British Cambrian to Ordovician Stratigraphy

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Photographs of fossils

Many contributors supplied photographs of fossils for this book, and the authors are glad to acknowledge their assistance below.

Details of localities, museum numbers etc. of the figured fossils are given, together with the names of individuals who supplied prints. Unattributed photographs are from the authors' collections. National grid references are in square brackets. The repositories most commonly cited are abbreviated as follows: BGS = British Geological Survey, Keyworth; BU = Lapworth Museum, University of Birmingham; GLAHM = Hunterian Museum, Glasgow; NHM = Natural History Museum, London; NMW = National Museum of Wales, Cardiff; SM = Sedgwick Museum, Cambridge.

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Access to the countryside

This volume is not intended for use as a field guide. The description or mention of any site should not be taken as an indication that access to a site is open or that a right of way exists. Most sites described are in private ownership, and their inclusion herein is solely for the purpose of justifying their conservation. Their description or appearance on a map in this work should in no way be construed as an invitation to visit. Prior consent for visits should always be obtained from the landowner and/or occupier.

Information on conservation matters, including site ownership, relating to Sites of Special Scientific Interest (SSSIs) or National Nature Reserves (NNRs) in particular counties or districts may be obtained from the relevant country conservation agency headquarters listed below:

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

English Nature,
Northminster House,
Peterborough PE1 1UA.

Scottish Natural Heritage,
12 Hope Terrace,
Edinburgh EH9 2AS.

Preface

Britain is singularly rich in geological sites of scientific importance, not least because so many of the leading figures in geology in its early days developed their concepts on home turf. These geological exposures – some of them rather modest – generated ideas that spread across Europe in the 19th century and around the world in the 20th. This is particularly true of the Lower Palaeozoic, where the discrimination of subdivisions of geological time was made on the basis of the strata cropping out in Wales and the Welsh Borderlands, the Lake District and central Scotland. 'Cambrian' and 'Ordovician' can be understood equally in Novosibirsk and Nantucket, as can many of the British subdivisions of these systems. The great men of geology in its formative years – Sedgwick, Murchison, Lapworth, Peach, Horne – have left their signatures on our geological landscape for all time. It would be a proper employment of an overused word to describe this as our geological heritage. Much of the narrative of geological time was written in the 'language' of fossils, and sites that have yielded useful or famous fossils are no less part of our legacy than the localities where formations or unconformities were recognized. Our great museums house the fruits of more than 150 years' collecting endeavour, but the 'ground truth' remains the localities where the original discoveries were made. Nor is this just a matter of history, for classic sites frequently demand re-investigation when new scientific questions arise. The geological past is not preservable in a kind of 'temporal aspic' – instead it is continually under review. Hence many sites of scientific interest relate to discoveries made since the turn of the century, and even within the last few years. Adrian Rushton and his colleagues have made an invaluable inventory of geologically significant sites in Cambrian and Ordovician strata in Britain: now for the first time we actually know what constitutes our geological heritage. The sites range in size from sea cliffs to scrapings. Some sites have been referred to only once in the literature; others are classic localities, a visit to which is considered a *sine qua non* for a complete geological education. All are important. In many respects this is sacred ground, and a publication that heightens public awareness is timely and welcome. Both the scientific and lay communities need to know that what may seem to be no more than an abandoned quarry may have played an important part in developing crucial scientific concepts. Documentation helps secure the respect for this kind of site that locations harbouring rare animals or plants already enjoy. Not least, this book can provide the basis for a rational conservation policy.

Richard Fortey
Spring 1999

Chapter 1

General introduction

A. W. A. Rushton

INTRODUCTION

The Cambrian and Ordovician systems are recognized throughout the world as two of the major divisions of the geological column. Together they represent a period of about 100 million years (Ma), during which the seas, the continents and the biosphere underwent great changes. For well over a century stratigraphical research on British Cambrian and Ordovician sections has contributed significantly to the global understanding of this important period. The Cambrian and Ordovician systems originated from study of rock successions in Wales, and the resulting classification set a stratigraphical standard that was adopted in other parts of the world and has been followed widely, especially through advances in intercontinental correlation. For example, the international development of graptolite biostratigraphy owed much to Lapworth's 19th century studies of Scottish and Welsh successions; and many recent improvements in Lower Palaeozoic geochronology rely on the interbedding, widespread in Britain, of volcanic ashes that can be dated isotopically with fossiliferous sedimentary rocks whose biostratigraphy has been well studied.

British Cambrian and Ordovician rocks have yielded their share of fossil taxa, a high proportion of which are well described and are necessarily referred to by palaeontologists worldwide, and British sections have contributed data relevant to evolutionary processes (e.g. Sheldon, 1987a) and many palaeoecological studies (Fortey and Owens, 1978, 1987; Lockley, 1983; Price and Magor, 1984). Geologists throughout the world constantly examine and re-examine British Cambrian and Ordovician rocks on account of their outstanding importance as standards of reference.

Economically valuable material, notably the Welsh slates from Caernarfon and Ffestiniog (which provided roofing-slates for large areas of Britain) and lead, gold and manganese from various workings, was formerly extracted from the Cambrian and Ordovician rocks of Britain. Most such exploitation has now diminished or ceased, except where bulk extraction of road-stone or aggregate continues. The sites described here include many small quarries that were opened long ago for local building stone, or for lime (in places where that was a scarce commodity). This book shows that these sites, along with natural coastal and inland exposures, are equally important in providing evidence for understanding the geology of Britain: their conservation is a matter of the utmost importance.

SCOPE

The present volume describes sites selected during the Geological Conservation Review in England, Wales and Scotland that exemplify the Cambrian and Ordovician systems and thereby represent a substantial and important part of the geological history of Britain. The Geological Conservation Review (GCR) was undertaken by the Nature Conservancy Council between 1977 and 1990 with the object of sampling the whole range of British Cambrian–Ordovician stratigraphy, and in particular to indicate those sites most needing conservation – the most important stratotype sections, key stratigraphical contacts and also those displaying the principal lithologies and biofacies. Furthermore, since both the Cambrian and Ordovician systems were conceived primarily for British rocks and their long-established and widely recognized subdivisions, several of the sites are also important from a historical perspective.

Several GCR sites were selected because they yield important fossil faunas, and whilst this has led to GCR volumes that are given over to certain fossil groups (e.g. reptiles), those sites with fossil groups of particular stratigraphical significance are appropriately treated in stratigraphical volumes such as the present one. Brachiopods, trilobites and graptolites are among the fossils most widely used stratigraphically in the Cambrian and Ordovician, so at the end of the present chapter there is a summary of key sites for representatives of those groups. Such sites may be the source of information on their morphology, ontogeny, evolution, palaeoecology and palaeogeographical affiliation.

