Chapter 1 Introduction to the Precambrian rocks of England and Wales

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Overview

The Precambrian rocks of England and Wales are associated with some of Britain's most beautiful countryside (see for example, the front cover): Charnwood Forest, the Malvern Hills, Shropshire and the Welsh Borders, the fringes of Snowdonia and the rugged coastline of Anglesey and Ll■n (the Lleyn Peninsula). This scenic diversity is largely a consequence of the hardness of these rocks and is a legacy of the tectonic, metamorphic and alteration processes they have suffered in their long history, rendering them resistant to the forces of erosion.

The Precambrian outcrops are sparsely distributed and generally occupy relatively small areas of southern Britain (Figure 1.1). Their intrinsic geological interest, however, is out of all proportion to their size and they encompass an amazing diversity of rock type, providing many of the internationally important geological sites of the UK. The descriptions that follow include details of interest to those wishing to examine: varied volcanic sequences, sedimentary strata ranging from deep-water to terrestrial environments, plutonic igneous rocks, low- to high-pressure metamorphic rocks and complex deformational structures. Many of these rocks have been the subject of heated debate in the past, and there is still much to be learned about their ultimate origin and plate tectonic setting.

An outstanding feature seen in three of the outcrop areas is the occurrence of enigmatic fossil impressions, which are the local representatives of the world-famous Ediacaran fauna. New fossil discoveries are still being made, and will contribute to the on-going debate (Chapter 8) about exactly what types of organisms flourished in the late Precambrian seas.

'Precambrian' is a broadly used term for rocks that pre-date the Phanerozoic Eon (i.e. Cambrian or younger). It encompasses such a vast span of time, extending back to at least 4000 Ma (four thousand million years ago), that it has been subdivided into two Eons, the Archaean which in the UK only occurs in NW Scotland (to be described in the GCR companion volume *Lewisian, Torridonian and Moine Rocks of Scotland)* — and the younger Proterozoic Eon. The Precambrian rocks described in the present volume belong to the latter, specifically to its youngest part, which has been given the chronological term 'Neoproterozoic'. Their precise range within the Neoproterozoic, and the age of the chronological boundary with Cambrian Period, will be discussed further below.

It should be noted that three of the GCR sites, featured in Chapter 9, contain rocks that, on the balance of current evidence, may not be Precambrian. Two of these sites, in Charnwood Forest, contain trace fossils that indicate an early Cambrian age for the uppermost part of the succession (Bland, 1994). At the third site, Ingleton Group strata of the Chapel-le-Dale Inlier at Thornton in northern England are now believed to be contemporary, although not necessarily direct correlatives, with the Ordovician-age (Arenig–Llanvirn) Skiddaw Group of the Lake District (Cooper *et al.,* 1993). There is also an ongoing controversy regarding the age of the Monian Supergroup of Anglesey, which is discussed in the introduction to Chapter 7 of this volume.

The distribution of most of these outcrops is at least in part determined by fault systems that have episodically uplifted the Precambrian 'basement' from beneath successive coverings of younger (Phanerozoic) sedimentary strata. For example, the largest area of outcrop, in Anglesey and the adjacent Ll■n region of North Wales (Chapter 7), is controlled by the Menai Strait Fault System. A further extensive outcrop, forming the network of GCR sites in the Shropshire to Llangynog region (Chapter 5), lies within the Welsh Borderland Fault System. Both of these fault systems have had a long and complex history that probably began in latest Neoproterozoic time at about 600 Ma. The Precambrian inliers of Charnwood Forest (Chapter 2) and Nuneaton (Chapter 3) are simi larly controlled by major crustal lineaments on the eastern side of the wedge-shaped Midlands Microcraton, shown in (Figure 1.1). These major lineaments persist today as topographical features (Front cover), largely because of the repeated movements that have occurred along them, for example in response to the compressive stresses generated during the Caledonian, Acadian and Variscan orogenies in

Palaeozoic time. Later reactivations were mainly due to extensional stresses in Mesozoic times. Even today, 'neotectonic' activity may be the source of earthquake clusters in which many individual events were of relatively large magnitude, in the context of UK seismicity. These are concentrated in the Ll■n, Carmarthen–Church Stretton and Derby–Leicester regions (information from the BGS Bulletin of British Earthquakes). It is clear from this that much information about the Phanerozoic and present-day structure of southern Britain can be deduced once the disposition of, and boundaries between, the Precambrian basement massifs are known.

A scientific framework for the Precambrian rocks

The Precambrian basement of southern Britain is most conveniently grouped into a number of large crustal entities, called 'terranes'. Each terrane represents a microcosm of geological evolution (Figure 1.2) and its rock assemblages may have arisen from a diversity of geological processes, commonly involving episodes of volcanism, igneous intrusion, sedimentation and deformation, all of which can be framed in the context of plate tectonic interactions. This part of the introduction will discuss some of the basic principles of the terrane concept in its application to Precambrian rocks. Certain technical terms will be introduced, but these will either be explained in the text or in the selective Glossary at the back of this volume.

Explanation of the terrane concept

The geological 'terrane' is not to be confused with 'terrain' (a physiographical feature). The concept sprang from studies of the Western Cordilleran orogenic margin of North America in the late 1970s, which recognized that a large proportion of the crust in this region was 'sus pect' (exotic) with respect to the adjacent cratonic continental area (Coney *et al.,* 1980). It was soon determined that these exotic crustal slices had in fact originated as 'suspect terranes' in regions at some considerable remove, frequently by thousands of kilometres, from the orogenic belt where they had eventually ended up. It followed that the present orogenic belt was itself an *accretionary* collage, composed of numerous terranes derived from around the circum-Pacific region and now 'welded' together along major faults. These concepts were soon applied to other, older orogenic belts, e.g. the Appalachian belt of North America (Williams and Hatcher, 1982), the Caledonides and Variscides of Europe (e.g. Ziegler, 1982) — and subsequently to the Precambrian of southern Britain (e.g. Gibbons, 1987; Gibbons and Horik, 1996). Support for the new hypothesis came not only from structural and lithological studies, but also from studies of faunal biodiversity and palaeomagnetism.

The principles of terrane analysis require a rigorous evaluation of the stratigraphical and structural history of each geological domain to examine its *linkages* to the surrounding ones (Howell, 1995). If the tectonostratigraphical history of the domain is different to that of its neighbours, it is considered *suspect* with respect to the latter. Thus it is possible that some part of the region may be composed of *allochthonous* (= far travelled) crustal fragments that subsequently came into contact (sutured together or 'docked') with each other. While stratigraphical and structural criteria are very important in terrane definition, other useful criteria include: magmatic and metamorphic history; palaeomagnetic data, giving absolute values for palaeolatitudinal and rotational displacement when calibrated by high quality radiometric ages; and biostratigraphical data, indicating episodes of faunal provinciality (continental isolation).

The importance of geochemistry in Precambrian terrane characterization

The geochemical signature of magmatic suites, determined from plots of major and trace element and isotopic data, may be extremely useful in terrane correlation and their implications are much discussed in the introductions to the various GCR site networks and/or volume chapters.

Bimodal suites comprise magmas of contrasting, usually basic and acid, compositions. The basic magma, typically iron-rich or *tholeiitic* basalt, represents a mantle melt that may have suffered a comparatively minor amount of modification as it has passed through the crust. By contrast the acid magma (typically a rhyolite) may have been generated by interaction of the basic magma with the crust itself, e.g. by partial melting.

