# Part 1

## Introduction

# 1

# Regional Geological History: Why and How?

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## 1.1 DEVELOPMENT OF HISTORICAL GEOLOGY IN BRITAIN AND IRELAND

An understanding of the Earth requires a blend of two scientific methods. *Causal* scientific enquiry attempts to understand the fundamental processes of the Earth, irrespective of their age, typically using the analytical methods of physics, chemistry or biology. The geometrical rules of plate tectonics, the fluid mechanics of sediment transport or the chemical evolution of a magma chamber are all examples of such causal principles. Characteristic of geology, however, is its use of *historical* analysis, which recognizes that Earth processes depend on their place in geological time. In particular, geological processes may be strongly influenced by preceding events. So, a new plate boundary may preferentially follow an old weakness in the lithosphere, or the chemistry of a magma will be influenced by the compositional history of the source mantle or crust. Thus *historical geology* can be carried out either on a global scale or, more typically, on a regional scale.

The regional focus of this book, comprising Britain, Ireland and its surrounding crust, has a remarkably varied geology for so small a fragment of continent. This region contains a fine rock record from all the geological periods from Quaternary back to Cambrian, and a less continuous but still impressive catalogue of events back through nearly 2500 million years of Precambrian time. This protracted geological history would be interesting enough to reconstruct if it had been played out in relatively stable continental crust. However, Britain and Ireland have developed at a tectonic crossroads, on crust traversed intermittently by subduction zones and volcanic arcs, continental rifts and mountain belts. The resulting complexity makes the geological history of this region at once fascinating and perplexing.

The coincidence of this complex geology with a scientifically inquisitive human culture was the catalyst

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for a period of prodigious geological discovery and understanding in the late 18th and early 19th centuries. James Hutton was persuaded, by the unconformities that mark Britain's major tectonic phases, of both the longevity and cyclicity of geological events. His *Theory of the Earth* (1795), and its development by John Playfair and Charles Lyell, mark the beginning of modern historical geology. The foundation in London of the world's first Geological Society (1807) provided a forum in which Britain's geological history was rapidly pieced together. William Smith soon published his geological map of England and Wales (1815), based on the principles of correlating strata and their fossils, principles that have become modern stratigraphy. The Geological Survey of Great Britain was formed (1835) to produce a more detailed geological map of the country, and a few years later came Richard Griffiths' geological map of Ireland. At about the same time began the collaboration, and later confrontation, between Roderick Murchison and Adam Sedgwick, which resulted in the establishment of the Cambrian (1835), Silurian (1835) and Devonian (1839) systems and, through Charles Lapworth's eventual mediation (1879), the Ordovician System.

For a century and a half, therefore, Britain, Ireland and the European countries that host the type areas for Carboniferous and higher systems have provided a reference region for global geological history. This is justification enough to maintain an up-to-date understanding of the regional geological history; but there are other reasons.

## 1.2 WHY STUDY HISTORICAL GEOLOGY?

The rapid 19th-century growth of historical geology in Britain was partly stimulated by the search for and exploitation of geological resources, mainly metallic minerals and coal. This economic stimulus was revitalized in the 1960s with the exploration for offshore oil and gas resources. Finding petroleum requires an accurate knowledge of the stratigraphy and geometrical structure of a prospective area. However, any programme of exploration and production also needs detailed reconstructions of the geological history of the area, particularly of sedimentary environments and of the diagenetic, thermal and deformation history of the resulting rock sequence. The geological histories that are available for all onshore and most offshore areas of Britain and Ireland provide the essential basis for planning local investigations for geological resources. The results from exploration reveal, in turn, new details or even major modifications to the regional geological history. This modern symbiosis between academic and commercial interests has advanced understanding of the geological history of Britain and Ireland at a rate unprecedented since the 19th century.

Older even than the study of historical geology has been the search for the fundamental causal laws of how Earth works. Hutton and Lyell tried to use specific examples of local or regional geological history to diagnose and illustrate global geological principles. However, despite Lyell's uniformitarian principle that 'the present is the key to the past', our understanding of Earth processes relies heavily on knowledge of their historical context. The atmosphere, oceans, climate, biota, crust and mantle have all evolved through Earth history, so that many of their more complex processes depend on what came before them. A regional geological history, such as that of Britain and Ireland, provides the time frame for understanding the context of process-orientated research. Moreover, the feedback from this research stimulates the refinement of geological histories in the same way as the exploration for economic resources.

