Caledonian Structures in Britain

South of the Midland Valley

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Countryside Council for Wales,
Plas Penrhos,
Ffordd Penrhos,
Bangor,
Gwynedd LL57 2LQ.

English Nature,
Northminster House,
Peterborough PE1 1UA.

Preface

This volume deals with those sites selected as part of the Geological Conservation Review (GCR) within the southern British part of the Caledonides, that is, the paratectonic Caledonides – a Caledonian terrane without strong and pervasive deformation and metamorphism, such as occurred further north. This orogenic belt formed by long and complex processes of earth movements between 500 and 380 million years before the present (?late Cambrian to mid-Devonian times), and has been classic ground for geologists for two hundred years. It is perhaps no accident that James Hutton in 1795 chose to illustrate his geostrophic cycle (and unconformity) with three visually explicit examples of the deformation wrought on Lower Palaeozoic rocks by Caledonian events.

The former Caledonian mountain chain, which can be seen today in fragmented pieces in Scandinavia, Britain and Ireland, and North America, was ultimately the result of the collision of two continental plates and the closure of a former ocean, Iapetus. Some of these fragments, including those in Scandinavia, southern Britain, and the Republic of Ireland and the Maritime Provinces of Canada, are thought to have lain on the south side of the ocean before collision: the rest of North America, northern Ireland, and Scotland are thought to have lain north of the former Iapetus. The width of the late Precambrian to Early Palaeozoic ocean, at various stages before its closure, has been greatly debated (McKerrow and Cocks, 1976; Phillips *et al.*, 1976). Much concerning its formation, its narrowing and destruction, and the tectonic (and plate tectonic) consequences of these events has yet to be elucidated, but it is clear that the mountain chain that formed by mid-Devonian times was once continuous across what has become the Atlantic area, and that deformation phases which affected the rocks on the western side of the Atlantic are comparable with those of the Taconic and Acadian orogenies in the Appalachians (Bailey, 1929). Before the opening of the north Atlantic, around 60 million years before the present, the eroded Caledonides with their characteristic NE–SW tectonic grain, stretched for some 5000 kilometres, from the Arctic to the southern United States.

The orthotectonic Caledonides of Britain, that is those areas affected by metamorphism and tectonism north of the Highland Boundary Fault, will be dealt with in subsequent volumes of the GCR series. This volume describes key sites demonstrating Caledonian tectonism in Wales, the Lake District, and in Scotland, south of the Midland Valley. The first two areas lay, in pre-collision times, on the south side of Iapetus, Wales being the site of the deposition of a great thickness of Early Palaeozoic sediments and volcanics in a marginal basin. Of course, the Welsh Basin is even more famous for containing the type areas and type localities for the Early Palaeozoic Cambrian, Ordovician and Silurian systems. The Caledonian

structures in these rocks show particularly the influence of structures in the (Precambrian) basement. The Lake District has been interpreted as being the setting of an Early Palaeozoic island arc, in some interpretations lying south of a subduction zone in which the south-eastwards-moving oceanic floor of Iapetus was being destroyed.

In Early Palaeozoic times, Scotland, including the areas and sites in this volume in southern Scotland, lay on the opposite side of Iapetus to those in Wales and the Lake District above the complementary subduction zone. Rocks in the Southern Uplands have been interpreted as the product of an accretionary prism, that is as wedges of ocean floor pushed, thrust, and welded (accreted) by plate tectonic movements on to the north-western continental margin of Iapetus. These rocks include deep-sea sediments mixed with slivers of ocean crust on which they had been deposited during the Ordovician and possibly the Silurian Period, all carried on to the continental margin, lying to the north of the putative subduction zone, as they were 'scraped off' the back of the subducting ocean plate.

The Southern Uplands have been a proving ground for tectonic models and for testing the constraints imposed by the vitally important graptolite biostratigraphy. One model, for instance, suggests that subduction and deformation may have ceased on its northern margin by the early Silurian Period. In this view, the early Devonian culmination of the Caledonian deformation is really confined to the folds and cleavage of the Lake District and Wales, although the subsequent sinistral fault movements throughout the British area provide final, unifying evidence of Iapetus' closure.