Calc-alkaline suites exhibit a range of composition, e.g. basalt-andesite-dacite-rhyodacite, but are unimodal and dominated by rocks of intermediate composition, in particular andesite and dacite (or their plutonic equivalents).

Geochemical patterns commonly utilize the immobile major and trace elements that are the least susceptible to change as a result of subsequent alteration and/or metamorphism. Their content in lava is normalized, for example with respect to mid-ocean-ridge basalt (MORB), and then compared to the abundances in samples from known tectonic environments (Pearce, 1982). The pattern that results may be used to identify the nature of the lithospheric mantle source region, for example whether it has *volcanic arc* or *within plate* components, and thus provide a useful indication of the tectonic environment of origin of a particular magmatic suite. This in turn can be used as a constraint to deduce the environments of lava and pyroclastic eruption, or of accumulation in the case of thick volcano-sedimentary sequences.

Determination of absolute ages of the Precambrian rocks

Considerations of terrane evolution are crucially dependent upon accurate determinations of age. This is difficult because Precambrian rocks do not possess the highly diverse and rapidly evolving fossil assemblages characteristic of many Phanerozoic sequences. Their age, when determined, must therefore be an *absolute age* based upon radiometric dating using the decay schemes of the various radiogenic isotopes contained within the rocks or their mineral components. The absolute age is then referenced to recognized and well-calibrated geological timescales based upon the most precise radiometric data for stratigraphically controlled rock units around the world. For example, the Phanerozoic timescale used here is that published by Gradstein and Ogg (1996). The Precambrian rocks of southern Britain yield isotopic data indicating that they were formed at various times between about 700 and 550 Ma, as shown in the chronologically based correlation chart of (Figure 1.2). This places them within the Neoproterozoic period, discussed earlier, which ranges from 1000 Ma to 543 Ma, the younger datum being the age that is currently accepted for the Precambrian–Cambrian chronological boundary (Bowring *et al.,* 1993). Evidence for the presence of much older rocks is sparse, and discussed later in this chapter.

The most reliable radiometric techniques for determining the absolute age of Precambrian rocks is the analysis of the U-Pb isotope system in minerals, and this has yielded analytical precisions as good as 1 Ma for age of crystallization of late Precambrian magmatic rocks in southern Britain (Tucker and Pharaoh, 1991). In addition, the U-Pb isotopic '*concordia*' system is inherently robust, allowing complications such as the incorporation of more ancient inherited grains, or the effects of complex thermal, hydrothermal and other alteration histories to be recognized and evaluated by modelling. The ages of crystallization of igneous rocks from many of the rock suites (labelled U or M in (Figure 1.2)) have therefore been determined using this method. Techniques based on the Rb-Sr whole-rock isochron method yield ages for the same suites that are less precise, with errors frequently of the order of ± 30 Ma (suites with wider error bars labelled 'R' in (Figure 1.2)). This is in part because the Rb-Sr isotopic system is much more easily reset by hydrothermal and other alteration processes which have affected these rocks since their crystallization. The ^{40}Ar–^{39}Ar technique, using step reheating of mineral grains to generate plateau ages, which constrain interpretation, is inherently more robust than the K-Ar technique, which frequently suffers from problems arising from the diffusivity of Ar. It has been applied both in Anglesey (Dallmeyer and Gibbons, 1987) and in the Malverns (Strachan *et al.,* 1996). Some of the results are indicated in (Figure 1.2), labelled 'A. The Sm-Nd technique has been used to generate 'model ages', indicating the time at which the protolith (composition of a metamorphic rock prior to recrystallization) separated from its mantle source region, e.g. in Anglesey (Davies *et al.,* 1985).

A generalized chronological sequence for the Precambrian rocks

Application of these radiometric-dating tech niques to the Precambrian rocks of England and Wales south and east of the Menai Strait Fault System has led to recognition of the following chronological sequence of events:

1. *c.* 1598 Ma Formation of inherited zircons in Malverns Complex.
2. *c.* 1100 Ma Nd isotope model ages of the Malverns Complex plutonic rocks.
3. 700–640 Ma Crystallization of plutonic suites (Stanner–Hanter, Malverns, Johnston Complex) at moderate crustal depths followed by pervasive metamorphism and shear deformation.
4. 620–585 Ma Eruption of early arc volcanic and related plutonic suites (Pebidian Supergroup, Sarn Complex, Arfon Group, Charnian Supergroup, volcanics in Orton and Glinton boreholes).
5. 570–560 Ma Eruption of late marginal basin-type volcanic suites (Uriconian Group, Warren House Formation).

6. 560–?540 Ma Deposition of thick sedimentary sequences (Longmyndian Supergroup, upper part of Arfon Group) in rapidly subsiding pull-apart basins followed by their inversion (uplift and erosion) during late stage Avalonian orogenic events.
7. *c.* 535 Ma Deposition of the Cambrian overstep sequence commences.

By contrast, the Precambrian rocks of Anglesey and northern Ll■n, to the north and west of the Menai Strait Fault System, exhibit the following history

1. 1800–1200 Ma Nd isotope model ages of protolith to some of the Central Anglesey gneisses.
2. Unknown age. Polyphase deformation-metamorphism of gneisses.
3. 615 Ma Emplacement of Coedana Granite into country-rock hornfelses.
4. 600 Ma? Formation of oceanic protolith to blueschists.
5. 600-?535 Ma Deposition of Monian Supergroup in a fore-arc or arc-trench basin, and development of subduction zone.
6. 560–550 Ma Unknown age. Ductile shearing during accretion of Monian terranes followed by terrane dispersion and juxtaposition to Avalonian terranes of England and Wales. Blueschists tectonically emplaced along Menai Strait Fault System.
7. *c.* 490 Ma Deposition of Arenig overstep sequence.

A summary of the Precambrian terranes of southern Britain

The value of terrane analysis is that it provides a highly appropriate conceptual framework for the late Precambrian rocks of England and Wales, which between 700 and about 545 Ma occupied an active plate boundary along the margin of a large continent in the Southern Hemisphere ((Figure 1.3)a). This supercontinent is named 'Pannotia' (Dalziel, 1997), and is sometimes loosely referred to as the Nendian supercontinent'; it evolved from its forerunner, 'Rodinia' (Dalziel, 1991). Pannotia underwent rifting into smaller components during latest Neoproterozoic time, one of the largest being Gondwana. One side of Gondwana consisted of an elongate area that stretched from Belgium via England, Ireland and Maritime Canada into the Appalachians of the USA. Known as the 'Avalon Composite Terrane' (Keppie, 1985), or Superterrane (Gibbons, 1990), virtually all its components comprise subduction-related arc magmatic complexes and the sedimentary fill of marginal basins derived from them. The arcs were located on a crust of variable maturity, some on juvenile, perhaps even oceanic, crust, others on more mature crust. These characteristics point to derivation from the oceanward side of a long-lived destructive margin, located either on the North African or South American margin of Gondwana ((Figure 1.3)a). The likely plate tectonic evolution of this margin is encapsulated in the model of Gibbons and Horák (1996), which shows that the disparate and apparently confusing segments of southern Britain's Precambrian basement can be placed within the context of successive late Precambrian geodynamic events (Figure 1.4).