There is a third, less tangible, reason for studying regional geological history: the distinctive intellectual challenge and discipline of the study itself. Philosophers of science have struggled to characterize the way that a geologist works and thinks. Having identified physics as the quintessential science, they have typically measured other sciences against its supposed objectivity, predictability and precision. Geology has therefore been viewed merely as a derivative and imprecise form of physics. In practice, geologists rarely work solely by the process of deductive and inductive logic that we call the scientific method. Geology has an essential historical dimension, which distinguishes it from pure physics, chemistry or biology. The geological record is inevitably complex and incomplete, and deciphering it requires an interpretative reasoning similar to that applied to human history. A geological history is charted that best fits the available observations; then it is iteratively improved, revised or rejected as new data become available. Interpretative reasoning is criticized, particularly by pure scientists, for its circularity. However, it has the overriding strength of being the way in which our human understanding of most everyday problems is built up. Geologists are therefore well equipped to solve complex problems that occur at the interface between science and society.

## 1.3 ARRANGING AND DATING EVENTS: STRATIGRAPHY

How is a regional geological history reconstructed? Sections 1.3–1.6 outline the relevant methodology. This introduction is brief, because a comprehensive introduction would become a textbook of geology in itself. Any history is potentially a synthesis of all available geological information, and no type of evidence is irrelevant. This chapter stresses only general principles, but provides pointers to more detailed topics together with suggestions for further reading.

The rock record is made of igneous, sedimentary and metamorphic rocks, with a geometrical arrangement due partly to their original formation and partly to their later deformation. The first step in charting any geological history is to translate this rock geometry into a sequence of geological events through time. This interpretation uses a set of assumptions (Fig. 1.1) sometimes described, perhaps too formally, as the laws of stratigraphy. So, the principle of *superposition* is that younger rocks in a bedded sequence overlie older rocks, and that of *inclusion* is that younger rocks may include fragments of older rocks. *Cross-cutting* relationships are generally such that younger features – typically rock bodies or faults – cut across older features. The assumption of *lateral continuity* allows units to be matched across intervening faults, intrusions or other interruptions. Igneous rocks are dated by the rule of *extrusion* – that the age of an extrusive unit in a bedded sequence lies between that of underlying and overlying units – and the rule of *intrusion* – that intrusive bodies are younger than any country rocks that they cut. The assumption of *original horizontality*, at least for many sedimentary units, determines that most tilted or folded rocks have been later deformed. The principles of *deformation and metamorphism* are that these events are younger than the rocks that they affect.

A catalogue of successive geological events can be reconstructed for most regions of the Earth, however complex. More sophisticated stratigraphic subdivision can be achieved in areas dominated by bedded sedimentary or volcanic rocks, and their deformed equivalents. In an example from the Lower Palaeozoic of Cumbria (Fig. 1.2) strata are shown as a graphic log, subdivided into named units. This *lithostratigraphic* division is based on rock characteristics observable in the field, for instance composition, grain size, colour, primary textures and structures. The basic subdivision is into *formations*, which are units distinctive enough to be mapped over at least tens of kilometres.