The present site descriptions were initiated in 1983, building to some extent on the small coverage of existing SSSIs. The Southern Uplands sites were mostly visited and described in 1983/4, with some updating in 1986, whereas the Lake District and Welsh site descriptions were not completed until 1988. Contributors were asked to employ the standard Geological Conservation Review criteria, that is to identify sites of national importance, to describe their features, and detail the scientific justification for GCR selection and ultimately SSSI notification. However, a slightly different approach was required in assessing structural sites than would be required when, for instance, selecting more conventional stratigraphical or palaeontological sites; the guidelines followed were that localities should be selected for structural features which best illustrated Caledonian deformation, but in three distinct subareas. In effect, this meant scrutiny of the literature and canvassing of expert opinion in identifying all sites which were known to exhibit important structural features to advantage and, to some extent, the seeking out of sites which might display a particular structural characteristic. From this preliminary list it was necessary to select those localities which best illustrated the typical features of the various phases of deformation, as well as the principal variations and exceptions. Many potential sites had to be excluded because they duplicated features seen elsewhere; and it has not been possible to illustrate some aspects of deformation as no appropriate site was known.

This last point raises the matter of the great burst of geological research activity there has been in the areas described, since the site descriptions were written. All three areas have not only undergone considerable scrutiny by academic researchers in the last three years, but have also been locally subject to very detailed attention from the British Geological Survey. This has revealed many new potential sites which illustrate known features of Caledonian deformation or features that have acquired a new significance as research has progressed. In this latter category are sites which might better illustrate the timing of Caledonian events (for example, as a result of the dating of igneous bodies, cleavage), details of internal processes (for example, fracture systems, cleavage development, shear criteria, strain variations) and evidence of external processes (for example, plate movement, major fault

displacements). It will be noted that sites from the Midland Valley have been excluded from this volume. At the time of its preparation there was very little information available concerning Caledonian structure, but it was clear that this was to become an area of significance in the 'jigsaw' of Caledonian evolution. Being so intimately involved in the stratigraphy, sedimentology, and igneous history, the structure of the area will be covered in later relevant GCR volumes.

W. A. Wimbledon

Chapter 1

Caledonian structures

INTRODUCTION

J. E. Treagus

The purpose of this volume is to describe and discuss the selected Geological Conservation Review sites which demonstrate structures of Caledonian age (Cambrian to early Devonian), south of the Southern Upland Fault. The sites, of national importance, have been selected to illustrate all the principal features of the Caledonian Orogeny in Britain (Scotland, England and Wales).

The volume has been divided into three sections; the Southern Uplands, the Lake District and Wales, for both geographical and geological reasons. Each of these sections is introduced and an outline of its structural features given, putting the sites into a Caledonian context. The purpose of the following paragraphs is to introduce the principal features of the Caledonian Orogeny in Britain south of the Southern Uplands Fault, so that the three-component sections can be seen in the context both of the British area and of the wider setting of the Caledonian–Appalachian Orogenic Belt.

THE CALEDONIAN OROGENIC BELT

The Caledonian–Appalachian Orogen can be traced (pre-Atlantic drift), for some 7500 km south-west to north-east, from south-eastern USA through the British Isles to Scandinavia, Greenland, and Ny Friesland (Figure 1.1). It is generally accepted, after the work of Wilson (1966) and Dewey (1969), that sedimentation and igneous activity took place at, or near, the margins of an ocean (the Iapetus) that separated the Laurentian and Gondwanaland plates, over a period from the Precambrian through the early Palaeozoic. From studies of fauna, sedimentary history, igneous activity, structural and metamorphic evolution, and palaeomagnetism on its two sides, it is considered that deformation of sediments and volcanics, resulting from the episodic closure of the Iapetus Ocean, took place through the early Palaeozoic to culminate in continental collision during the early Devonian.

Since the initial plate tectonic model for this orogen (Dewey, 1969; see Figure 1.2), many variations and refinements have been proposed. Subduction and obduction of the Iapetus oceanic crust is regarded as having occurred on both sides of the ocean at various times, with attendant accretion and deformation. The opening and closing of marginal basins, the collisions of volcanic arcs and microcontinents, as well as the final continent to continent collision and suturing, have all been used to explain various deformation events (Barker and Gayer, 1985). It has long been recognized that various regions within the orogen have had very different histories and different deformation timings (see Figure 1.1), but recently emphasis has been placed on the differences between smaller areas (terranes) with distinct geological histories within these regions. In particular, the work of Williams and Hatcher (1982) in the Appalachians, has led to the recognition that thrusting and strike-slip movements may be responsible for the very distinct geological histories of many of these terranes (see Barker and Gayer, 1985).

