. and Eales, M. H. 1979. The Southern Uplands of Scotland: a Lower Palaeozoic accretionary prism. *Journal of the Geological Society, London*, Vol. 136, 755-770.

Merriman, R. J., Rex, D. C., Soper, N. J. and Peacor, D. R. 1995. The age of Acadian cleavage in northern England, UK: K-Ar and TEM analysis of a Silurian metabentonite. *Proceedings of the Yorkshire Geological Society*, Vol. 50, 255-265.

Morris, J. H. 1987. The Northern Belt of the Longford-Down Inlier, Ireland and Southern Uplands , Scotland: an Ordovician back-arc basin. *Journal of the Geological Society, London*, Vol. 144, 773-786.

Phillips, E. R., Barnes, R. P., Boland, M. P., Fortey, N. J. and McMillan, A. A. 1995. The Moniaive Shear Zone: a major zone of sinistral strike-slip deformation in the Southern Uplands of Scotland. *Scottish Journal of Geology*, Vol. 31, 139-149.

Phillips, E. R., Evans, J. A., Stone, P., Horstwood, M. S. A., Floyd, J. D., Smith, R. A., Akhurst, M. C. and Barron, H. F. 2003. Detrital Avalonian zircons in the Laurentian Southern Uplands terrane, Scotland. *Geology*, Vol. 31, 625-628.

Rock, N. M. S., Gaskarth, J. W. and Rundle, C. C. 1986. Late Caledonian dyke-swarms in southern Scotland: a regional zone of primitive K-rich lamprophyres and associated veins. *Journal of Geology*, Vol. 94, 505-522.

Smellie, J. L. and Stone, P. 2001. Geochemical characteristics and geotectonic setting of early Ordovician basalt lavas in the Ballantrae Complex ophiolite, SW Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 91 (for 2000), 539-555.

Stone, P. and Merriman, R. J. 2004. Basin thermal history favours an accretionary origin for the Southern Uplands terrane, Scottish Caledonides. *Journal of the Geological Society, London*, Vol. 161, 829-836.

Stone, P and Smellie, J. L. 1988. *Classical areas of British geology: The Ballantrae area*. (London: HMSO for British Geological Survey).

Stone, P., Floyd, J. D., Barnes, R. P. & Lintern, B. C. 1987. A sequential back-arc and foreland basin thrust duplex model for the Southern Uplands of Scotland. *Journal of the Geological Society, London*, Vol. 144, 753-764.

Stone, P., Breward, N. and Merriman, R. J. 2003. Mineralogical controls on metal distribution in stream sediment derived from the Caledonides of the Scottish Southern Uplands and the English Lake District. *Mineralogical Magazine*, Vol. 67, 325-338.

Stone, P., McMillan, A. A., Floyd, J. D., Barnes, R. P. and Phillips, E. R. In press. *British Regional Geology: South of Scotland* (Fourth edition). (Keyworth, Nottingham: British Geological Survey).

Thirlwall, M. F. 1988. Geochronology of late Caledonian magmatism in Northern Britain. *Journal of the Geological Society of London*. Vol. 145, 951-967.

Thirlwall, M. F. and Bluck, B. J. 1984. Sr-Nd isotope and geological evidence that the Ballantrae "ophiolite", SW Scotland, is polygenetic. *In*: Gass, I. G., Lippard, S. J. and Shelton, A. W. (eds.), *Ophiolites and oceanic lithosphere*. Geological Society, London, Special Publication No. 13, 215-230.

Williams, A. 1962. *The Barr and Lower Ardmillan Series (Caradoc) of the Girvan district of south-west Ayrshire, with descriptions of the brachiopoda*. Geological Society, London, Memoir No. 3, 267 pp.

Recommended additional sources of up-to-date regional overviews

Clarkson, E. and Upton, B. 2009. Death of an Ocean – a Geological Borders Ballad. (Edinburgh: Dunedin Academic Press), 224 pp.

Kelling, G. 2001. Southern Uplands geology: an historical perspective. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, Vol. 91, 323-339.

McMillan, A. A. and Stone, P. 2008. *Southwest Scotland – a landscape fashioned by geology*. Scottish Natural Heritage. 41 pp.