The period encompassed by the Cambrian and Ordovician systems was one of great changes, in geography, in climate and in the evolution of life itself. Most striking of all are the differences in geology of Anglo-Welsh sites as compared with Scottish, caused by their former separation across the now-closed Iapetus Ocean. Some 130 sites are considered herein, but, even so, the scope of the British Cambrian and Ordovician sedimentary rocks is so great that the present GCR coverage of nationally important sites can do no more than exemplify the key aspects; it should be noted that there are sever-

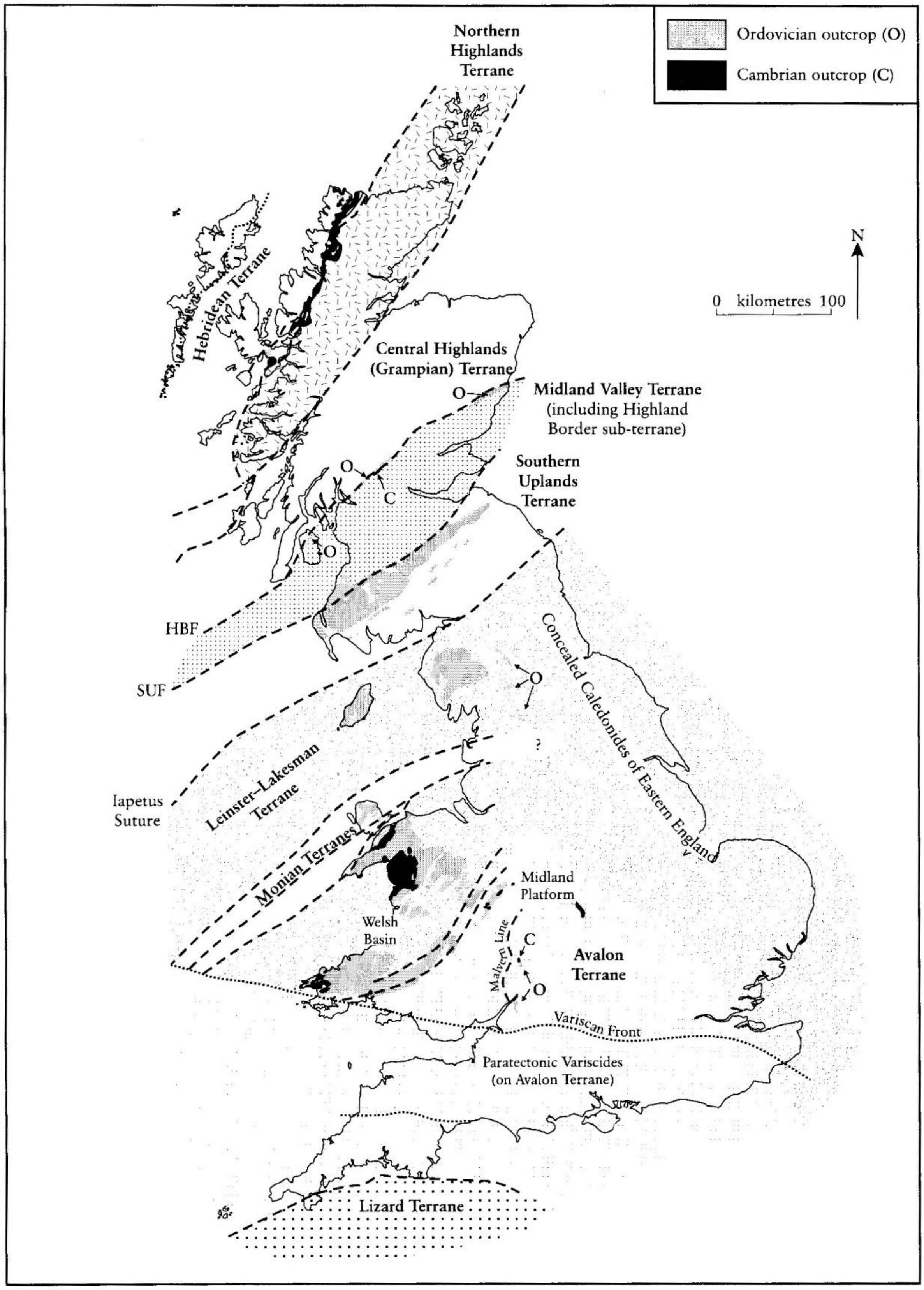

Figure 1.1 Distribution of Cambrian and Ordovician rocks in the principal terranes in Great Britain, after Bluck *et al.* (1992). HBF, Highland Boundary Fault; SUF, Southern Upland Fault.

al areas and a large number of formations of regional importance that are not covered by the GCR networks of nationally scientifically important sites.

When originally selected, the GCR sites were organized in stratigraphically thematic networks that represented the following: the Cambrian System, the Cambrian–Tremadoc boundary, the Tremadoc Series, the Tremadoc–Arenig boundary, the Arenig to Llanvirn Series, the Llandeilo Series and the Caradoc to Ashgill Series. This arrangement emphasized the intervals of time represented but brought together unrelated stratigraphical successions from different tectonic terranes and also unduly subdivided regional stratigraphical schemes. For the present compilation it proved much more satisfactory to organize the sites geographically. The earlier chapters deal with the Anglo-Welsh sites, commencing with the Cambrian System, each principal area of which – North Wales, South Wales and England – is dealt with in turn. The Ordovician commences with the Tremadoc Series, the chapter on which also includes the main sites for the Cambrian–Ordovician boundary. The remainder of the Ordovician, from the Arenig to the Ashgill, forms nearly continuous successions in Wales and includes the largest number of sites. These are treated in two regionally based chapters, on South Wales (including the Builth Inlier) and North Wales respectively, followed by chapters on Shropshire and northern England. Finally, the Cambrian (where present) and the Ordovician of Scottish sites are treated in four chapters, each of which deals with a different structural terrane (Figure 1.1).

Geological investigation is a continuous process, and in the decade since the sites were selected important new results and interpretations have affected the significance or classification of some GCR sites. For example, a base to the Cambrian System has now been defined in Newfoundland, and as this lies at a lower level than was commonly accepted at the time of site selection, rocks formerly treated as Precambrian have now been transferred, more or less definitely, to the Cambrian. One formation thus affected is the Swithland Formation at the top of the Charnian Supergroup in central England. This volume merely lists the relevant sites, leaving their full description to the companion volume, *Precambrian Rocks of England and Wales* (Carney *et al.*, in prep.) of the present series, in which the whole Charnwood Supergroup is discussed. Similarly, the Mona Complex in Anglesey has conventionally been referred to the Precambrian and is discussed in Dr Carney's volume, but along-strike correlation with the Cahore Group in south-east Ireland, parts of which have yielded poorly constrained Cambrian ages, suggests to some authorities that it may include Cambrian rocks (Tietzsch-Tyler, 1996). Another division formerly treated as Precambrian but now considered of Lower Palaeozoic age is the Ingleton Group in the Craven area, northern England. It is overlain unconformably by the Dent Group of Ashgill age, but beyond that its age is uncertain. Woodcock (1990) and Tietzsch-Tyler (1996) treated it in the most general way as of Cambrian age, whereas Arthurton *et al.* (1988) favoured an Arenig age. The site in Thornton and Twistleton glens, near Ingleton will receive full consideration in Dr Carney's GCR volume on the Precambrian of England and Wales (Carney *et al.*, in prep.).