THE BRITISH CALEDONIDES

Scottish Highlands

In the British Isles (Figure 1.3) two groups of contrasting terranes are of long standing: the Scottish Highland Terranes (and Irish equivalents) with their early, 590–480 Ma Caledonian (= Grampian) deformation and metamorphism, and the Southern Upland, Lake District, and Welsh Terranes (and their Irish equivalents) dominated by late or end-Caledonian (= Acadian) deformation and low-grade metamorphism, dated around 400 Ma. The first of these areas itself has a complex history, but culminated with the Grampian Orogeny imposed on rocks ranging in age from Archaean basement (Lewisian) through the Proterozoic (Moine) to the Late Proterozoic to early Cambrian (Dalradian) cover. The principal deformation events took place before 490 Ma, resulting in polyphase folding, thrusting, and regional low- to high-grade metamorphism. Subsequent folding in this area has not been precisely dated, but it pre-dates intrusion of Upper Silurian to Lower Devonian granites and faulting on the Great Glen Fault system. Some of this late folding, and certainly the faulting, must correlate in time with the late-Caledonian deformation of the terranes to be considered below.

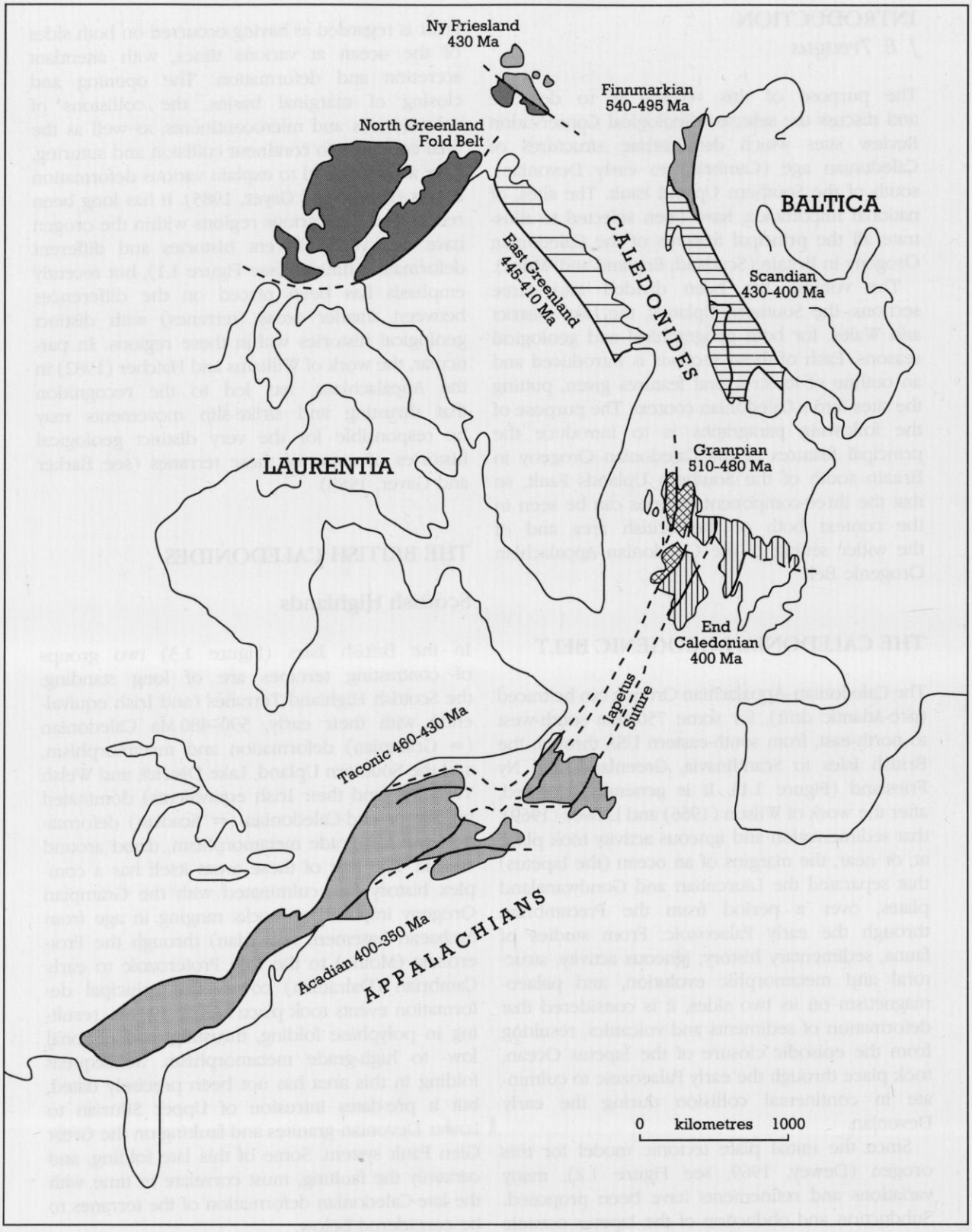


Figure 1.1 Regions of the Caledonian–Appalachian Orogen in their pre-Mesozoic drift configurations, showing ages of principal deformation events (after Barker and Gayer, 1985).