The Palaeozoic history of Avalonia is too complex to detail here, but some of the more significant plate movements are shown in (Figure 1.3)b,c. The earliest of these caused the Avalonian Terrane to be rifted off and moved away from the Gondwana margin in early Ordovician time. The microcontinent subsequently docked with Baltica in the late Ordovician, causing the Shelveian (early Caledonian) deformation event (Toghill, 1992), and was subjected to strong deformation resulting from the Acadian (late Caledonian) deformation, in late Silurian to early Devonian time. The structures and tectonic fabrics imposed on the rocks by this last event are intensely developed in places, and will be frequently mentioned in the accounts that follow this chapter.

In southern Britain the Precambrian rocks of the Avalon Composite Terrane can be divided into two main groups of terranes (Figure 1.2). Precambrian rocks in England and Wales south of the Menai Strait Fault System closely resemble the 'type Avalonian' rocks exposed in south-east Newfoundland. They are separated from the 'Monian' Precambrian rocks of Anglesey and Ll■n, which do not resemble the type Avalonian, by a major tectonic boundary along the Menai Strait Fault System. The latter may therefore be interpreted as a suspect terrane boundary along which the 'Monian' terranes have been docked against typical British Avalonian rocks, during the late Precambrian plate reorganizations detailed in (Figure 1.4) (Gibbons, 1987; Gibbons and Horik, 1996). A third group of terranes, of 'Cadomian' affinity and forming part of the Armorican Massif, is exposed in the Channel Islands, which are beyond the scope of this publication. Gibbons and Horák (1996) refer all three groups of terranes to an Avalonian Superterrane', on the grounds that despite their suspect nature (with respect to each other), their similarities are greater than their differences, and all were created, displaced and accreted within the same subduction system. An alternative view is that these three terrane groupings are all suspect and should be labelled as such. For example, the Rheic Suture in the English Channel region (Cocks and Fortey, 1982) separates the Cadomian terranes from the British Avalonian terranes. Consequently, and as also implied by (Figure 1.3)c, there is no certainty that the Armorican terrane, of which they form part, was in late Ordovician time derived from the same part of the Gondwana margin as the Avalonia terrane, rifted away at the start of the Ordovician (Ziegler, 1990). Furthermore the terrane-linking basal Cambrian overstep sequence so typical of the British type Avalonian in England and Wales does not extend across the Menai Strait to encompass the lithologically distinct Monian terranes, which were only certainly docked by Arenig time (Gibbons and Horák, 1996). In this volume, the terranes are therefore described as *British type Avalonian* (chapters 2–6) and the *Monian Composite Terrane'* (Chapter 7).

British Avalonian terranes

These terranes each exhibit lithological similarity to the Avalonian sequences of the type area in Newfoundland. The Avalonian belt was sited at high southern latitudes along the Gondwanan plate margin in Neoproterozoic times (Keppie *et al.,* 1998), but it was subsequently fragmented, as shown in (Figure 1.3), and its components dispersed unknown distances along strike-slip faults before subduction activity was renewed in Ordovician times. The southern Britain representatives constitute six terranes, each the basis of a GCR site network (Figure 1.5), which are given below:

The Fenland Terrane, defined here for the first time, comprises the Precambrian basement of the concealed Caledonides of eastern England (Pharaoh *et al.,* 1987a). This basement is unexposed, proven only by boreholes, and therefore not represented by any GCR sites. A Precambrian age is proven or suspected for felsic tuffs penetrated by three boreholes in eastern England. Ignimbritic ash-flow tuffs of felsic composition (Dearnley, 1966) were encountered by the Glinton and Orton Boreholes (Figure 1.1), and have yielded precise U-Pb zircon ages in the range 616–612 Ma (Noble *et al.,* 1993). Although they are rather similar in age to Charnian magmatic rocks (see below), they are petrographically and geochemically distinct, with eNd isotopic ratios indicating the involvement of mature continental crust (Noble *et al.,* 1993). Similar geochemical and isotopic compositions are exhibited by tuffs proved by the Oxendon Hall Borehole (Pharaoh *et al.,* 1991). The nature of the boundary with the adjacent Charnwood Terrane is unknown. It is likely to be a NW-trending fault (NECBF, (Figure 1.1)) defining the north-east margin of the Charnwood Massif and the Midlands Microcraton.

The Charnwood Terrane, defined by Pharaoh *et al.* (1987b), includes a large network of sites within Charnwood Forest (Chapter 2) and near Nuneaton (Chapter 3). In Charnwood Forest the Charnian Supergroup comprises at least 3.5 km of volcaniclastic rocks deposited in moderately deep water adjacent to a calc-alkaline volcanic arc. Geochemical data suggest that this arc was founded on immature continental crust (Pharaoh *et al.,* 1987b), rather different from that underlying the Fenland Terrane. Numerous bodies of diorite, commonly granophyric textured (North and South Charnwood Diorites and equivalent rocks at Nuneaton), represent the late generation of relatively more evolved, high-K calc-alkaline magmas (Pharaoh *et al.,* 1987b), at about 603 Ma (fucker and Pharaoh, 1991). They intrude most of the bedded sequence, including horizons with Ediacaran fossils.

The Kempsey and Withycombe Farm Boreholes (Figure 1.1) proved volcanic rocks with Charnwood-type geochemical signatures (Pharaoh and Gibbons, 1994), demonstrating that the terrane extends beneath the Worcester Basin and South Midlands (Barclay *et al.,* 1997). The boundary between the Neoproterozoic Charnwood and Wrekin Terranes has been inferred to lie at the Malvern Lineament. However, this interpretation is not universally accepted (e.g. see Strachan *et al.,* 1996).

The Wrekin Terrane was first defined by Pharaoh *et al.* (1987b). The oldest rocks constitute the bimodal (gabbro–granophyre) Stanner–Hanter Intrusive Complex and the calc-alkaline Malverns Complex of the Malvern Hills GCR site. These plutonic rocks were emplaced at about 702 and 680 Ma respectively (Patchett *et al.,* 1980; Thorpe *et al.,* 1984; Tucker and Pharaoh, 1991), and in the case of the Malverns Complex at least, were recrystallized in the greenschist to low amphibolite metamorphic facies soon after this (Strachan *et al.,* 1996). This plutonic suite probably extends well to the west of the Malverns, perhaps to the Pontesford Lineament of the Welsh Borderland Fault System (Woodcock, 1984a), where the Primrose Hill and Rushton metamorphic suites are thought to be of similar age (Thorpe *et al.,* 1984). The latter are metasedimentary rocks and they, together with the plutonic suites, form a basement to the younger volcano-sedimentary successions of the terrane.

The younger cover sequence commenced with the bimodal-style magmatism of the Uriconian Group, mainly described from the Shropshire GCR sites (Chapter 5), the geochemistry of which indicates eruption within a largely subaerial marginal basin that developed at 566–560 Ma (Tucker and Pharaoh, 1991). The U-Pb zircon date for emplacement of the subvolcanic Ercall Granophyre, at 560 Ma, is presently the most precise constraint for the minimum age of Precambrian magmatism in southern Britain. Another bimodal volcanic suite, so far undated, bearing lithological and geochemical resemblance to the Uriconian Group, is the Coomb Volcanic Formation (Cope and Bevins, 1993; Bevins *et al.,* 1995) of Llangynog in South Wales (Figure 1.1). Nearby, the Johnston Complex comprising heterogeneous diorite, granodiorite and granite emplaced at about 643 Ma (Patchett and Jocelyn, 1979), is lithologically similar to the Malverns Complex and like the latter was affected by Variscan overthrusting. In Shropshire a 6.5 km thickness of Longmyndian strata were deposited during the waning stages of volcanism, within a rapidly subsiding basin. Such a setting is in keeping with the bimodal style of Uriconian volcanism, which reflects either a late phase of rifting and marginal-basin generation in the Wrekin Terrane, or is the expression of extensional basins controlled by strike-slip faulting during dispersal of the Avalonian arc-related terranes (Gibbons and Horák, 1996; (Figure 1.4)).