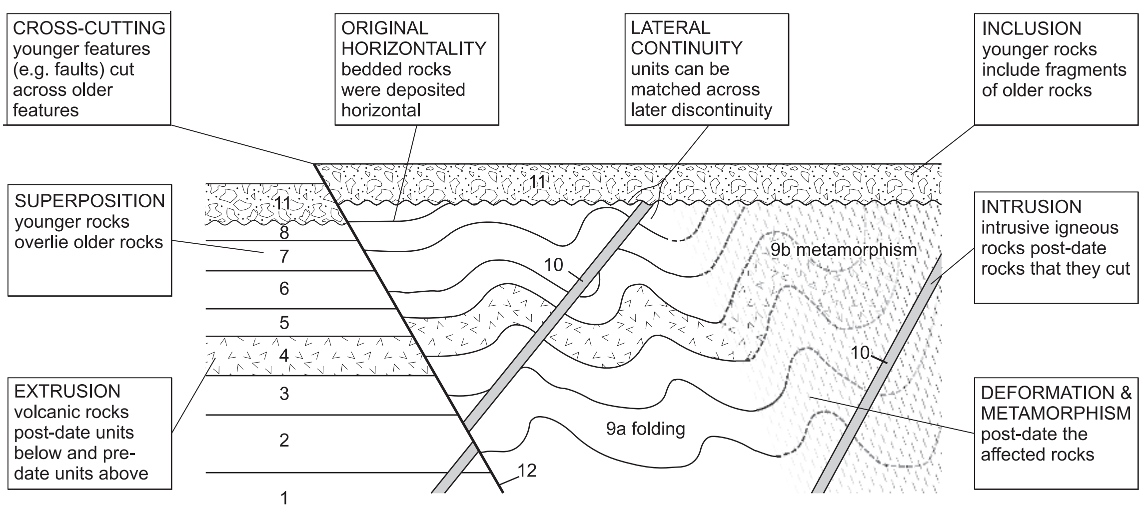


**Fig. 1.1** Cross-section illustrating the rules of stratigraphy, which allow rock geometry to be translated into a sequence of events (numbered 1–12).

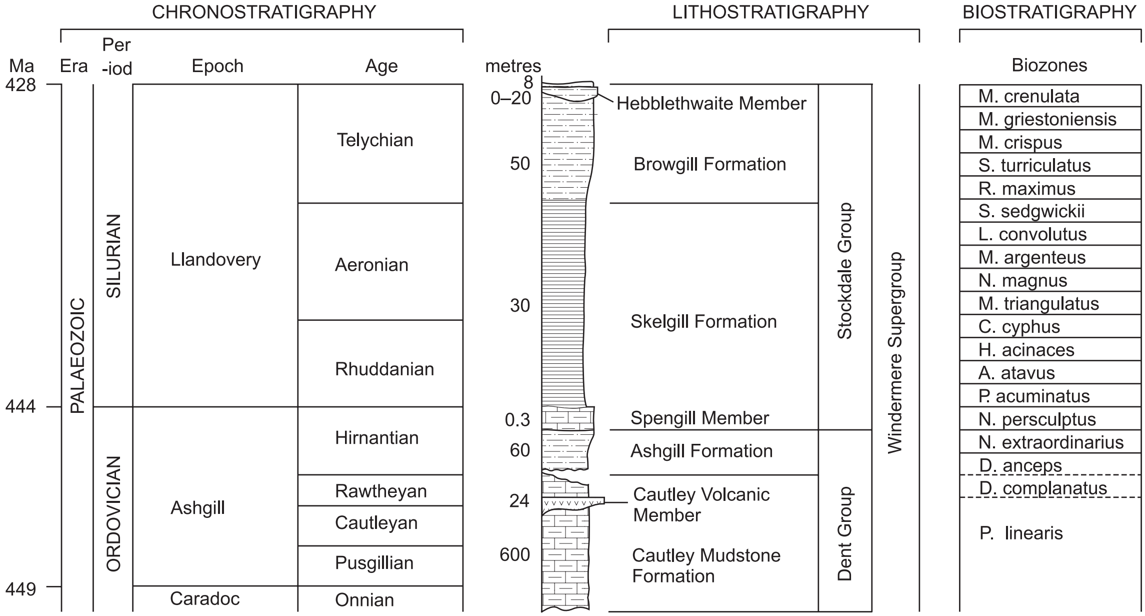


**Fig. 1.2** The different components of formal stratigraphic procedure in bedded rocks, illustrated with part of the Windermere Supergroup, north-west England.

Formations are one level in a hierarchy of lithostratigraphic units, each named after a typical geographical locality. So, three of the Cumbrian formations (Fig. 1.2) contain locally mappable, though regionally discontinuous, *members*. The formations are gathered into two *groups*, and the groups into a *supergroup*. In other areas, intrusive and metamorphic rocks may be too complicated to subdivide on such a scheme, and may be designated as *complexes*.

Rock sequences can be subdivided on criteria other than their lithological character, for instance by their magnetic or chemical properties. An example is the oxygen isotope *chemostratigraphy* used to calibrate and subdivide Quaternary sequences. However, fossil content is the prime discriminator in most sedimentary rocks. In the example in Fig. 1.2, graptolites have been used to define a *biostratigraphic* division into *biozones*. Each zone is named after a distinctive species of index fossil, typically in a larger assemblage of other species. Other available fossil groups yield their own independent zonation.