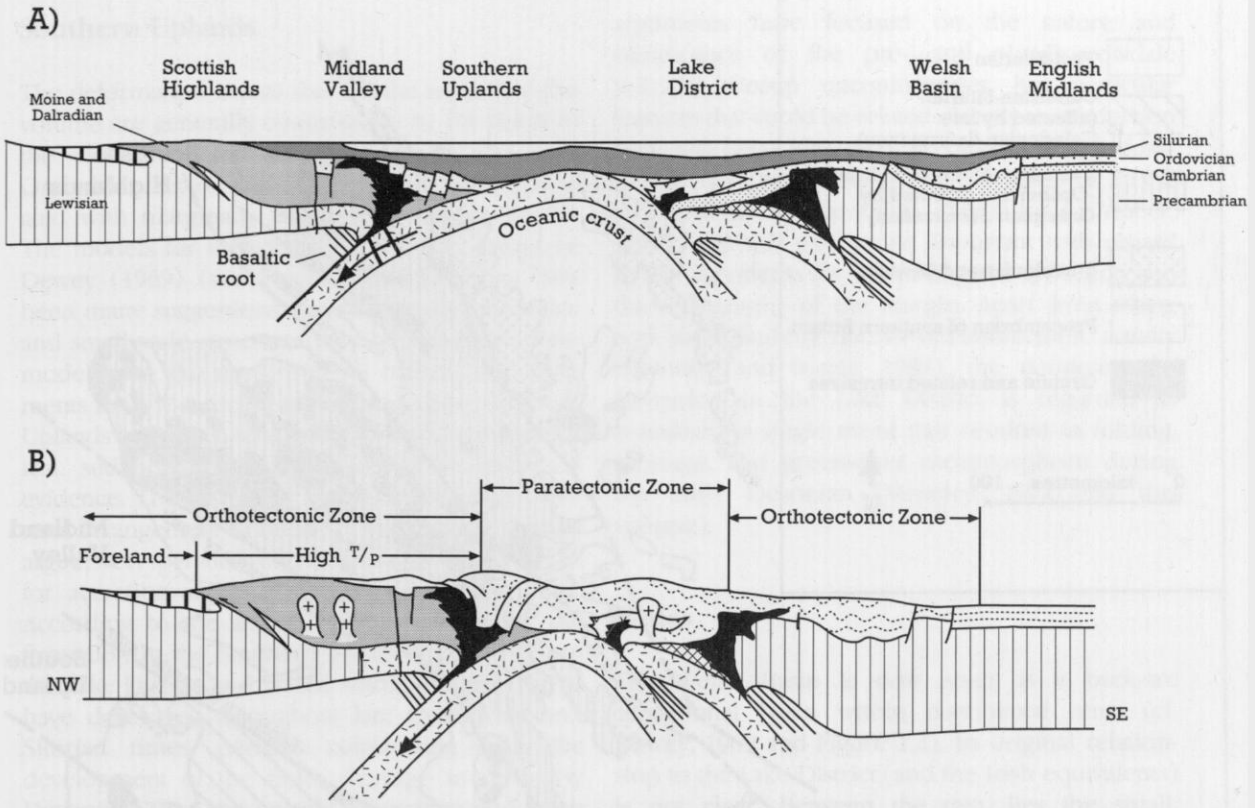
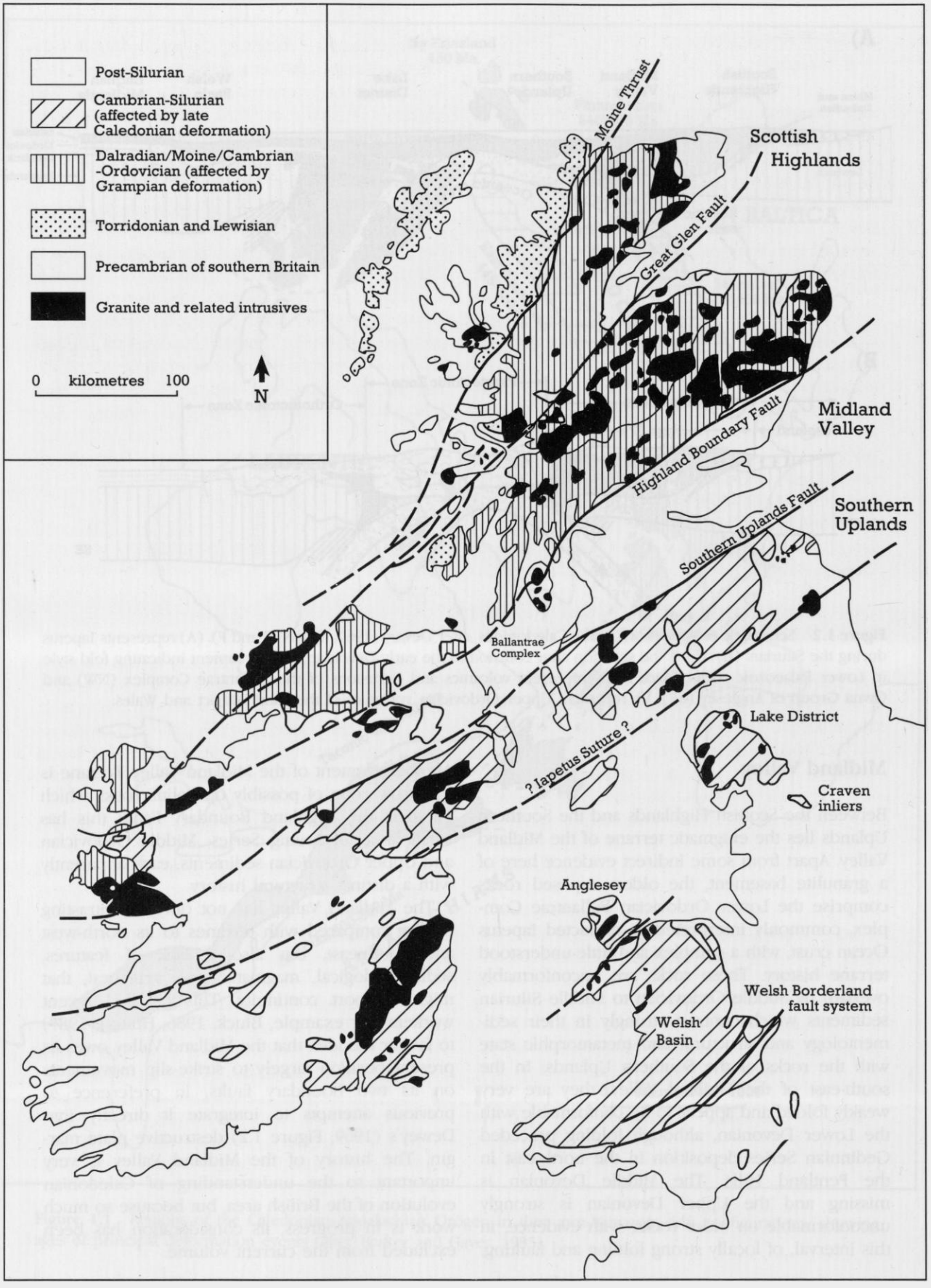


Figure 1.2 Schematic cross-sections of the Caledonides, after Dewey (1969, figure 2E and F). (A) represents Iapetus during the Silurian. (B) shows the situation after collision in the early Devonian, with ornament indicating fold style in Lower Palaeozoic rocks. Black areas represent volcanics and intrusions of the Ballantrae Complex (NW) and Gwna Group of Anglesey (SE); Vs represent Upper Ordovician volcanics of the Lake District and Wales.