Oliver, G. J. H., Stone, P. and Bluck, B. J. 2002. The Ballantrae Complex and Southern Uplands Terrane. Chapter 6 in Trewin, N. H. (ed.) *The Geology of Scotland*. (London: The Geological Society), 167-200.

Stone, P. 2008. *Bedrock Geology UK North. An explanation of the bedrock geology map of Scotland, northern England, Isle of Man and Northern Ireland – 1:625 000 fifth edition*. (Keyworth, Nottingham: British Geological Survey).

Stone, P., Millward, D., Young, B., Merritt, J. W., Clarke, S. M., McCormac, M. and Lawrence, D. J. D. 2010. *British Regional Geology: Northern England* (Fifth edition). (Keyworth, Nottingham: British Geological Survey)

Woodcock, N. H. and Strachan, R. A. 2000. *Geological History of Britain and* Ireland. (Oxford and Edinburgh: Blackwell Science Publishing), 432 pp.

Figure Captions

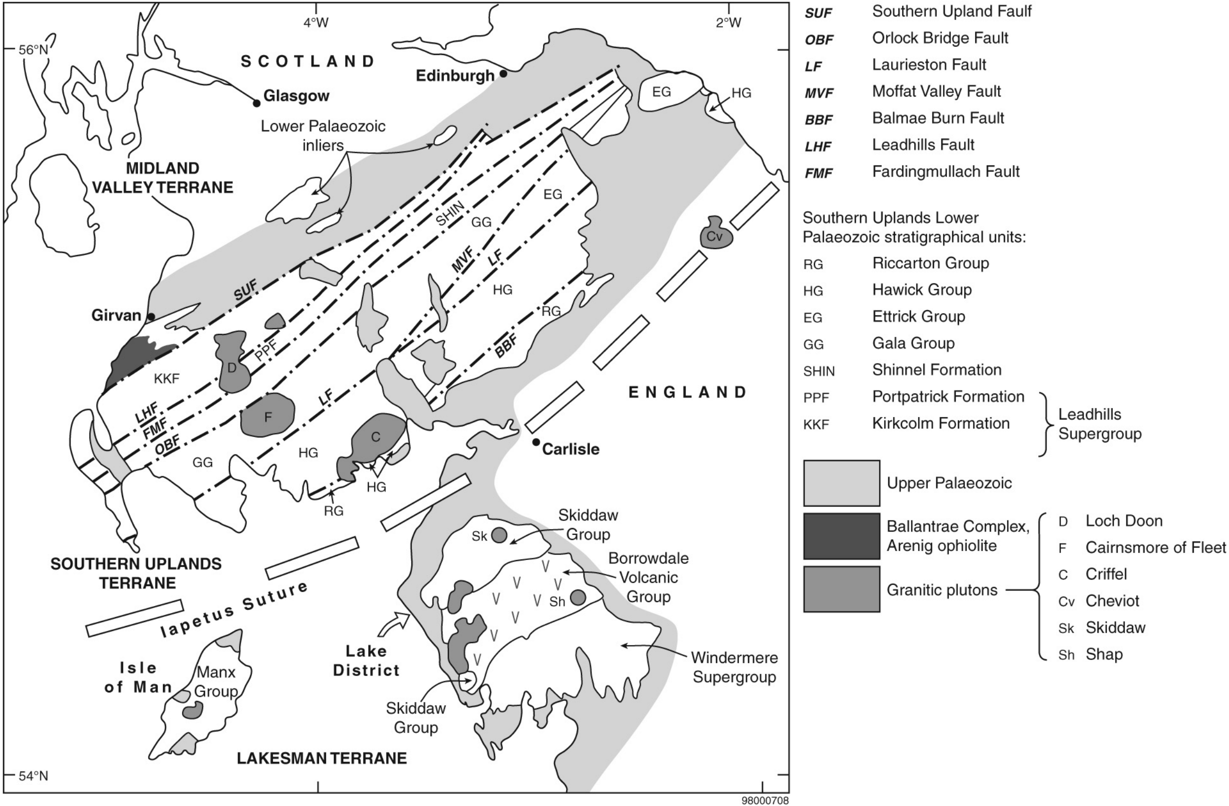
1. Outline geology of the Iapetus Suture zone, with the Southern Uplands terrane to the north and the Lake District terrane to the south.
2. Stages in the closure of the Iapetus Ocean illustrating the formation and obduction of the Ballantrae Complex (a and b: late Cambrian to mid Ordovician), the depositional environment of the Girvan succession and growth of the Southern Uplands accretionary complex (c: late Ordovician to early Silurian), and the