Important changes were made to the series of the Ordovician System when they were reviewed by Fortey *et al.* (1995). In particular they proposed lowering the base of the Caradoc Series to the base of the *gracilis* graptolite zone and reducing the status of the Llandeilo from a series to a stage of the Llanvirn, as discussed in Chapter 6. This arrangement has been adopted here. In a few instances the study of new sections has eclipsed the importance of earlier designated sites, as in the case of Pengawse Hill, Whitland, mentioned in the Mylet Road site report.

OVERVIEW

The Cambrian and Ordovician rocks of Britain are essentially of marine origin; freshwater and subaerial deposits have been identified only in settings where volcanic edifices were raised above sea level. Within the marine setting there are rocks of the widest variety, from sandstones and limestones of the shoreline and shallow shelves to beds that accumulated in deep basins or on the continental slopes. Transects from shelf to basin are seen in both Cambrian and Ordovician rocks, and examples of shallow- and deep-water deposits are recognized in both Anglo-Welsh and Scottish areas.

The complex plate-tectonic make-up of Britain (Bluck *et al.*, 1992) has an important bearing on the character and distribution of

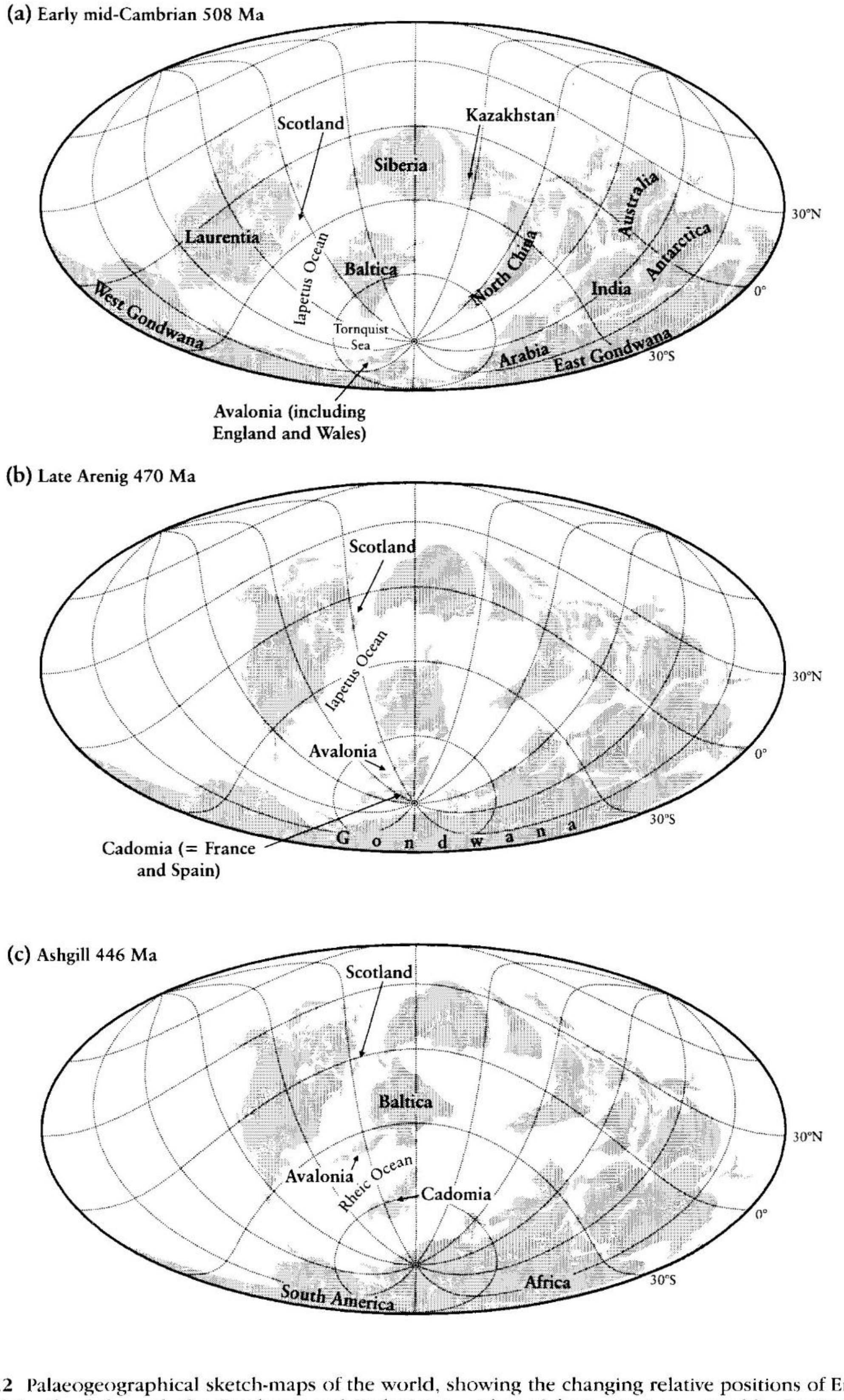

Figure 1.2 Palaeogeographical sketch-maps of the world, showing the changing relative positions of England, Wales and Scotland through the Cambrian and Ordovician. Adapted from maps generated by Dr David Lees using Atlaswinpro (Cambridge Paleomap Services).

Cambrian and Ordovician outcrops, because the early history of each terrane shown in Figure 1.1 is more or less distinct. Nearly all the terranes north of the Variscan Front contain Cambrian or Ordovician GCR sites, the exceptions being the Precambrian metamorphic rocks of the Scottish Central Highlands and Northern Highlands terranes.

During the Cambrian and early Ordovician, most of Wales and England lay at passive plate margins, though Tietzsch-Tyler (1996) brought together evidence that an early Ordovician (or Monian) orogeny affected the limited area of Anglesey and south-east Ireland. Late Precambrian rifting initiated the Welsh Basin, whose infilling constituted the first of the megasequences identified by Woodcock (1990) and named by him the 'Dyfed Supergroup'. Further episodes of minor rifting are postulated during the late Cambrian, Tremadoc and Arenig, and have been linked to the rifting off of Avalonia from the margin of Gondwana (Prigmore *et al.*, 1997). The onset of south-east-directed subduction during the early Ordovician saw the development in Wales of a back-arc basin with renewed sedimentation and abundant volcanic rocks. These constitute Woodcock's second megasequence, the Gwynedd Supergroup. His third megasequence, the Powys Supergroup, commences in the upper Ordovician (Ashgill) and extends up into the Devonian. The Welsh Basin, with its relatively thick sequences of basinal rocks, has the largest exposures of Cambrian and Ordovician rocks, and appropriately that area has the largest number of GCR sites. The adjoining Midland Platform exposes thinner shelf sequences in a scattering of relatively small but stratigraphically and historically important inliers. The passive ocean-facing margin in northern England accumulated thick clastic deposits in the earlier Ordovician (mainly Arenig), overlain by thick arc volcanics of about early Caradoc age. A diachronous marine transgression followed, introducing relatively thin neritic deposits. These include a full succession of the higher Caradoc and Ashgill series, in which many sites have been designated, and they form the base to a thick foreland basin succession deposited in the later Silurian.