In Cambrian and later rocks, fossils usually provide the most important tool for correlating the local rock sequence with a global or regional stratotype sequence, and assigning a *chronostratigraphic* age. Chronostratigraphic names are arranged in two hierarchies (Fig. 1.2), one used for the standard intervals of time (*era*, *period*, *epoch*, *age*) and the other for the volumes of rock formed during those intervals (*erathem*, *system*, *series*, *stage*). In the example (Fig. 1.2) the top of the Spengill Member of the Skelgill Formation is equated with the base of the Llandovery Series, because the global stratotype for this boundary, in the Southern Uplands of Scotland, defines it at the base of the *acuminatus* Biozone. International agreement has nearly been achieved on the names and type sequences of all stages. Even so, difficulties of correlation with the type sequences mean that many local chronostratigraphic names will still be used. A chronostratigraphic chart for Britain and Ireland (Fig. 1.3) reflects the mix of international and local names used in this book, and is supplemented by more detailed stratigraphic diagrams in individual chapters.

The chronostratigraphic scale can be calibrated in millions of years, based on radiometric dating of the type sequences or of other correlated sections. A number of methods are now available (Table 1.1) for the dating of geological events as diverse as the

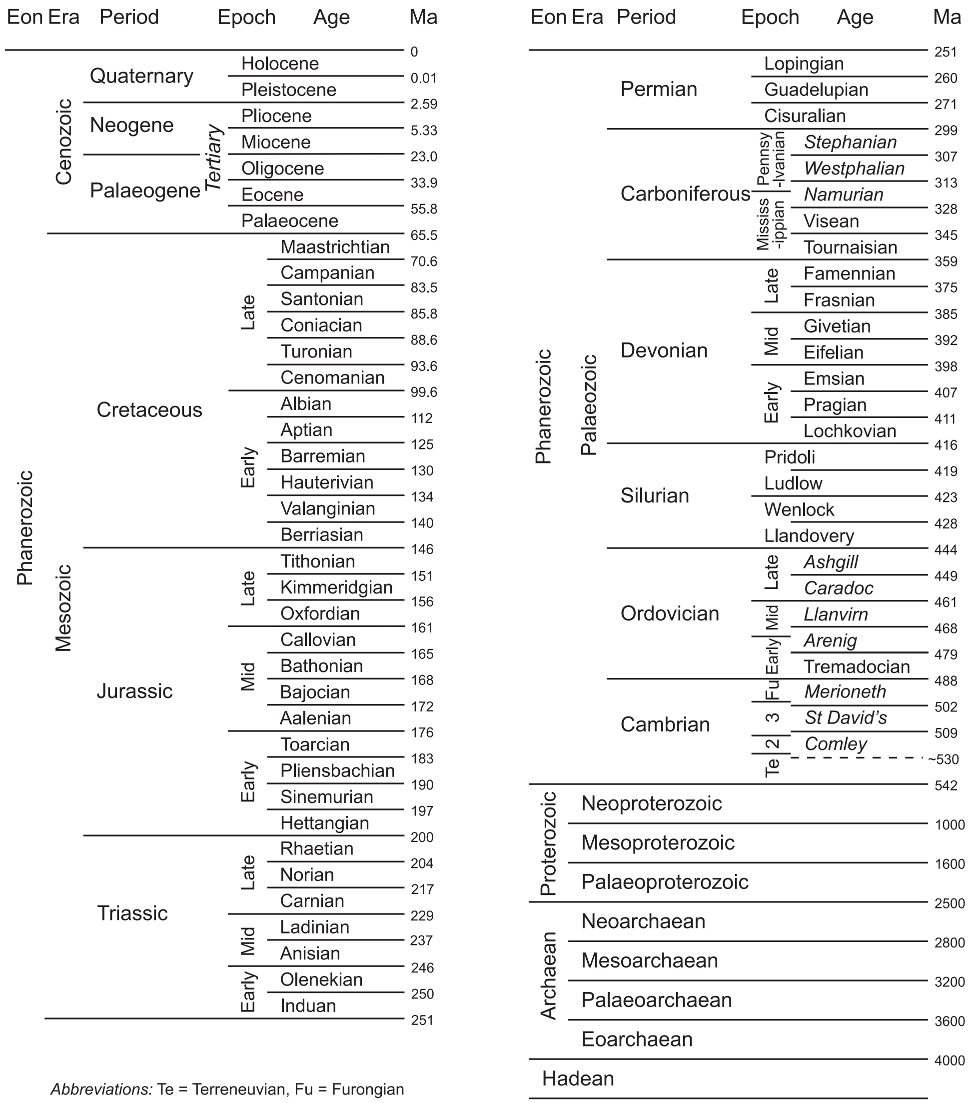


**Fig. 1.3** A chart of chronostratigraphic names commonly used in Britain and Ireland, together with their chronometric calibration in millions of years before present (Ma) (data from Ogg *et al.* 2008).