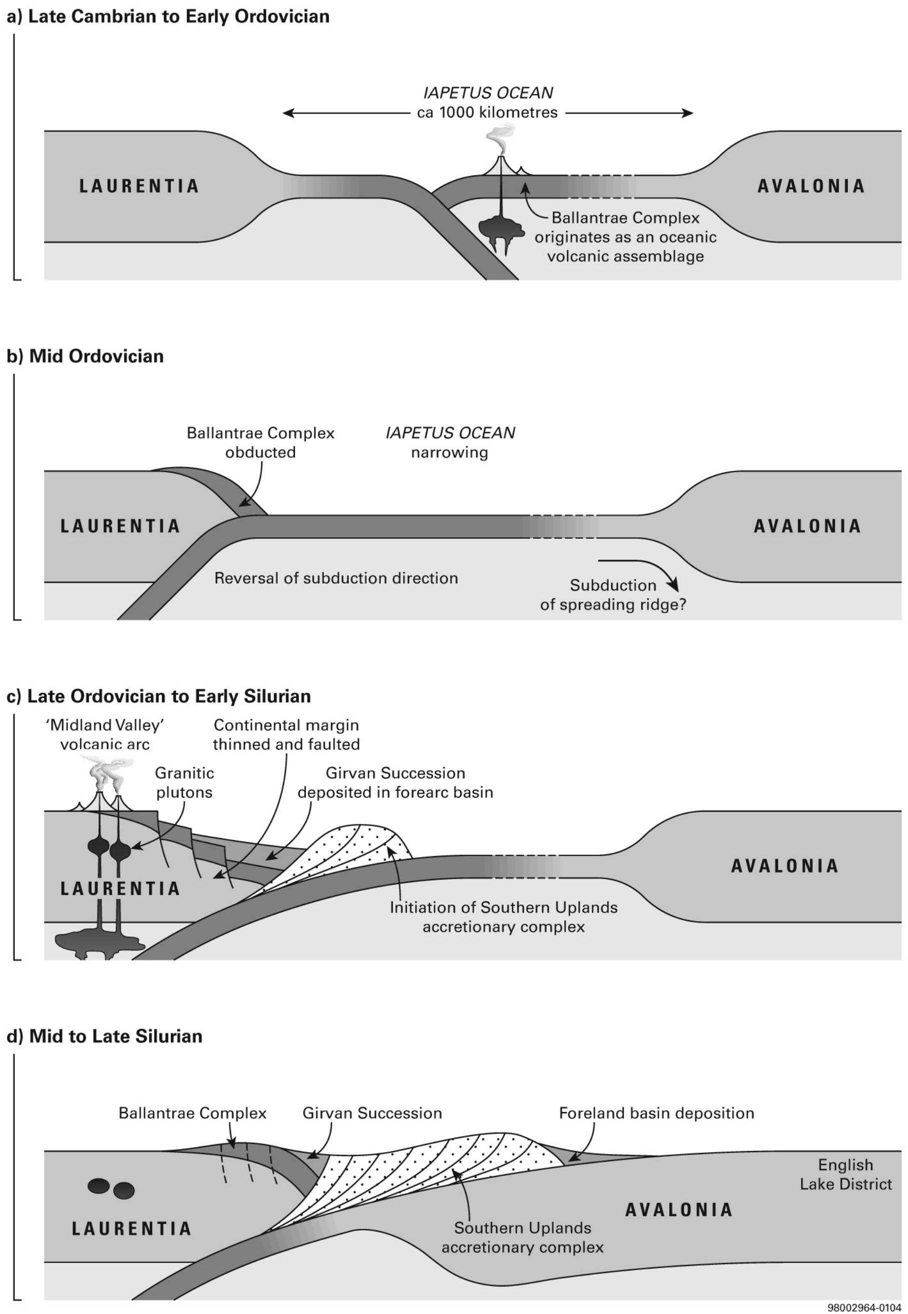
migration of the accretionary complex onto the Avalonian continental margin (d: mid to late Silurian).