In the Southern Uplands of Scotland there are thick developments of Ordovician rocks in a basin produced during the closure of the Iapetus Ocean, for which a variety of tectonic settings have been mooted (see Chapter 15). Adjacent to these outcrops, but separated from them by the Southern Upland Fault, is the famous Girvan district, in which Ordovician successions show striking changes of thickness and facies. The concentration of GCR sites there is a measure of the importance attached to those successions. The Highland Border area lies along a terrane boundary. It is highly faulted and a uniform stratigraphy is elusive, but there are two sites of importance in the area, one Cambrian and one Ordovician. The Hebridean Terrane in northern Scotland has a foreland margin succession that consists of relatively thin shelf deposits, mainly of Cambrian age.

PALAEOGEOGRAPHY

During the Cambrian, the microcontinent known as Avalonia, which includes the area of England and Wales, Belgium and northern Germany, together with south-east Newfoundland, New Brunswick and other parts of eastern maritime North America (Cocks *et al.*, 1997), lay far to the south of the equator (Figure 1.2a). According to Cocks *et al.* (1997) and Torsvik (1998), it was effectively part of the huge continent of Gondwana at least until Arenig times, whereas Landing (1996) has claimed an independent status for Avalonia (or 'Avalon') as an 'insular continent' from the latest Precambrian. During the Ordovician, Avalonia migrated northwards to a temperate (Figure 1.2b) or sub-equatorial position and was first brought into proximity with the Baltic continent (Figure 1.2c), ultimately to collide with the bulk of the North American continent, known as Laurentia. As Avalonia moved from near-polar latitudes to a subtropical position, its climate became modified, effecting changes in sedimentary and biotic environments that are duly reflected in the rocks and the fossils preserved in them. A detailed account of the changing palaeogeography and lithofacies of the British Isles is given in the synthesis by Cope *et al.* (1992). Figure 1.3 shows a few examples of their maps in simplified form. There is evidence from Africa and Arabia of an exceptional episode of glaciation at the end of the Ordovician. This caused a large, though temporary, fall in sea level and wrought great changes in the marine environment, which in turn brought about a major extinction in marine life. This episode left its mark in British rocks, even though the whole area was at that time lying at low latitudes.

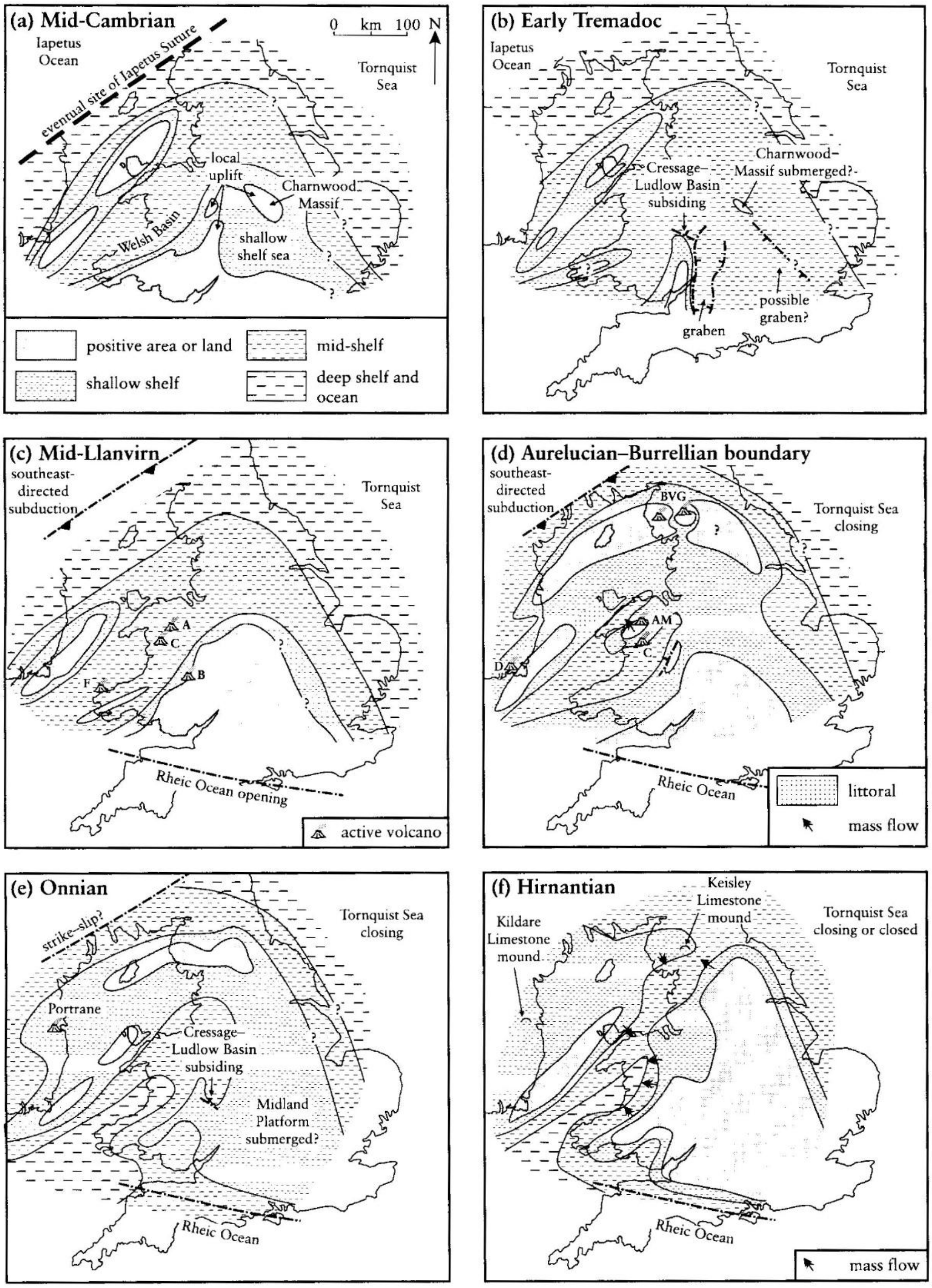

Figure 1.3 Simplified palaeogeographical maps for the Cambrian and Ordovician of England and Wales, modified from Cope *et al.* (1992). In (c) the active volcanic areas are A, Arenig; B, Builth; C, Cadair Idris; F, Fishguard. In (d) the volcanic areas are AM, Aran and Moelwyn; BVG, Borrowdale Volcanic Group; C, Cadair Idris; D, Duncannon.

Throughout the Cambrian and Ordovician, Scotland lay in the tropics at the margin of Laurentia and during most of this time was separated from Avalonia by the wide ocean known as the Iapetus Ocean (Figure 1.2). Scotland is made up of discrete fragments, or terranes, that were assembled progressively by strike–slip movements and were welded together during the collision of Laurentia with Avalonia and Baltica. The complex and partly controversial early Palaeozoic palaeogeography of Scotland is illustrated in Cope *et al.* (1992). Because the early Palaeozoic history of Scotland is so different from that of England and Wales it is treated here independently, though during the later Ordovician the convergence of such features as fossil faunas is taken as evidence of the approach of England and Wales to Scotland as the Iapetus Ocean narrowed.