The Warren House Formation lavas of the Broad Down (Malvern Hills) GCR site, which are in faulted contact with the Malverns Complex, are of identical age to the Uriconian lavas. Their chemistry, however, is appropriate to an oceanic marginal-basin tectonic setting (Pharaoh *et al.,* 1987b), suggesting that crustal extension may have proceeded further in this part of the Wrekin Terrane.

The Cymru Terrane (literally the 'Wales Terrane'; cymru is pronounced: 'coomray'), defined here for the first time, comprises the Precambrian basement of the deep, early Palaeozoic Welsh Basin, exposed around the northern and southern rims of the latter. In North Wales it includes the Penrhyn Nefyn GCR site showing the Sarn Complex (chapters 6 and 7), of diorites, gabbros and granites forming a calc-alkaline plutonic series emplaced at about 615 Ma (Horák, 1993; Horák *et al.,* 1996). A further component of the Sarn Complex, consisting of garnetiferous rocks (Parwyd Gneisses) is seen at the south-west tip of Ll■n at the Braich y Pwll to Parwyd GCR site.

The Arfon Group (Chapter 6) represents voluminous calc-alkaline felsic magmatism (Padarn Tuff Formation of Reedman *et at,* 1984) likewise emplaced at about 614 Ma (Tucker and Pharaoh, 1991). Both the Sarn Complex and Arfon Group lie to the south of the Menai Strait Fault System and are in presumed faulted contact with the Monian terranes of Anglesey (Chapter 7). Small, isolated exposures of tuffaceous rocks (Bwlch Gwyn Tuff and Baron Hill Formation) which are lithologically comparable to parts of the Arfon Group succession (Reedman *et at,* 1984), nevertheless occur within the Berw Shear Zone on Anglesey. According to Gibbons and Horák (1996) these represent fragments of the Cymru Terrane tectonically incorporated within the Monian Terranes and cannot be used to provide an overstep linkage of the type inferred by Tucker and Pharaoh (1991).

The > 2 km thick Pebidian Supergroup, described at the St David's GCR site (Chapter 6), is dominated by volcaniclastic rocks of calc-alkaline composition and was intruded by the St David's Granophyre at about 587 Ma (Patchett and Jocelyn, 1979). Calc-alkaline arc volcanism thus persisted in the Cymru Terrane after 600 Ma. The Monian Terranes of Anglesey and northern Ll■n exhibit no linkage whatever to the Cymru Terrane until Arenig time, and are therefore regarded as suspect to the latter (Gibbons, 1987). The Fenland Terrane (see above) exhibits calc-alkaline volcanism of comparable age and composition to that of the Cymru Terrane but with the limited sampling of the basement in the former provided by boreholes, any correlation of these terranes must remain tentative.

Monian Composite Terrane

This series of terranes, amalgamated into the network of GCR sites described in Chapter 7, represents by far the largest exposure of Precambrian rock in southern Britain. It has at least three distinct components informally referred to by Gibbons and Horák (1990) as 'terranes 1, 2 and 3' (Figure 1.2). Each of these shows lithological dissimilarity to the sequences of the Avalonian type area in Newfoundland, but there are similarities to the Rosslare Complex of south-east Ireland. Major transpressional displacements between the three terranes were completed prior to deposition of a terrane-linking overstep sequence of Arenig age. The boundary between the disparate Cymru and Monian Composite terranes lies at the Menai Strait Fault System (Gibbons, 1987), a major shear zone exhibiting sinistral transcurrent movements, which is a candidate for a suspect terrane boundary (Gibbons and Horik, 1990, 1996).

Monian Supergroup ('Terrane 1'). This terrane (Figure 1.1) comprises the Monian Supergroup (Shackleton, 1975) , a 5.4–7.5 km thick (Gibbons *et al.,* 1994) polydeformed and metamorphosed sequence, repeated by faulting at least four times. The sequence comprises clastic rocks of turbiditic origin and interbedded pelitic rocks, overlain by a phyllitic unit with an arc volcanic source and intruded by numerous basic and ultrabasic bodies (Maltman, 1975). It passes up into the famous Gwna Group mélange ('Gwna Mélange') classic sites of which are described in Chapter 7. The Gwna unit includes rare clasts of granite, which have been matched to the Coedana Granite (Horák, 1993; Horák *et al.,* 1996) of the Coedana Terrane (see below), but clasts of blueschist and mylonite from the Aethwy Terrane are absent. Poor palaeontological evidence for a Precambrian to possible early Cambrian age is provided by stromatolites, trace fossils and acritarchs (Wood and Nicholls, 1973; Muir *et al.,* 1979; Peat, 1984b). An early Cambrian age for at least part of the supergroup is favoured by lithostratigraphical correlation with the Cahore Group in south-east Ireland (Gibbons *et al.,* 1994). On the other hand, the occurrence of Monian-type granitic and mylonitic debris in Cambrian strata (Nicholas, 1915; Greenly, 1919; Gibbons, 1983) suggests erosion of this terrane before at least the upper part of the Lower Cambrian.

The supergroup probably represents the fill of a latest Proterozoic trench-forearc basin (Figure 1.4) which suffered metamorphism and multiple deformation during the ductile shearing that juxtaposed it with terranes 2 and 3.

Coedana Terrane ('Terrane 2'). This terrane in central Anglesey comprises various types of gneisses and a large body of intrusive granite, together with mylonitic rocks derived from these protoliths. Although the metamorphic age of these gneisses remains unknown, the emplacement of the Coedana Granite has been dated at about 613 Ma (Tucker and Pharaoh, 1991). An inherited zircon component has an age of about 1440 Ma, which falls within the range of Sm-Nd depleted mantle model ages of 1000–1800 Ma derived from the gneisses themselves (Horák, 1993). Ductile shear zones in the south-east (Central Anglesey Shear Zone) and a steep belt of cataclasite in the north-west (Llyn Traffwll Fault Zone) separate this terrane from its neighbours. Rather similar gneissose and plutonic rocks, with a comparable isotopic history, are present in the Rosslare Complex of south-east Ireland (Horák, 1993).

Aethwy Terrane ('Terrane 3'). The blueschists, exposed within a narrow linear belt in south-east Anglesey, represent the most famous component of the Monian composite Terrane (Chapter 7) and are one of the oldest (possibly *the* oldest) and best-preserved occurrences of such rocks in the world. They are intensely foliated rocks isolated from all other tectonostratigraphical units by ductile shear zones; the Berw Shear Zone in the north-west and the Bryn Meurig Shear Zone (Gibbons and Horák, 1990; fig.3) in the south-east. The typical mineral assemblage of these rocks is sodic amphibole (glaucophane) together with epidote + haematite + quartz. The blueschists are of prime importance to plate tectonic reconstructions in southern Britain. They are interpreted as the product of early low pressure subsea floor metamorphism at about 590–580 Ma, followed by high pressure/low temperature subduction-related metamorphism at 560–550 Ma (Dallmeyer and Gibbons, 1987).