3. Graptolites: the biostratigraphical facilitators of geological interpretation in the Southern Uplands of Scotland. Shown are Silurian (Llandovery) examples from the Birkhill Shales Formation of the Moffat Shale Group: a) *Rastrites* sp. b) *Campograptus communis rostratus* (Elles and Wood). c) a climacograptid. This fossil assemblage indicates a level within the *gregarius-convolutus* biozones (see Figure 4). BGS image P772042 (© NERC, all rights reserved).
4. A composite time-stratigraphy profile for the south-west part of the Southern Uplands, illustrating the tract relationships.
5. a) Steeply inclined (slightly overturned) turbidite strata of the Ordovician Kirkcolm Formation, as exposed on the west coast of the Rhins of Galloway at Salt Pans Bay [NW 962 620]. BGS image P008483 (© NERC, all rights reserved). b) Steeply inclined, thinly bedded turbidite strata of the Cargidown Formation (Hawick Group) exposed at Brighouse Bay [NX 632 453] to the south of Borgue. BGS image P220426 (© NERC, all rights reserved). Note the well-developed cleavage.
6. Flute casts, two examples from the Ordovician Kirkcolm Formation showing different styles and current directions: a) Finnarts Bay [NX 053 722]: BGS image P008425 (© NERC, all rights reserved); b) Portobello [NW 960 665]: BGS image P008463 (© NERC, all rights reserved). The shape of the linear flute casts from Finarts Bay indicates current flow from top right to bottom left; the linguiform flute casts from Portobello indicate current flow from top left to bottom right. In both cases the steeply inclined beds are slightly overturned and are viewed looking north.
7. Regional geochemical maps for chromium and strontium; for explanation of underlying geological linework see BGS 1:625k bedrock geology map for UK North. Summary statistics for Cr and Sr are shown in the table below:

Percentile	95	75	50 (median)	25	5
Cr ppm	380	210	150	110	50
Sr ppm	270	160	120	90	60

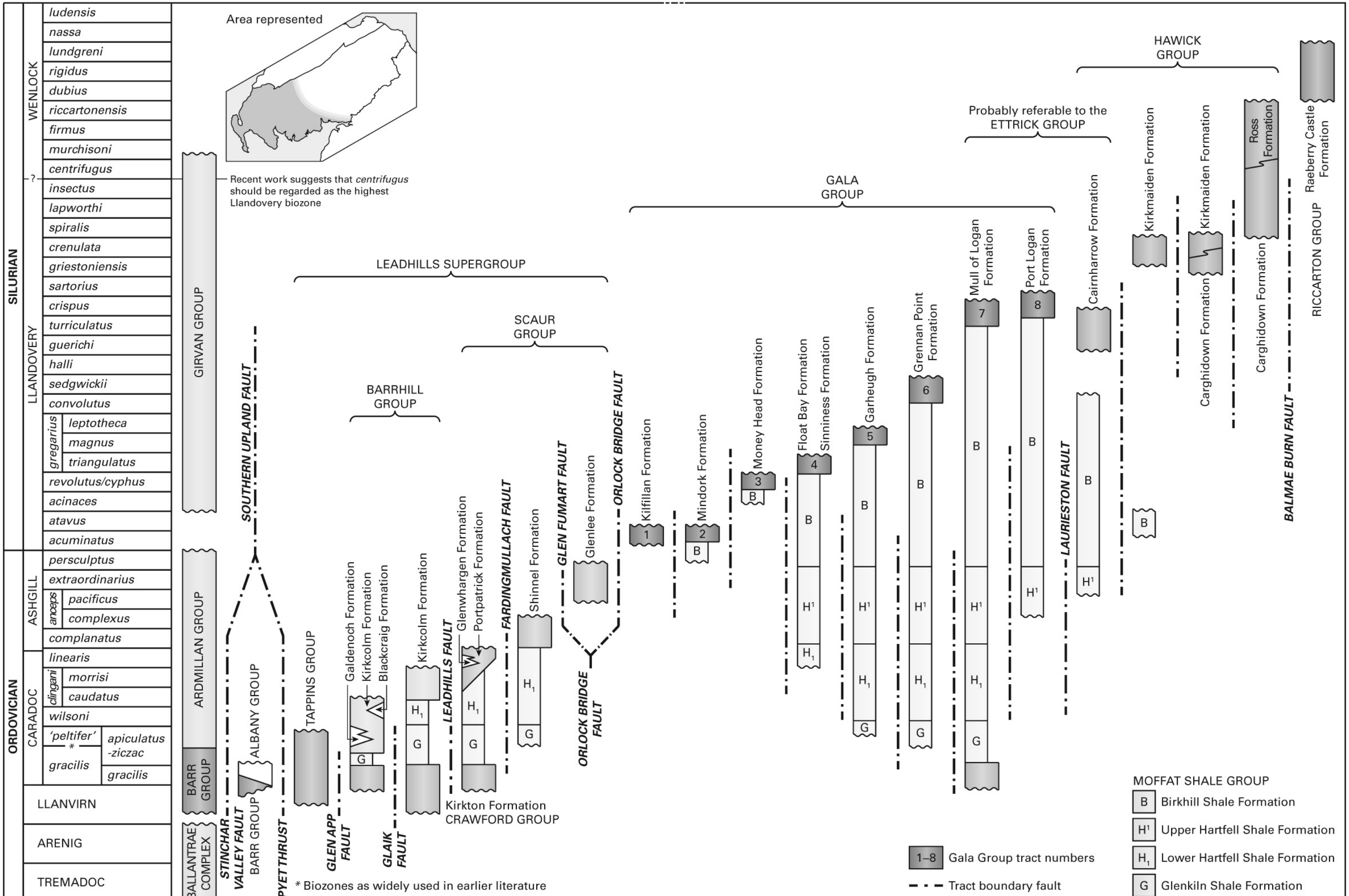
8. A deep crustal section across the Iapetus Suture Zone based on geophysical evidence and illustrating the long-wavelength magnetic anomaly known as the ‘Galloway High’.