THE SIGNIFICANCE OF FOSSILS

During this period of Earth's history, life itself underwent two phases of evolutionary change of the utmost significance. The early Cambrian was the time of the 'Cambrian evolutionary explosion' (Conway Morris, 1992), when a great variety of life-forms first appeared in the fossil record, though the reasons for these appearances are debated (Fortey *et al.*, 1997). The resulting faunas, which included the first representatives of several groups of animals whose descendants exist today, formed the basis of the 'Cambrian Fauna' of Sepkoski (1981). In the early Ordovician the Cambrian Fauna was largely replaced by the more diverse 'Paleozoic Fauna', which, despite suffering a mass extinction at the end of the Ordovician, dominated the marine world for the next 250 Ma, the greater part of Phanerozoic history. Elements of the faunas are discussed more fully below.

Apart from their significance as primary evidence for past life and its evolution, fossils are important in stratigraphy because they help to characterize stratal units and give evidence for their relative ages and correlation; in practice, stratigraphy is at its most secure where adequate fossils are found. Fossils commonly also enable the interpretation of the environments in which the animals and plants lived. Fossils occur at many horizons throughout the Ordovician and are found in a wide range of rock types, and at some localities they are abundant and may be well preserved. In the Cambrian, fossils do not occur so widely and are on the whole more difficult to find, whilst some stratigraphical divisions are unfossiliferous or nearly so. However, even modest finds of fossils can have far-reaching stratigraphical implications, as is the case at Trwyn Carreg-y-tir in North Wales and Leny Quarry in Scotland.

Fossils in stratigraphy

Ever since Murchison (1839) gave over a large section of his *magnum opus* on the Silurian System to the description of the organic remains that characterized the formations of his Upper and Lower Silurian, fossils have played a central role in the development of Lower Palaeozoic stratigraphy. The terms 'Palaeozoic', 'Mesozoic' and 'Cainozoic' were based on faunal content, and Lapworth (1879a) used the differences in Lower Palaeozoic faunas to justify recognition of his Ordovician System – thereby restricting the terms 'Cambrian' and 'Silurian' to something approaching their present scope. Subsequent refinements in stratigraphy have been achieved by further palaeontological studies, the value attached to these being demonstrated by the faunal lists contained in many stratigraphical papers and Geological Survey memoirs. Furthermore, recognition of comparable faunas abroad since the time of such influential workers as Barrande and Walcott has given international currency to the use of the terms 'Cambrian', 'Ordovician' and 'Silurian'. When the present GCR sites were selected, therefore, the importance of fossil localities was taken into account, as reflected in the descriptions below. Many GCR sites are also of international importance because they are the type localities for species that typify major taxonomic groups or which are widely used in correlation. In every case, stratigraphers and palaeontologists need to be able to refer back to such localities.

One of the main tasks of stratigraphers is to determine the relative ages of strata and to compare or correlate them with strata of the same age elsewhere. Fossils have long provided one of the most reliable and accurate means of approaching these problems. There are various ways of co-ordinating stratigraphical information on fossils, that used here being the traditional use of 'zones' (or 'biozones'), thicknesses of strata characterized by a particular fossil or group of fossils (see for example Figures 2.2, 6.2 and 7.4). Such zones are assembled empirically into a working sequence, which then serves as a standard for comparison with sequences elsewhere. Each zone is referred to by the name of one or more of the fossils occurring within it, and some are divided into subzones (for further discussion see Whittaker *et al.* 1991). Different fossil groups can be used to erect independent zonal schemes, as has been done for example with graptolites and conodonts. Correlation between such schemes is a continuing problem, the resolution of which holds great potential for further stratigraphical refinement.

Cambrian and Ordovician life

Known life during the Cambrian and Ordovician was very largely confined to the marine realm. According to Sepkoski (1990) the distinctive 'Cambrian Fauna' was progressively replaced, from the early Ordovician onwards, by the much more diverse 'Paleozoic Fauna', wherein a great variety of benthic, nektonic and planktonic organisms appeared, notably during an early to mid-Ordovician evolutionary radiation (Droser *et al.*, 1996). Before the end of the Ordovician there were marine faunas occupying environments from the intertidal zone to the deep ocean, and there is evidence from the mid-Ordovician for forays into the terrestrial realm (Johnson *et al.*, 1994).

Different sedimentary and environmental settings gave rise to various rock types and influenced the kinds of organisms that lived and died there. Stratigraphers have found it useful to distinguish the general aspect, or 'facies', of stratal divisions, as characterized by the rock types and kinds of fossils present. In the Ordovician the most marked contrast is between fine-grained, offshore rocks containing fossils of the planktonic graptolites, which may be referred to as of the 'graptolitic facies', and near-shore beds containing the hard skeletal parts of few or diverse groups of animals such as brachiopods, trilobites, molluscs and echinoderms: this is the 'shelly facies'. These facies may alternate, as in the succession in the Shelve area, or may intergrade giving mixed graptolitic–shelly faunas, as in the Builth Inlier. Within the shelly facies numerous more subtle distinctions have been drawn on the basis of recurring associations of particular kinds of fossils or the dominance of certain types. These may represent communities of animals that lived in particular depths of water, or were influenced by particular conditions of turbulence or temperature: examples are cited in the descriptions of the Caradoc sites at Soudley Quarry, Marshwood and the Onny River. Once such communities have been interpreted satisfactorily in one area, they can act as a touchstone for recognition of comparable environments in other places and add materially to our understanding of stratigraphy and sedimentary environments. McKerrow (1978) illustrated examples of several typical Cambrian and Ordovician communities, though many others have since been recognized (Brenchley and Pickerill, 1980, 1993; Fortey and Owens, 1978, 1987; Lockley, 1983).

The most striking faunal differences in the British Cambrian and Ordovician lie in the contrast between the Anglo-Welsh faunas and those of Scotland. Although this contrast, and the affinity of Scottish faunas with those of North America, had been recognized in the middle of the 19th century, it acquired great significance with the development of plate tectonic theory and Wilson's (1966) proposal of a 'proto-Atlantic' ocean, now generally termed the 'Iapetus Ocean' (Harland and Gayer, 1972). Conway Morris and Rushton (1988) reviewed the development and distribution of Cambrian biotas around the Iapetus Ocean, whilst Cocks and Fortey (1982), Fortey and Cocks (1988) and Harper *et al.* (1996) likewise reviewed the Ordovician to Silurian around the Iapetus Ocean and the Tornquist Sea, which separated southern Britain and the Baltic craton. Generally speaking, Scottish faunas retained their North American similarities throughout the Cambrian and Ordovician. Meanwhile, the faunas of England and Wales, which had shown similarities to Gondwana during the Cambrian to the Arenig (Fortey and Mellish, 1992), lost those connections to the south as the Rheic Ocean opened, and during the Caradoc and Ashgill they became more akin to the faunas of Baltica as the Tornquist Sea closed.