Midland Valley

Between the Scottish Highlands and the Southern Uplands lies the enigmatic terrane of the Midland Valley. Apart from some indirect evidence here of a granulite basement, the oldest exposed rocks comprise the Lower Ordovician Ballantrae Complex, commonly interpreted as obducted Iapetus Ocean crust, with a complex and little-understood terrane history. These rocks are unconformably overlain by Middle Ordovician to Middle Silurian sediments which contrast strongly in their sedimentology and structural and metamorphic state with the rocks of the Southern Uplands. In the south-east of the Midland Valley, they are very weakly folded and appear to be conformable with the Lower Devonian, although folding preceded Gedinnian Series deposition in the north-east in the Pentland Hills. The Middle Devonian is missing and the Upper Devonian is strongly unconformable on older rocks, with evidence, in this interval, of locally strong folding and faulting. Another element of the Midland Valley Terrane is a narrow zone of possibly ophiolitic rocks which parallels the Highland Boundary Fault: this has small areas of Arenig Series, Middle Ordovician and Upper Ordovician sediments, each apparently with a distinct structural history.

The Midland Valley has not only a contrasting history compared with terranes to its north-west and south-east, but also a lack of features, sedimentological, magmatic, and structural, that might support continuity. This has led recent workers (for example, Bluck, 1986; Hutton, 1987) to favour the idea that the Midland Valley owes its present position largely to strike-slip movements on its two boundary faults, in preference to previous attempts to integrate it directly into Dewey's (1969; Figure 1.2) destructive plate margin. The history of the Midland Valley is very important to the understanding of Caledonian evolution of the British area, but because so much work is in progress, its consideration has been excluded from the current volume.


Post-Silurian
Cambrian-Silurian (affected by late Caledonian deformation)
Dalradian/Moine/Cambrian -Ordovician (affected by Grampian deformation)
Torridonian and Lewisian
Precambrian of southern Britain
Granite and related intrusives
0 kilometres 100
N
Moine Thrust
Scottish Highlands
Great Glen Fault
Midland Valley
Highland Boundary Fault
Southern Uplands
Southern Uplands Fault
Ballantrae Complex
Lake District
? Iapetus Suture ?
Craven inliers
Anglesey
Welsh Borderland fault system
Welsh Basin

Southern Uplands

The deformation events that are the subject of this volume are generally construed to be the result of the closing of the Iapetus between the mid-Ordovician Period and the early Devonian, associated with marginally directed subduction zones. The models for this closure are largely based on Dewey (1969) (see Figure 1.2) and there have been many suggestions as to how both large-scale and small-scale structures may be related to these models. On the north-western margin, the arguments for NW-directed subduction in the Southern Uplands have been strengthened by the stratigraphical, sedimentological, and large-scale structural evidence. The distinctive stratigraphical and structural arrangement of these rocks has been used to argue, very persuasively, (McKerrow *et al.*, 1977), for accretion above a descending oceanic plate. According to the accretionary prism model, deformation in the Southern Uplands, unlike that in the Lake District and Wales, would be expected to have developed throughout late Ordovician and Silurian times, perhaps culminating with the development of the finite cleavage in the early Devonian. Thus the upright SE-verging and steep reverse faults have been interpreted as original flat-lying, ocean-verging and NW-dipping thrusts respectively, which have been rotated into their present steep attitudes in the accretion process. The cleavage, which cuts across the folds, has been attributed to the late-stage closure of the Iapetus. However, there is still much debate concerning the detailed relationship of the structures observed to the evolution of the supposed accretionary prism (a wedge-shaped pile of deformed rocks) above the subducting plate. Indeed, recently, doubts have been cast upon the reality of the accretionary prism model, particularly as applied to the Silurian rocks (Hutton and Murphy, 1987).