4°W
2°W
56°N
54°N
SCOTLAND
Edinburgh
Glasgow
Lower Palaeozoic inliers
MIDLAND VALLEY TERRANE
Girvan
SUF
OBF
LF
MVF
BBF
LHF
FMF
PPF
KKF
SHIN
GG
EG
HG
RG
D
F
C
Cv
ENGLAND
Carlisle
SOUTHERN UPLANDS TERRANE
Iapetus Suture
Isle of Man
Manx Group
Lake District
Skiddaw Group
Borrowdale Volcanic Group
Sk
Sh
V
Windermere Supergroup
LAKESMAN TERRANE
98000708
SUF Southern Upland Faulf
OBF Orlock Bridge Fault
LF Laurieston Fault
MVF Moffat Valley Fault
BBF Balmae Burn Fault
LHF Leadhills Fault
FMF Fardingmullach Fault
Southern Uplands Lower Palaeozoic stratigraphical units:
RG Riccarton Group
HG Hawick Group
EG Ettrick Group
GG Gala Group
SHIN Shinnel Formation
PPF Portpatrick Formation
KKF Kirkcolm Formation
Leadhills Supergroup
Upper Palaeozoic
Ballantrae Complex, Arenig ophiolite
Granitic plutons
D Loch Doon
F Cairnsmore of Fleet
C Criffel
Cv Cheviot
Sk Skiddaw
Sh Shap