Main components of Cambrian and Ordovician biotas

Morphological features of all the main fossilized invertebrate groups can be found in such texts as Clarkson (1993, 1998), Murray (1985) and Harper and Owen (1996). In the Cambrian these include brachiopods, trilobites, other arthropods such as bradoriids, gastropod-like molluscs, hyolithids, sponges, echinoderms and paraconodonts. The Lower Cambrian faunas of 'small shelly fossils' also include many taxa of uncertain affinity. Most of the foregoing groups also occur, and in greater diversity, in the Ordovician, with the addition of other molluscan and echinoderm groups, plus bryozoa, corals, graptolites, euconodonts and chitinozoa, together with dasycladacean algae. However, from rare instances of exceptional preservation of soft-bodied animals (of which the Canadian Burgess Shale is the most famous), we know that the fossils most commonly preserved represent only a small sample of the life-forms of the time. Besides 'body fossils' (i.e. the remains of actual organisms), Cambrian and Ordovician rocks commonly contain a variety of 'trace fossils', that is, tracks, trails, burrows and footprints, representing the activity of animals that may be, or more typically are not, themselves preserved. Trace fossils are particularly useful for interpreting past environments.

The groups most widely used in British Cambrian and Ordovician stratigraphy are brachiopods, trilobites and graptolites. These are briefly characterized below and the sites of significance for their distribution and palaeobiology are listed. A few examples of each group are illustrated at relevant points in the site descriptions. Amongst the other fossil groups, conodonts occur sporadically and where they occur are often of great value, whilst cephalopod molluscs, ostracods and echinoderms have proved of use locally and in particular environments. Among the microfossils, organic-walled microfossils (acritarchs and chitinozoa) are important in certain parts of the geological column where their vertical distribution is well-enough known.

Brachiopods

Brachiopods are sessile filter-feeding animals with two longitudinally symmetrical shells (see for example, Figure 10.12). They were adapted to a range of environments within the benthos. Some were fixed to the substrate by a stalk or pedicle, whereas others rested in the sediment on their more convex valve. Species of one group, the lingulates (or 'inarticulates'), which had a horny-looking phosphatic shell, are among the commonest and most widespread of Cambrian fossils. The other main group, the articulate brachiopods, had a calcitic shell. There are few species of articulate brachiopod in the Cambrian, but they become extremely abundant and much more diverse in the Ordovician, in which they form the basis of several benthic communities. Cocks (1978) listed the British Lower Palaeozoic species.

Important sites for brachiopod faunas and communities include Ogof Hên, Ffairfâch, Nant Aberderfel, Coston Farm, Soudley Quarry, Marshwood and Gelli-grîn. The peculiarity of the brachiopod assemblage at Treiorwerth in Anglesey caused Neuman and Bates (1978) to recognize that Williams' so-called 'Celtic Province' there represents an opportunistic 'island fauna'. Aber Hirnant was one of the original sites at which Temple (1965) recognized the distinctive and almost globally distributed *Hirnantia* Fauna (Figure 9.22). Brachiopods from sites in the Girvan district give some of the best evidence that the Scottish Ordovician faunas are of Laurentian (North American) affinity.

Trilobites

Trilobites are extinct marine arthropods distingished by a threefold longitudinal division of the body (see, for example, Figure 9.22). Unlike many other much less commonly found arthropods, their exoskeleton was largely of calcite, which greatly increased the likelihood of their being preserved. Whittington (1992) gave a general description of the group, and Morris (1988) listed the British species. Trilobites are valuable in correlation (Thomas *et al.*, 1984), notably in the Cambrian (see Figure 2.2) and remain so in the Ordovician, especially in deeper-water settings. Particularly important are the trinucleids, with their complicated pitted marginal fringes (e.g. Figures 8.18 and 10.20).

There are many sites of importance for their trilobites. In the Cambrian these include Comley Quarry, Illing's Trenches, several sites in the St David's area, and Moel Gron and Ogof Ddû. Many of the Tremadoc sites are notable for trilobite faunas. Sheinton Brook and Coundmoor Brook (Evenwood) have yielded growth stages of various species, including the material for Stubblefield's (1926) classic study of *Shumardia*. The Arenig trilobite faunas from the Carmarthen and Whitland areas of South Wales not only form a stratigraphical standard (Fortey and Owens, 1987) but also provided evidence for certain environmentally influenced trilobite associations that can be recognized elsewhere both in the Arenig and in rocks of later parts of the Ordovician. Llanvirn sites in the

Builth Inlier furnished the large collections that Sheldon (1987a) used in his population studies. Sholeshook has yielded large faunas of Ashgill age. In Scotland, trilobites from Dounans Quarry and sites in the Girvan district (notably Aldons Quarry) add to the brachiopod evidence that the Scottish Ordovician faunas are of Laurentian type. The evolution of the trinucleid group of trilobites has been studied using specimens from many localities in South Wales (e.g. Ffairfâch and Talar Wen) and North Wales (Trilobite Dingle), Shropshire (Mytton and Betton dingles, Coundmoor Brook (Harnage) and the Onny River), several localities in the Cross Fell and Cautley areas of northern England and in the Girvan district in Scotland.

Graptolites

Graptolites are extinct marine colonial animals whose skeleton consisted of horny collagen tubes (see, for example, Figure 8.12). Their mode of life has been debated, but it is now widely agreed that although some (dendroids) lived attached to the sea-floor, most were planktonic, living at some depth in offshore waters. They may be preserved abundantly in strata, commonly dark-coloured or black mudstones and shales, that contain few other fossils ('graptolitic facies'); evolving rapidly and being widely, some even globally, distributed, they are of particular use in wider correlation. Palmer and Rickards (1991) gave fine photographs of these obscure animals, and Strachan (1996–1997) listed the British species.

Planktonic graptolites appeared early in the Tremadoc (as seen at the Bryn-llin-fawr, Ogof Ddû and Cherme's Dingle sites) and diversified through the Arenig and Llanvirn (as seen at Barf, Randel Crag, Howey Brook and Abereiddi Bay). Significant faunas of Caradoc age are present at Spy Wood Brook, Cadnant Cutting and Pengawse Hill (discussed in the Mylet Road site report), but the richest graptolite faunas in the Caradoc and Ashgill are found in Scottish rocks, as at Laggan Burn (magnificently preserved), Morroch Bay, Glenkiln Burn and, above all, at Dob's Linn (Figure 15.7), where their distribution is used to define the international base to the Silurian System (Williams, 1988).