Precambrian tectonic settings and the terrane accretion model

Various plate-tectonic models e.g. Dewey, (1969), Baker (1971), Wood (1974), Barber and Max (1979), have been applied to the Precambrian rocks of southern Britain, emphasizing such tectonically diagnostic features as:

- Blueschists: subduction metamorphism
- Mélange: trench fill
- Pyroclastic rocks: arc volcanism

These models inferred subduction of oceanic lithosphere to the south-east, beneath the Welsh mainland, and assumed that all of the components represented part of one contemporaneous subduction system. Radiometric data available at this time were largely Rb-Sr and K-Ar age dates of uncertain reliability and with relatively large analytical errors, which did not allow the age relationship of the different elements to be confirmed. Subsequently the application of the more precise and robustly interpretable U-Pb zircon and Ar–Ar mineral techniques has enabled the sequence of events in the history of this destructive margin association to be recognized, as summarized earlier in this chapter and detailed in (Figure 1.4).

The early models paid little or no attention to the possibility of transcurrent displacements. Subsequent work (Gibbons, 1983, 1987, 1990) has shown this mechanism to be of great importance, to the extent that it is no longer possible to assume that the juxtaposed terranes (and the diagnostic units identified above) always had the same spatial relationship in the past. Neither is it certain that the distinctive Monian Composite Terrane was part of the same arc-trench system as the British type-Avalonian terranes, as suggested by Gibbons and Horák (1996). The following synthesis is therefore presented in the light of the caveats identified above.

- The oldest suites recognized (Stanner–Hanter, Malverns, Johnston complexes) are associated with an *early phase,* from 700—?640 Ma, of subduction-related calc-alkaline arc magmatism within the Cymru and Wrekin Terranes (Figure 1.4). The pre-existing continental crust in these terranes is nowhere exposed, but isotopic evidence suggests that it may be as old as mid-Proterozoic (Tucker and Pharaoh, 1991). Pervasive metamorphism, ductile deformation, uplifi and erosion followed crystallization of plutonic suites at moderate crustal depths. This was followed after a considerable period of time by the 'Main Magmatic Event' of Gibbons and Horák (1996), during which several subduction-related calc-alkaline magmatic suites (Padarn, Sarn, Charnian, Glinton) were erupted or emplaced in the Cymru, Charnwood and Fenland terranes between 620 and 585 Ma.
- Rifting of some of these arc terranes, particularly the Wrekin Terrane, is reflected in the late (570–560 Ma) eruption of transtensional and marginal basin volcanic suites (Uriconian, Coomb, Warren House), but as it is unclear to which arc they lie marginal with, the polarity of subduction is equally uncertain. If the arc was the same as that forming the source of the Pebidian lavas, in the Cymru Terrane, then subduction may have been toward the southeast as proposed in the early models, although with an increased oblique component of convergence (Figure 1.4).
- Voluminous sedimentation in rapidly subsiding transtensional pull-apart basins (Longmyndian, upper Arfon Group) reflects either the increasingly oblique nature of convergence and/or the onset of terrane dispersal (Gibbons and Horák, 1996), as shown in (Figure 1.4).
- Subsequent inversion of these basins was accompanied by deformation resulting in recumbent folding, mild metamorphism and weak cleavage formation (BGS, work in progress). Unlike the Cadomian terranes of Armorica (northern France), there is an apparent lack of intense cleavage development and syntectonic plutonism, although this may simply reflect a different level of erosion.

The implications of the above sequence of events are that the amalgamation of the Avalonian terranes, at least in southern Britain, was a rather long-lived and progressive affair.

Gibbons and Horák (1996) have suggested that the Coedana Complex may be interpreted as a frontal arc sliver generated, during late oblique convergence, from the same destructive margin as the British Avalonian terranes. The similar age of the main calc-alkaline plutonic phase in Anglesey (Coedana Granite) to the Main Magmatic Event in the British Avalonian terranes is compatible with this idea. The blueschists and Monian Supergroup can then be interpreted as fragments of an accretionary prism caught between slivers of dismembered arc (e.g. Bwlch Gwyn Tuff on Anglesey and Padarn Tuff of the Arfon Group) and fore-arc (Central Anglesey Gneiss) crust. Hence the overall polarity of this system, with more primitive oceanic components to the north-west, would be in agreement with SE-directed subduction polarity proposed in the early published models.

The Precambrian events described above had by mid-Cambrian time (at the latest) produced a somewhat heterogeneous amalgamation of disparate terranes at the margin of Gondwana. In early Ordovician time part of this recently accreted crust was rifted away, producing a new terrane, known as Avalonia' (Ziegler, 1982), of which the crust of southern Britain occupies the eastern part. Benchmarks in the history of this new terrane and its subsequent accretion into the Caledonian Orogen are documented in (Figure 1.3). This subject is more fully covered by the explanations and site descriptions given in the companion GCR volume on the Cambrian and Ordovician stratigraphy of Britain (Rushton *et al.,* 1999).

The GCR Precambrian site networks, and rationale of site selection

In this account the general principles of site selection described in the introductory GCR volume (Ellis *et al.,* 1996) are adapted to the complex problem of assembling the Precambrian sites into what is hoped will be an easily understandable and usable descriptive framework. It has been seen that the outcrops within the Precambrian GCR Block in England and Wales are strongly controlled by the reactivation of ancient crustal lineaments, the most important dividing the Precambrian into crustal domains that are geological '*terranes'* (see above for definition and explanation of this term). In this volume therefore, each terrane forms the basis for an individual GCR site *network,* composed of a cluster of sites that are generally in close proximity to each other. The relationship between the Precambrian GCR Block, its various terrane-dependent networks and the sites within each network is portrayed diagrammatically in (Figure 1.5), which is also intended to guide the reader around the chapters of this volume. On this diagram, each site is assigned to one of the three principle components of the GCR, as utilized by the JNCC for determining scientific value and importance to geoscience studies. These are listed as follows.

I The site includes features of international geological importance (for example, all of the palaeontological sites are given this category).