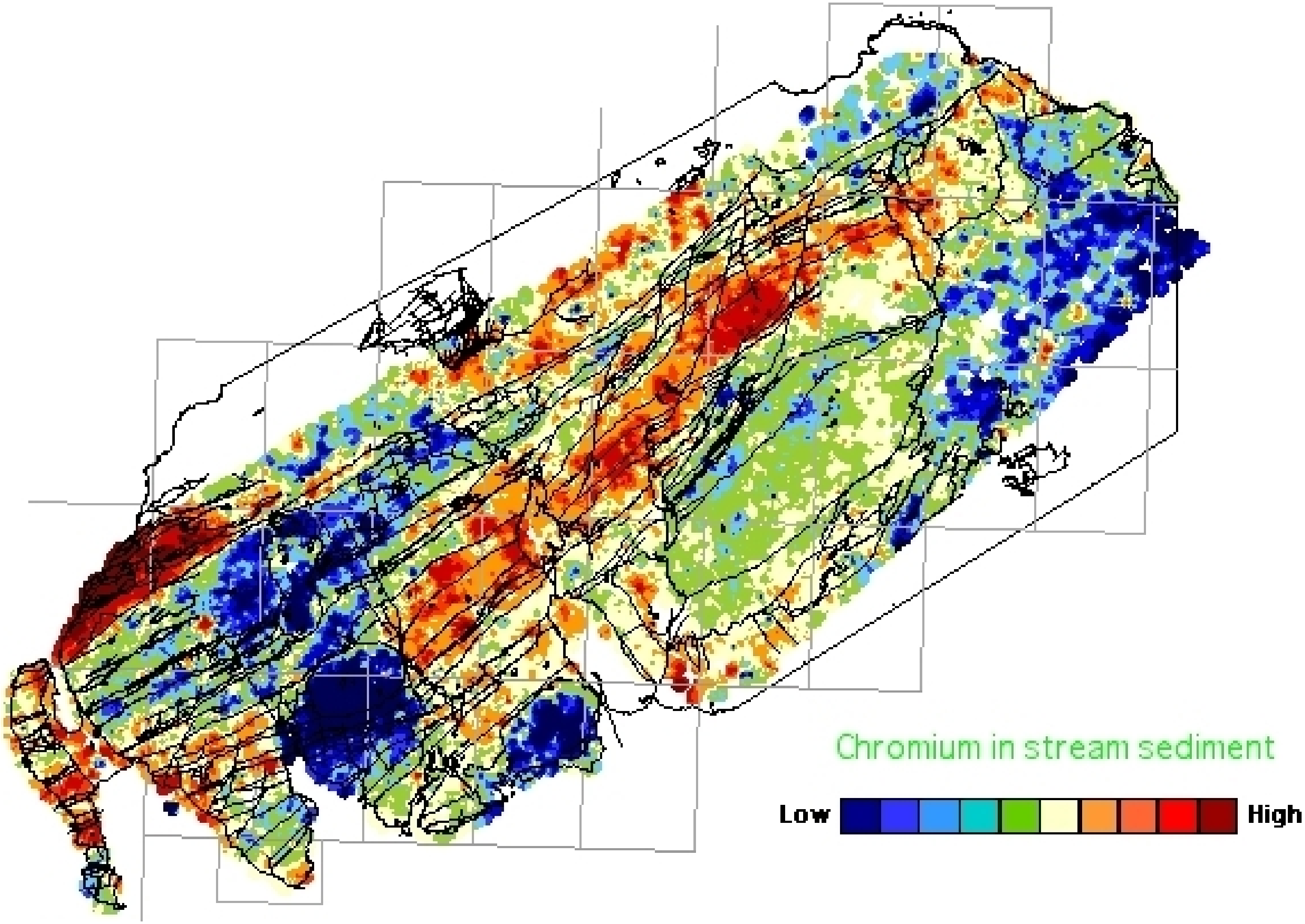


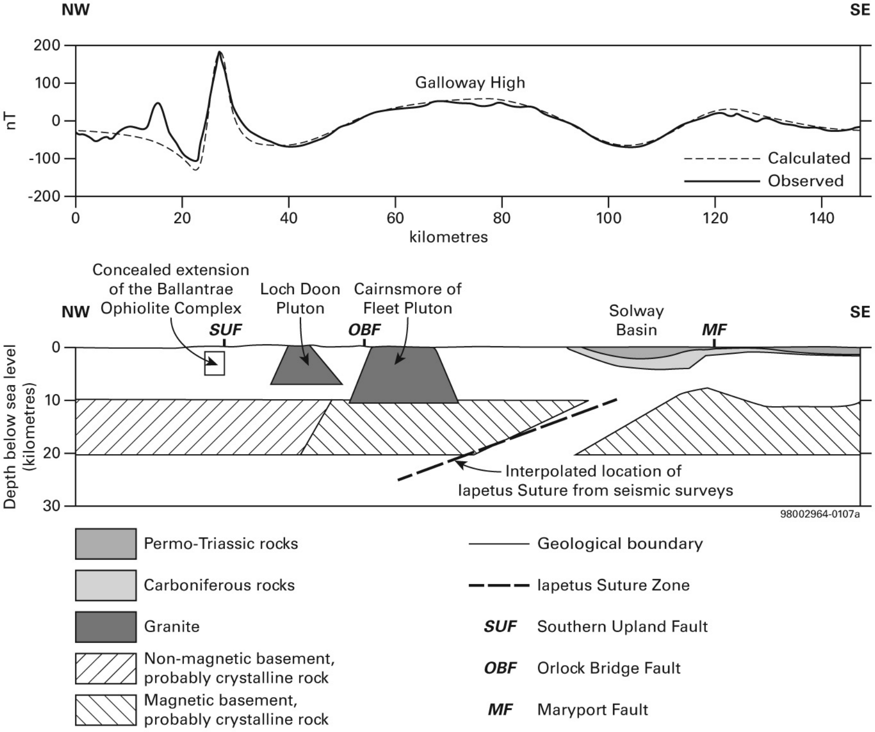
98002964-0104


a
b
c
4 cm



Graptolite biozones
SILURIAN
WENLOCK
LLANDOVERY
ludensis
nassa
lundgreni
rigidus
dubius
riccartonensis
firmus
murchisoni
centrifugus
insectus
lapworthi
spiralis
crenulata
griestoniensis
sartorius
crispus
turriculatus
guerichi
halli
sedgwickii
convolutus
gregarius
leptotheca
magnus
triangulatus
revolutus/cyphus
acinaces
atavus
acuminatus
ORDOVICIAN
ASHGILL
persculptus
extraordinarius
anceps
pacificus
complexus
complanatus
CARADOC
linearis
clingani
morrisi
caudatus
wilsoni
'peltifer'
apiculatus -ziczac
gracilis
gracilis
LLANVIRN
ARENIG
TREMADOC
Area represented
Recent work suggests that centrifugus should be regarded as the highest Llandovery biozone
GIRVAN GROUP
ARDMILLAN GROUP
BARR GROUP
BALLANTRAE COMPLEX
SOUTHERN UPLAND FAULT
STINCHAR VALLEY FAULT
ALBANY GROUP
BARR GROUP
PYET THRUST
TAPPINS GROUP
GLEN APP FAULT
LEADHILLS SUPERGROUP
BARRHILL GROUP
Galdenoch Formation
Kirkcolm Formation
Blackcraig Formation
GLAIK FAULT
Kirkcolm Formation
Kirkton Formation
CRAWFORD GROUP
LEADHILLS FAULT
SCAUR GROUP
Glenwhargen Formation
Portpatrick Formation
FARDINGMULLACH FAULT
Shinnel Formation
GLEN FUMART FAULT
Glenlee Formation
ORLOCK BRIDGE FAULT
ORLOCK BRIDGE FAULT
GALA GROUP
Kilfillan Formation
Mindork Formation