Chapter 2

Introduction to Cambrian stratigraphy

A. W. A. Rushton

HISTORY

The founding of the Cambrian System and the subsequent modifications that it underwent have been recounted several times (Stubblefield, 1956; Holland, 1974) and the controversy over the upper limit of the system that led to the founding of the Ordovician was described in detail by Secord (1986). In summary, the name Cambrian was first applied by Sedgwick to a large assemblage of rocks in North Wales, encompassing outcrops from the island of Anglesey and Snowdonia to Bala and the Berwyn Hills (Sedgwick and Murchison, 1835). At that time both he and Murchison – who had already proposed the Silurian System, mainly for rocks in the Welsh Borderlands and South Wales (Murchison, 1835) – supposed that the Silurian overlay the Cambrian. Only later did it become apparent that there was major overlap between these stratigraphical systems. Although Sedgwick himself subsequently excluded the older (now Precambrian) rocks from his Cambrian System, he disagreed with Murchison as to what level should be taken as the upper boundary of the Cambrian. Secord (1986) tells how those workers' early co-operation turned into a bitter controversy that was resolved only after the death of both combatants – when Lapworth (1879a) argued for a tripartite division of the Lower Palaeozoic and proposed that the greater part of the disputed strata should form the basis of a new system, which he named Ordovician. Lapworth's suggestion steadily gained acceptance in Britain, and subsequently elsewhere. The international adoption of the Cambrian System and the formalization of the lower, middle and upper divisions with something like their present usage owe much to the advocacy of Walcott (Yochelson, 1993, p. 119).

DISTRIBUTION

The Cambrian rocks of Britain occupy a relatively small area (Figure 1.1). They were reviewed by Rushton (1974) and Cowie (1974) and their correlation was discussed by Cowie *et al.* (1972). The largest outcrops are in Wales, where they represent thick sedimentary accumulations (the greater part of the Dyfed Supergroup of Woodcock, 1990) that formed during an early phase of the development of the Welsh Basin. The best representation of the Cambrian System in the historical type area of North Wales is in the Harlech Dome (see Figure 3.2), together with the similar sequence as exposed in the small but important outlying area of St Tudwal's Peninsula (see Figure 3.3). In neither of these outcrops is the base of the Cambrian seen. The Arfon area to the north-west, which lies close to Anglesey and the Irish Sea Horst complex, presents a less complete sequence in which the Comley Series differs strikingly from that of the Harlech Dome (see Figure 3.1). The contact with the Precambrian there has been claimed as both conformable and unconformable. The Cambrian sites of North Wales are described in Chapter 3. The main area of Cambrian rocks in South Wales (Chapter 4) is in the west, around St David's (see Figure 4.2). The recently described succession in the small area at Llangynog (Figure 2.1) differs from that at St David's (Cope and Rushton, 1992; Cope and McIlroy, 1998), but no Cambrian GCR sites have been selected for the aforementioned area at the present time.

In the Cambrian of England (see Chapter 5), shelf deposits of the Midland Platform form thinner sequences, which are exposed in small inliers. They display two main facies: the rocks near the western edge, exposed in the Comley and Wrekin areas of Shropshire and in the Malvern Hills (Figure 2.1), show discontinuous deposition (see Figure 4.1) in shallow water. In contrast, the succession over the central part of the Midland Platform, exposed in the Nuneaton area and proved in boreholes over a wider area, was deposited more continuously in deeper water.

In northern Scotland the Cambrian of the Hebridean Terrane foreland comprises the greater part of the shallow-water succession that

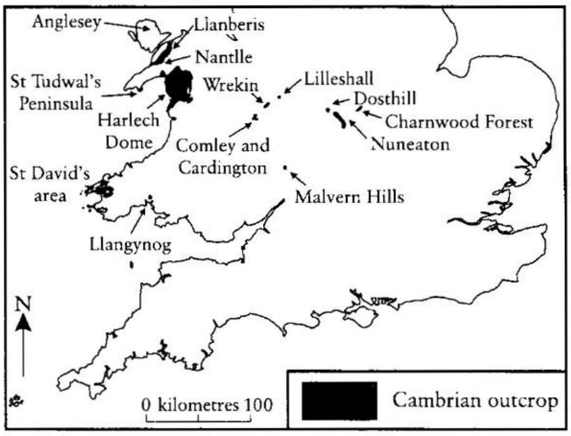

Figure 2.1 Distribution of Cambrian outcrops in England and Wales.

crops out in a narrow belt nearly 200 km long (see Chapter 12). The possible presence of Cambrian rocks farther to the south, in the Dalradian Supergroup and the Highland Border complex, was discussed by Cowie *et al.* (1972) and was generally discounted by Brasier *et al.* (1992b), with the exception of the Leny Limestone: this is satisfactorily dated as Cambrian but its stratigraphical relationships are contentious. It has a very small outcrop close to the Highland Boundary Fault Complex and has been considered to be part of the Highland Border Complex, but it is alternatively regarded as part of the Dalradian succession (Tanner, 1995; Molyneux, 1998). It is discussed in Chapter 13.

BOUNDARIES OF THE CAMBRIAN SYSTEM

Views on both the lower and upper boundaries of the Cambrian have varied. Earlier opinions on British rocks were reviewed by Stubblefield (1956).