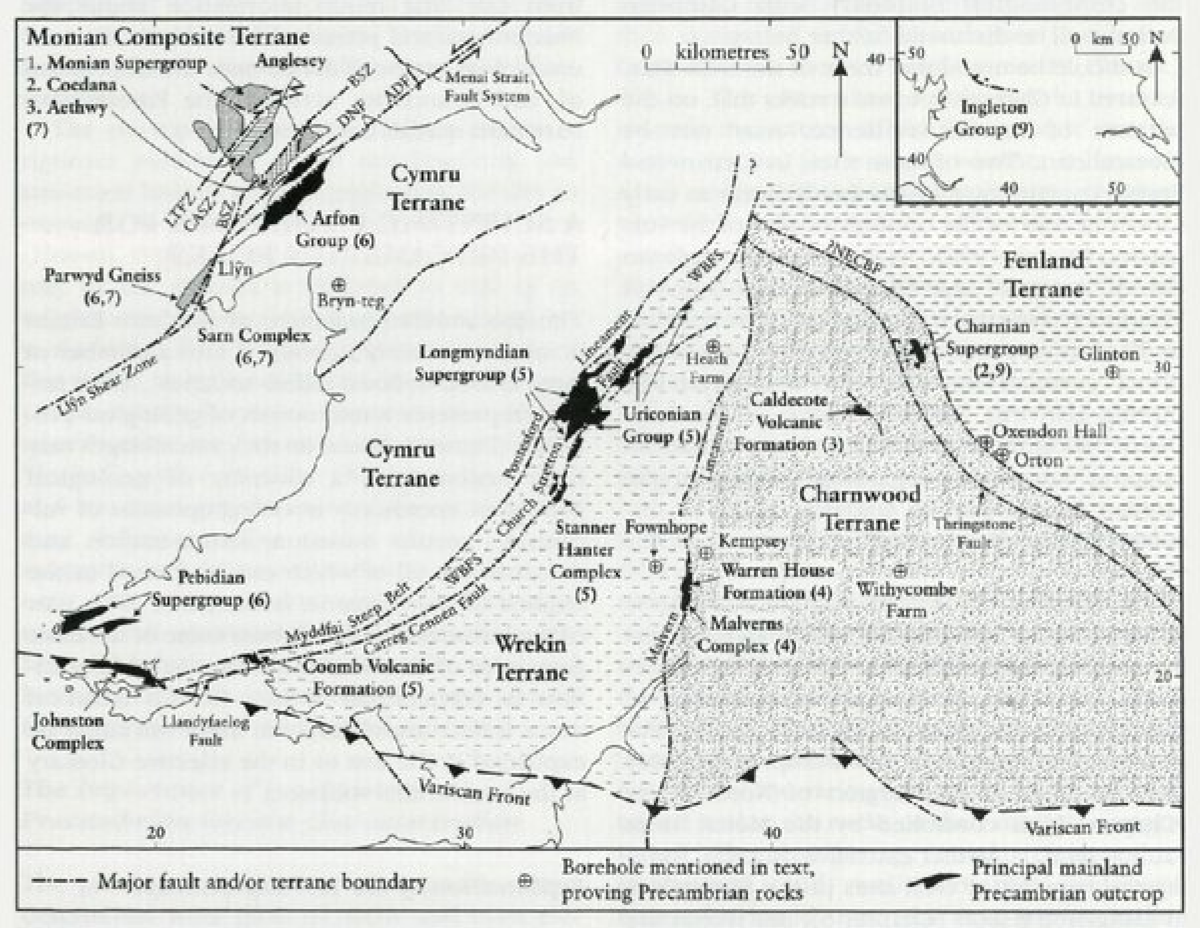
R The site includes features of national importance because they are representative of an Earth science event or process fundamental to Britain's Earth history, or the history of evolution of a particular GCR network.

E The site includes exceptional features that are scientifically important.

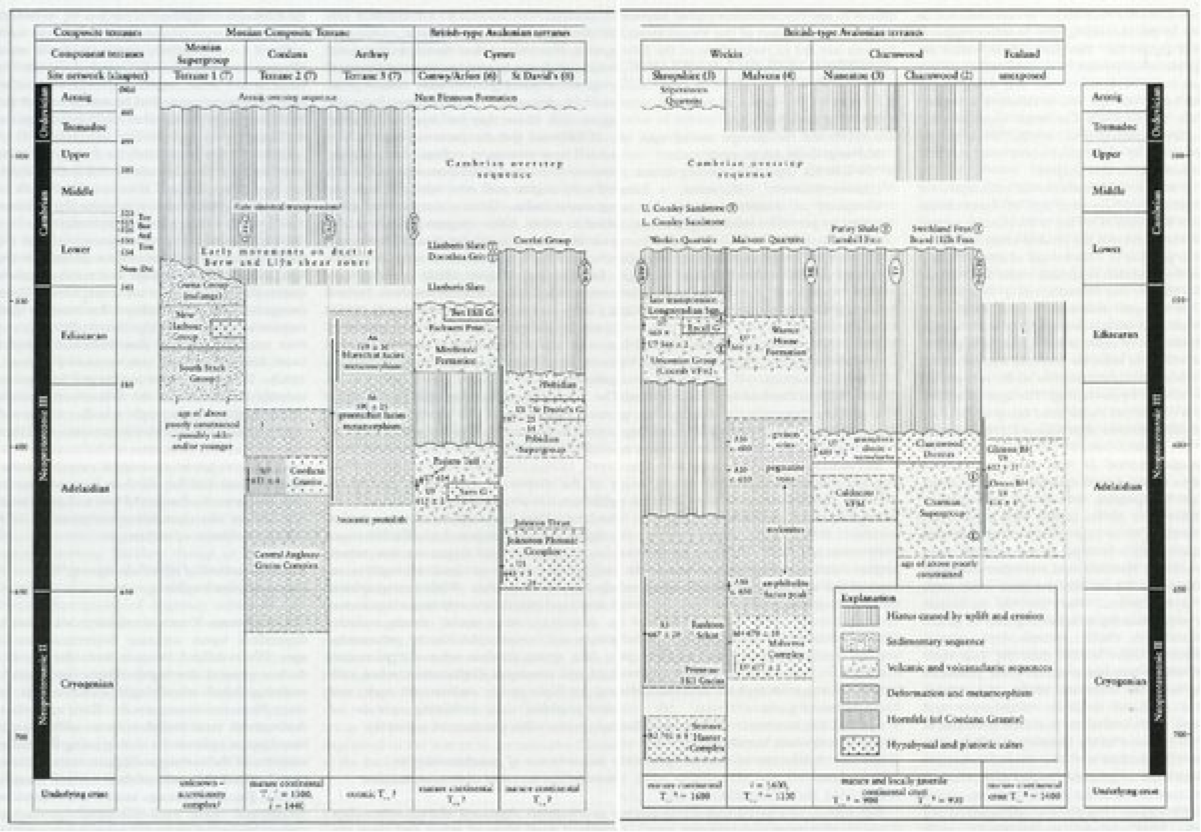
These components are not mutually exclusive, but for convenience, the highest of these components takes precedence in (Figure 1.5). For example, it should be assumed that an 'internationally' rated site (I) will also be representative (R) of an event or process and will logically include exceptional (E) features. In all cases, however, the sites within an individual network have been chosen to illustrate the diversity of lithology, compositional variation, metamorphic and structural features and relationships characteristic of the terrane within which they are located.

For the detailed site descriptions that follow, each network of sites is usually allocated a single chapter, but to take account of user convenience some of the chapters are geographically based. For example, Chapters 2 and 3 represent sites within a single terrane (or GCR network) which happen to fall within different regions. Areas occurring between site networks, where the Precambrian basement is invariably deeply buried by Phanerozoic strata, can yield important information on the nature of the Precambrian rocks from the sparse coverage of deep boreholes shown in (Figure 1.1).