Lake District

On the south-eastern margin, the argument for SE-directed subduction (Figure 1.2) rests largely on the presence of arc volcanism in the Lake District during the Llandeilo or Caradoc epochs. Structural arguments have focused on the nature and significance of the pre- and post-Borrowdale Volcanic Group unconformities, but particular features that could be related directly to subduction have not been identified. Folding in the Skiddaw Group has recently been reinterpreted as being the product of slumping (Webb and Cooper, 1988), and this may prove important with regard to the arguments for the timing of subduction and the topography of the margin. Apart from tilting and block faulting due to volcanotectonic activity (Branney and Soper, 1988), the dominant deformation in the Lake District is regarded as essentially a single event that resulted in folding, cleavage, and greenschist metamorphism during the early Devonian (Moseley, 1972 and this volume).

Wales

The Welsh Basin is now seen as a back-arc extensional basin within continental crust (cf. Dewey, 1969 and Figure 1.2). Its original relationship to the Lake District (and the Irish equivalents) is not clear. Between the two, lies the small, isolated area of the Precambrian rocks of Anglesey. The boundary of the Anglesey terrane with the Lake District terrane is not exposed. Its south-eastern boundary, with the Welsh terrane, which has previously been interpreted as a subduction zone active in early Palaeozoic times, is now seen (Gibbons, 1987) to be a fault boundary marking Late Precambrian strike-slip docking of the small terranes that now make up Anglesey. The significant deformation related to folds and cleavage in Wales represents, as in the Lake District, essentially an early Devonian event. There are, however, many variations on a simple pattern, attributed, variously, to soft-sediment, tectonic, and volcanic activity.

Two particular structural features have provoked discussion. Firstly, there is the arcuate pattern of folds and cleavage from E–W turning to N–S, which has been most commonly attributed to basement control, and regarded by Soper *et al.* (1987) as part of the same curvature as that seen between the Lake District and the Craven Inliers. Secondly, there is the diminution of deformation south-eastwards, seen as the diminished affects of the Caledonian Orogeny towards the south-east margin of the orogen, represented by the basement rocks of the Welsh Borders and the English Midlands.

Figure 1.3 Simplified map of the British Caledonides modified from Leake *et al.* (1983).

CONCLUSIONS

Although there are uncertainties concerning the timing and mechanisms of the Southern Upland structures, the three areas are apparently united by their common history of cleavage formation and maximum shortening which climaxed in the early Devonian. Evidence is accumulating (Soper *et al.*, 1987; McKerrow, 1988; Soper, 1988) that this event may be equivalent to the Acadian Orogeny (Emsian in age) of the Canadian Appalachians. One feature of this cleavage that unites the two sides of the Iapetus suture, running through the Solway Firth, is the transection (cross-cutting) of folds by the cleavage, which has now been recognized widely in the Southern Uplands, Lake District and Wales. The Southern Uplands and the Lake District are also united by their flat-lying D_2 folds and cleavage, which may be related, in time and space, to the major granite intrusives that characterize both areas.

Another feature which unites the latest Caledonian deformation across the whole of Britain is faulting, much of which is strike-slip and much of that sinistral (Hutton, 1987). The faults range from the Great Glen Fault system in the Scottish Highlands to the Welsh Borderland Fault system (Woodcock and Gibbons, 1988). The minor faults, in the Scottish Highlands, the Southern Uplands, and the Lake District especially, commonly show a more NNE–SSW trend and sinistral displacement. These two features, cleavage transection and faulting, have been used by both Hutton (1987) and Soper *et al.* (1987) to reconstruct the positions of the British Caledonian terranes and the relative movements and geometries of the margins of Iapetus itself.

Throughout the British Caledonides it is being increasingly recognized that certain structures, both folds and faults, have origins related to basin development that pre-date the main Caledonian structures. This recognition has not only allowed a clearer understanding of the early development of the area, but also removed some apparent tectonic ambiguities. For example, recent studies in both the Southern Uplands and the Lake District have recognized that certain folds are of soft-sediment origin. Similar folds have long been recognized in the Silurian of Wales (Woodcock, 1976) and other anomalous structures there (in older rocks) are also being attributed to this origin. Again, in Wales, early faults have been related to volcanic activity, as well as to facies and thickness changes. Comparable features are now being recognized in the Lake District.

In the Southern Uplands, the major strike faults are seen to have an early history that controlled the development of sedimentation in the accretionary prism, and recently, smaller-scale fractures have been attributed to shortening and extension in the accreting sediments.

Further details and references may be found in the 'Introductions' to the following chapters, which deal individually with the sites in the Southern Uplands, Lake District, and Wales.