Money Head Formation
Float Bay Formation
Sinniness Formation
Garheugh Formation
Grennan Point Formation
Mull of Logan Formation
Port Logan Formation
Probably referable to the ETTRICK GROUP
LAURIESTON FAULT
Cairnharrow Formation
HAWICK GROUP
Kirkmaiden Formation
Kirkmaiden Formation
Carghidown Formation
Ross Formation
Carghidown Formation
Raeberry Castle Formation
BALMAE BURN FAULT
RICCARTON GROUP
1
2
3
4
5
6
7
8
B
H¹
H1
G
* Biozones as widely used in earlier literature
1–8 Gala Group tract numbers
Tract boundary fault
MOFFAT SHALE GROUP
B Birkhill Shale Formation
H¹ Upper Hartfell Shale Formation
H1 Lower Hartfell Shale Formation
G Glenkiln Shale Formation
98002964-0302b


Chromium in stream sediment
Low
High


NW
SE
200
100
0
-100
-200
nT
Galloway High
Calculated
Observed
0
20
40
60
80
100
120
140
kilometres
Concealed extension of the Ballantrae Ophiolite Complex
Loch Doon Pluton
Cairnsmore of Fleet Pluton
NW
SE
Solway Basin
SUF
OBF
MF
Depth below sea level (kilometres)
0
10
20
30
Interpolated location of Iapetus Suture from seismic surveys
98002964-0107a
Permo-Triassic rocks
Carboniferous rocks
Granite
Non-magnetic basement, probably crystalline rock
Magnetic basement, probably crystalline rock
Geological boundary
Iapetus Suture Zone
SUF Southern Upland Fault
OBF Orlock Bridge Fault
MF Maryport Fault