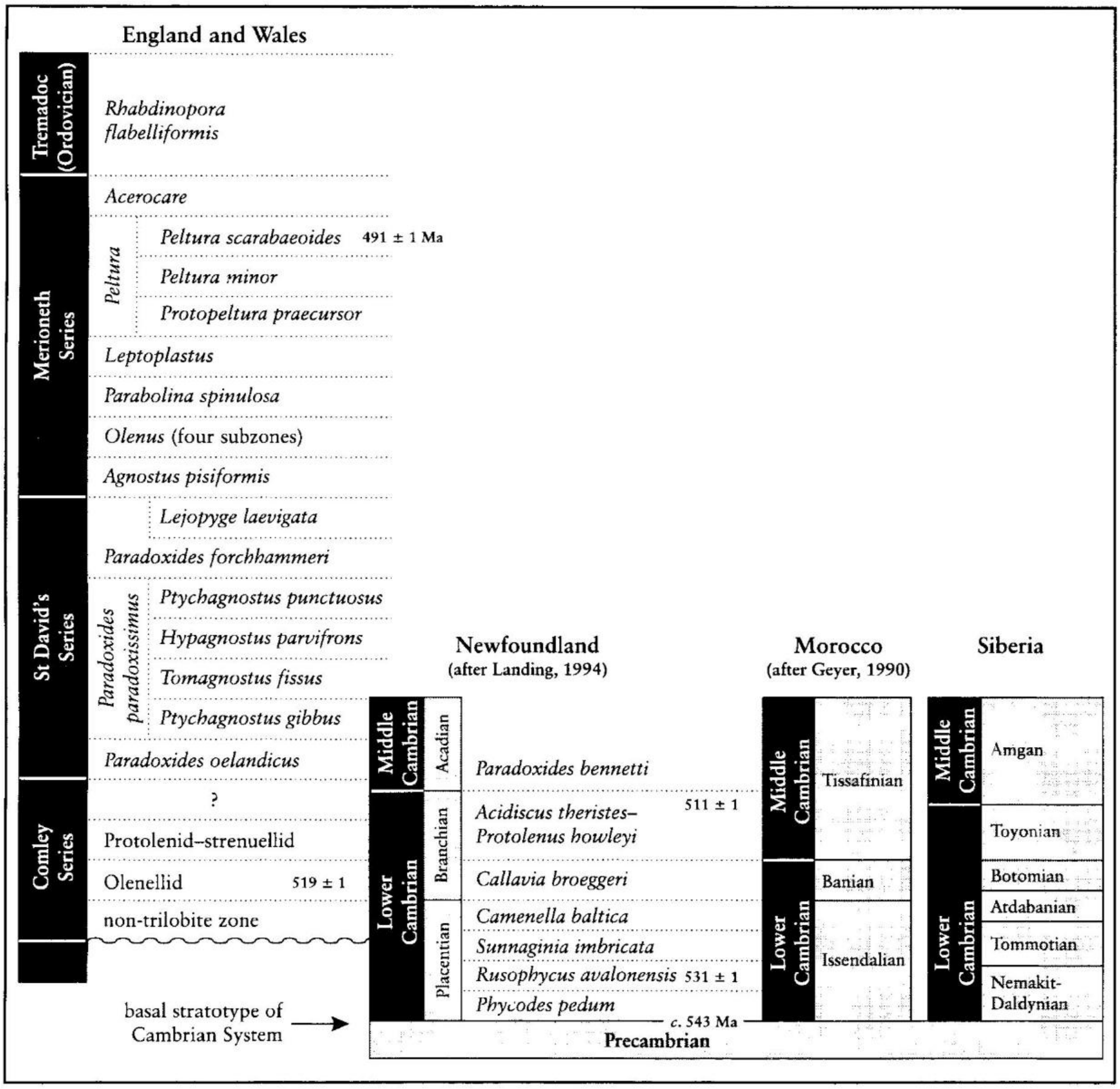

Figure 2.2 Cambrian chronostratigraphy and trilobite zones in England and Wales, with Lower Cambrian schemes for south-east Newfoundland and Morocco shown for comparison. The base of the Cambrian System is defined at the base of the *Phycodes pedum* Zone at Fortune Head, south-east Newfoundland. For sources of radiometric dates, see Davidek *et al.* (1998) and Landing *et al.*, 1998.

Lower boundary

Because most of the British Cambrian rocks occur in association with uplifted Precambrian rocks, historically it proved convenient to take the base of the Cambrian at the widespread unconformity between proven Cambrian and the presumed Precambrian below, though in certain places, where no such unconformity was clearly evident, controversies developed in the late 19th century as to the extent of the Cambrian and the significance of the Precambrian (see discussion of the Arvon area (Chapter 3) and the St David's area (Chapter 4)).

Extended international discussions to identify a stratotype by which to define the base of the Cambrian have resulted in the selection of a level in the Chapel Island Formation at Fortune Head in south-east Newfoundland (Brasier *et al.*, 1994; Landing, 1994). The level chosen is at the base of the *Phycodes pedum* trace-fossil zone (Figure 2.2) and is thought to have an age of about 543 Ma (Grotzinger *et al.*, 1995). Correlations by Landing (1996) and Conway Morris *et al.* (1998) suggest that this stratotypic base lies at a markedly lower stratigraphical level than British rocks previously regarded as basal Cambrian (Cowie *et al.*, 1972), whilst drawing strata previously regarded as late Precambrian into the Lower Cambrian (Bland and Goldring, 1995; McIlroy *et al.*, 1998).

Upper boundary

In Britain, the top of the Cambrian was for many years taken at the widespread unconformity between rocks of Tremadoc and Arenig age, as originally indicated by Lapworth (1879a). The Tremadoc outcrop parallels that of the Cambrian throughout Wales and England and was regarded as a natural part of the Cambrian. In continental Europe and North America, faunal considerations allied the equivalents of the Tremadoc with overlying Ordovician strata, the Tremadoc Series being regarded as basal Ordovician – a consideration that Lapworth himself was ready to entertain (in discussion of Groom, 1902, p. 148). The subject was reviewed by Henningsmoen (1973), and following international discussions a level at or close to the base of the Tremadoc was adopted for the Cambrian–Ordovician boundary (see Webby (1998) for a review). A stratotype has been recommended at Green Point, north-west Newfoundland (see Chapter 6), but has still (1999) to be ratified. The level chosen is very close to the base of the Tremadoc Series as proposed by Rushton (1982) at Bryn-llin-fawr, North Wales. Its age is close to 490 Ma (Davidek *et al.*, 1998), making the duration of the Cambrian just over 50 million years.

DIVISIONS OF THE CAMBRIAN

Stage and series divisions of the Cambrian have been employed in a regional sense in many parts of the world, but there is no globally agreed standard. Although the terms 'Lower', 'Middle' and 'Upper' Cambrian are widely used, they have different senses in different regions, as exemplified by Shergold's correlation chart (in Whittington *et al.*, 1997, p. 303). The discrepancies in usage are most marked at the base of the Middle Cambrian. Cowie *et al.* (1972) introduced, but did not formally define, the regional series terms 'Comley', 'St David's' and 'Merioneth', which stabilized respectively the 'Lower', 'Middle' and 'Upper' Cambrian (excluding the Tremadoc), as conventionally used in Britain. These terms, although provisional, are used here to facilitate reference to earlier compilations (Cowie *et al.*, 1972; Rushton, 1974). Harland *et al.* (1982) rejected the term 'Comley Series' because the term 'Comley' is applied also to the Comley Sandstone, and they introduced the term 'Caerfai Series' instead, even though it was open to the same objection, in that the nomenclature is shared with the Caerfai Group (Landing *et al.*, 1989). However, it may be feasible to abandon both of those terms and use instead the terms used for two better-defined series proposed for the Lower Cambrian in Newfoundland (Figure 2.2), namely the 'Placentian' and 'Branchian' (Landing, 1992). The old term, 'Acadian Series', recently revived for the Middle Cambrian as recognized in Newfoundland and New Brunswick (Landing, 1996), has priority over, and may be more apt than, 'St David's Series', which is of comparable scope. Unfortunately 'Acadian' is also widely used in the context of a Devonian phase of the Caledonian Orogeny, and its revival in a stratigraphical sense may lead to confusion. Therefore 'St David's Series' is retained here. 'Merioneth Series' is also retained, and Landing (1996) has adopted it (as 'Merionethian') for all of Avalonia.

No stages have been formally proposed for

British Cambrian rocks. There has been some use of stage-level terms derived from the lithostratigraphically conceived Solva, Menevian, Maentwrog and Dolgellau divisions (Harland *et al.*, 1982), but none of them has yet been defined and their use is to be deprecated. Orłowski (1992) gave approximately the same intervals the informal designations stages C, D, E and F, and suggested that they could be used in Polish, Scandinavian and British stratigraphy.

The zonal scheme shown in Figure 2.2 is based on that of Cowie *et al.* (1972). The zones of the Comley Series are generalized and due for revision, taking into account more recent work, especially in Newfoundland, as indicated by Brasier (1989; in Brasier *et al.*, 1992b). Those of the St David's Series are based on the Scandinavian succession, which is modified by discarding the *Goniagnostus nathorsti* Zone, as recommended by Berg-Madsen (1985). The Merioneth zones are based on the Scandinavian succession of olenid trilobites. The subdivision of the *Olenus* Zone into four subzones follows Rushton (1983).