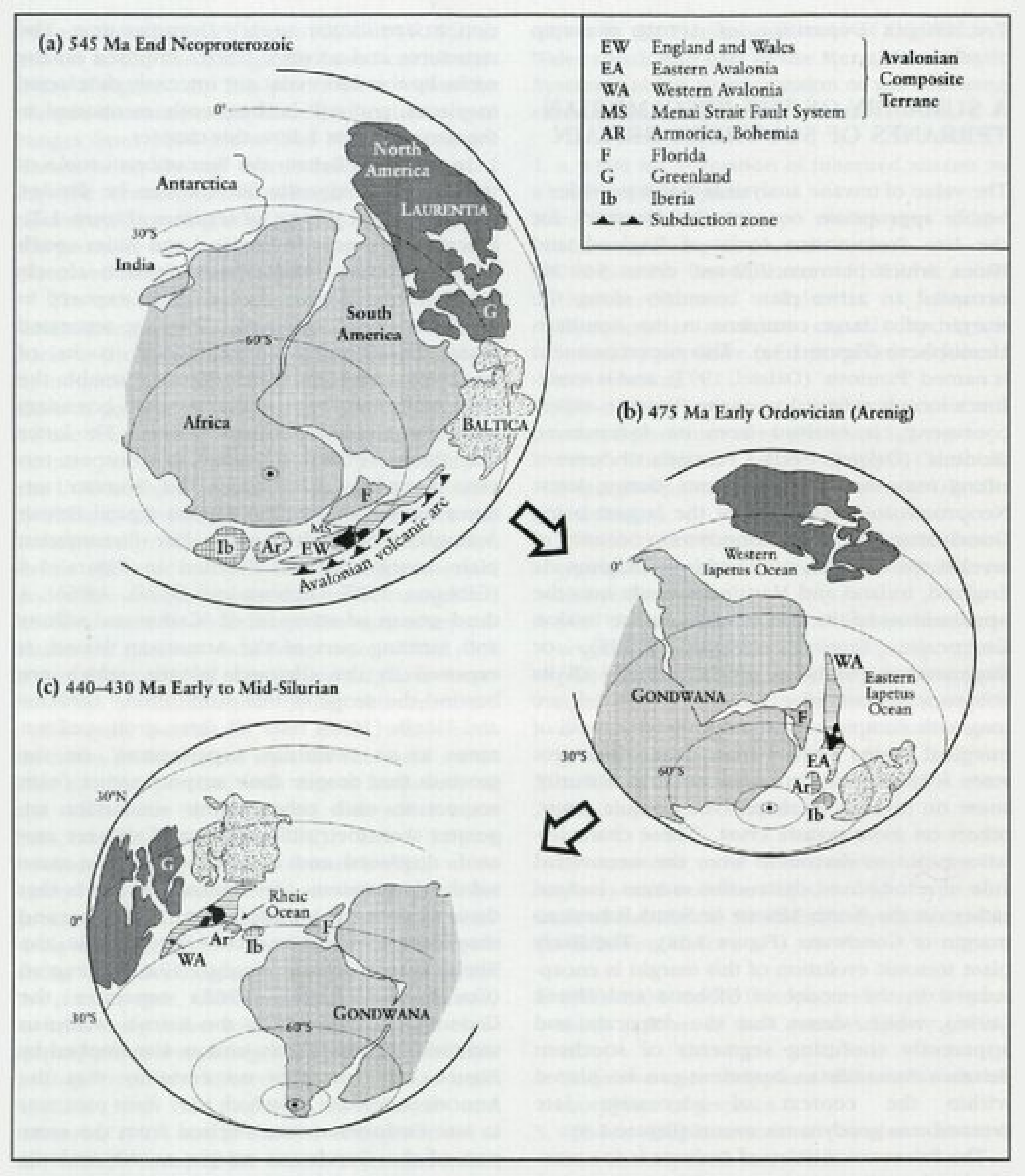
References



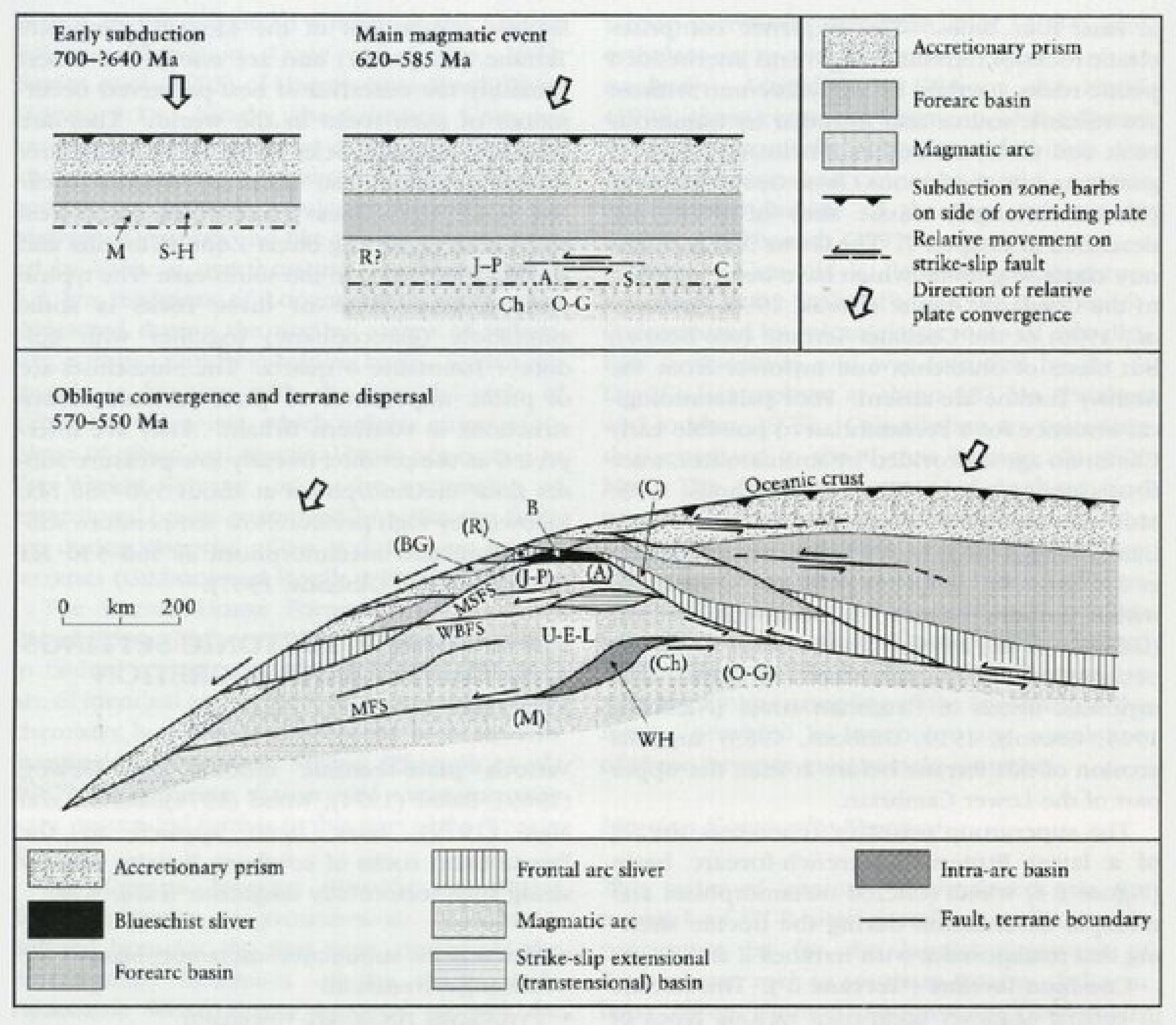
(Figure 1.1) Sketch map showing the distribution of Precambrian outcrop, and boreholes proving Precambrian rocks, in southern Britain. Note that the outcrops are labelled with the names of the principal geological units, followed by numbers (in brackets) of the chapters for the relevant GCR sites. Terrane boundaries are slightly modified after British Geological Survey (1996); Myddfai Steep Belt after Woodcock (1984a); Monian Composite Terrane after Gibbons and Horák (1990). Key: ADF, Aber-Dinlle Fault; BSZ, Berw Shear Zone; CASZ, Central Anglesey Shear Zone; DNF, Dinorwic Fault; LTFZ, Llyn Traffwll Fault Zone; ?NECBF, postulated NE Charnwood Boundary Fault. The boundary of the Midlands Microcraton basement domain is outlined by the NECBF and Pontesford-Myddfai lineament systems; WBFS, Welsh Borderland Fault System.



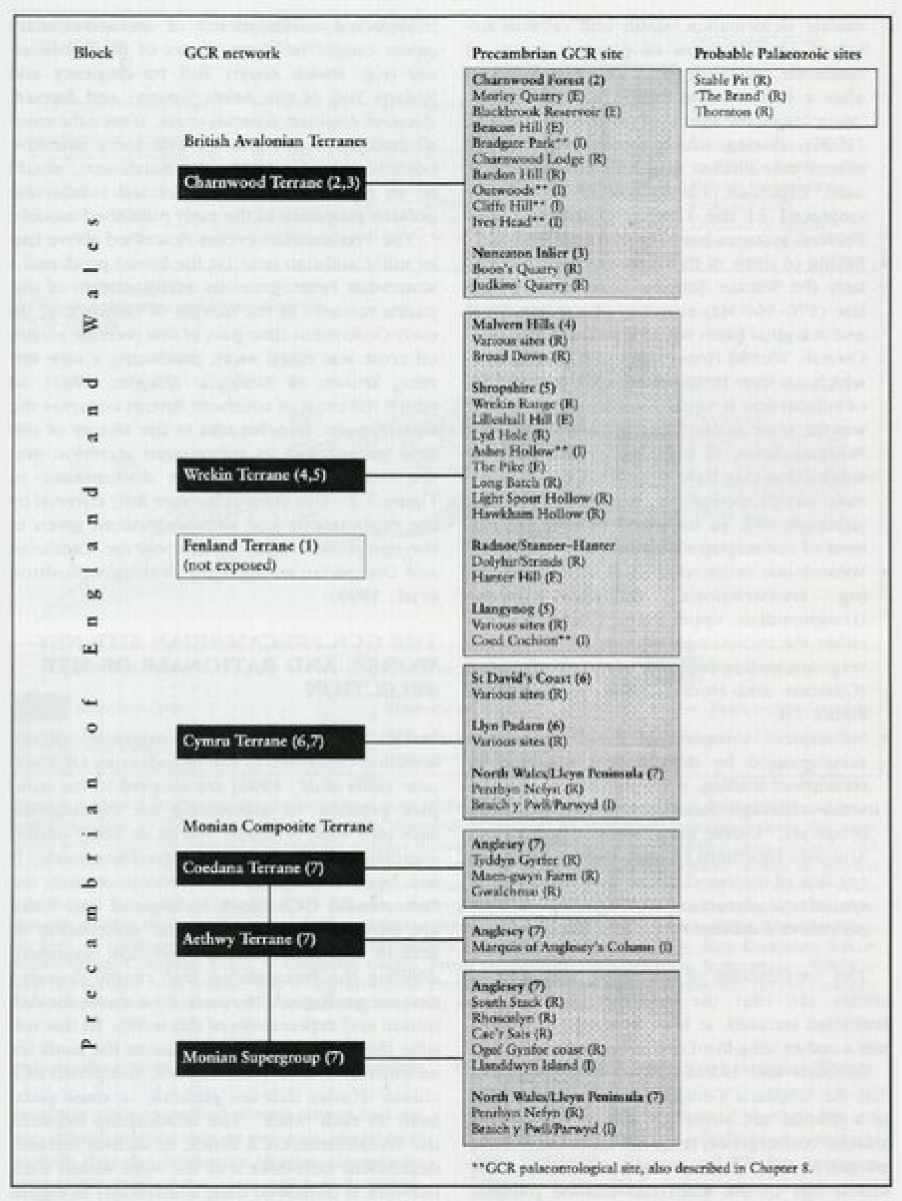
(Figure 1.2) Correlation chart for the late Neoproterozoic history of southern Britain. Key: A, ^{40}Ar–^{39}Ar age; M, U-Pb monazite age; R, Rb-Sr whole-rock isochron age; U, U-Pb zircon age; T_{DM}, Depleted mantle Sm-Nd age; i, inherited zircons. Key to faunas; (E) Ediacaran fossils; (T) Teichichnus trace fossils. Key to horizontal boundaries; continuous line, conformable stratigraphy; wavy line, unconformity; dashed T line, tectonic contact; dashed line, nature of contact uncertain. Terrane boundaries: BSZ, Berw Shear Zone; CASZ, Central Anglesey Shear Zone; LTFZ, Ll■n Traffwll Fault Zone; ML, Malvern Lineament; MSFS, Menai Strait Fault System; ?NECBF, postulated NE Charnwood Boundary Fault; TF, Thringstone Fault;WBFS, Pontesford Lineament of Welsh Borderland Fault System. Literature sources: 1, Patchett and Jocelyn (1979); 2, Patchett et al., (1980); 3, Beckinsale et al., (1984); 4, Thorpe et al., (1984); 5, Davies et al., (1985); 6, Dallmeyer and Gibbons (1987); 7, Tucker and Pharaoh (1991); 8, Noble et al., (1993); 9, Horák et al., (1996); 10, Strachan et al., (1996). Stratigraphical data for Lower Cambrian sequence, and fossil occurrences after McIlroy et al., (1998): nem-Dal, Nemakit-Daldynian; Tom, Tommotian; Atd, Atdabanian; Bot, Botomian; Toy, Toyonian.



(Figure 1.3) Global reconstructions showing the changing palaeogeography of the Avalonian microcontinent from the late Precambrian through to the late Silurian, modified from Dalziel (1997). Models of this type are geologically constrained where possible but the details may change, as more information becomes available. (a) Reconstruction of the Pannotia supercontinent, showing its main components, towards the end of activity of the Avalonian volcanic arc and prior to the Cambrian overstep sequence (Figure 1.2). (b) Conjectural position of Avalonia at the time of the Arenig overstep sequence in England and Wales, and following rifting and the breakup of Pannotia. (c) Situation just before the Acadian deformation, caused by collision when the converging microcontinent of Armorica impinged against Avalonia. Note that Avalonia had earlier 'docked' with Baltica in latest Ordovician time. It was to encroach upon Laurentia in the earliest Silurian, along the line of the Iapetus suture, which is located between the English Lake District and the Southern Uplands of Scotland.



(Figure 1.4) Model for the late Precambrian evolution of the Avalonian subduction system: episodic Precambrian magmatism (top two cartoons) followed by the dispersal of terranes by transcurrent faulting along the plate margin as convergence became increasingly oblique during the latest Precambrian (modified from Gibbons and Horik, 1996). Note that the presence of the Monian Composite Terrane within this system cannot be proved until Arenig time. A = Arfon Group; B = Anglesey blueschists; BG = Bwlch Gwyn Tuff and related strata (Anglesey); C = Coedana Complex; Ch = Charnian Supergroup; J-P = Johnston Plutonic Complex and Pebidian Supergroup; M = Malverns Complex; MFS = Malverns lineament or fault system; MSFS = Menai Strait fault system; O-G = volcanics in Orton and Glinton boreholes; R = Rosslare Complex; S = Sam Complex; S-H = Stanner-Hanter Complex; U-E-L = Uriconian Group, Ercall Granophyre, Longmyndian Supergroup; WBFS = Welsh Borderland fault system; WH = Warren House Formation. The same letters in brackets (lower cartoon) refer to the relative positions of those volcanic belts that were by then extinct.



(Figure 1.5) Diagram showing the relationship between Precambrian terranes, GCR networks and site clusters. Figures in brackets refer to the relevant chapters in which the descriptions occur. Letters in brackets indicate the JNCC scientific 'ranking' of each site (see text for explanation). Note that sites with probable Palaeozoic rocks are treated outwith the main GCR site networks.