age of high-grade metamorphism in Precambrian gneisses (using uranium and lead isotopes in zircon) and the formation of peat and charcoal in Quaternary sedimentary rocks (using carbon-14). Recent improvements in analytical techniques mean that it is now possible to date the crystallization of minerals such as zircon to a precision of 1 or 2 million years, even in the oldest Precambrian rocks.

The resulting ***geochronometric*** age can be derived from a local rock sequence only if it contains radiometrically datable rocks. The radiometric ages of lava flows and volcanic ashes, for example, correspond closely to the ages of interbedded sedimentary rocks. The dating of bentonites, clays derived from volcanic ash, has allowed accurate dating of the part of the Early Palaeozoic time-scale in Fig. 1.2. Radiometric

**Table 1.1** The principal methods of radiometric age determination referred to in this book.

| Isotopic system | Useful age range | Commonly dated materials |
|---|---|---|
| Carbon-14 | <40000 years | Wood, peat, charcoal, carbonate shells |
| Potassium–argon (K–Ar) | >100000 years | Muscovite, biotite, hornblende, glauconite, whole volcanic rocks |
| Rubidium–strontium (Rb–Sr) | >5 million years | Microcline, muscovite, biotite, whole igneous or metamorphic rocks |
| Uranium–lead (U–Pb) | >5 million years | Zircon, monazite, titanite, baddeleyite |
| Samarium–neodymium (Sm–Nd) | >250 million years | Pyroxene, garnet, whole igneous or metamorphic rocks |

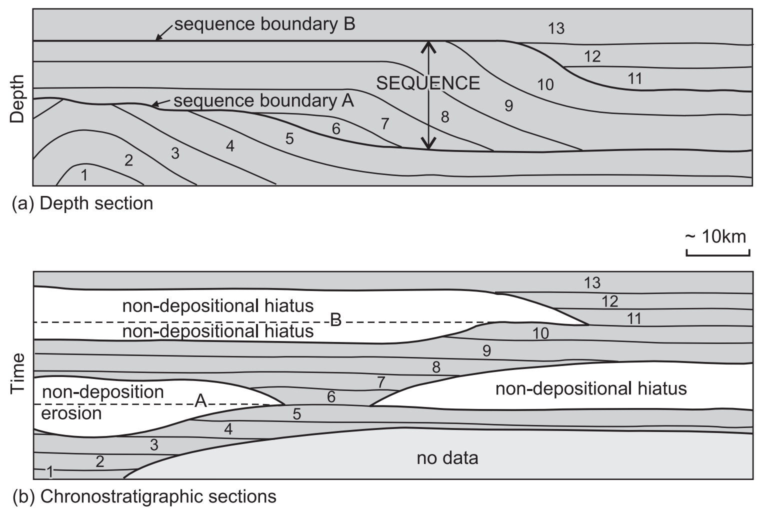


**Fig. 1.4** The essential features of a depositional sequence in sedimentary rocks, shown in a depth section (a) and a corresponding chronostratigraphic (time) section (b).

dating is the only usable stratigraphic method in many unfossiliferous successions, particularly in the Precambrian where the boundaries of chronostratigraphic units are mostly defined as precise but arbitrary ages in millions of years. Even in the Phanerozoic, the radiometric calibration of chronostratigraphic boundaries is necessarily subject to errors, both from the analytical procedures and from interpolation to the boundary from dated rocks below and above it. These errors are reflected in the use, in other parts of this book, of some ages that differ in detail from those on the time chart (Fig. 1.3).

The stratigraphic methods described so far have primarily been developed onshore, where limits of exposure typically provide a one- or at best two-dimensional transect through rock successions. A method particularly applied to the offshore successions around Britain and Ireland is *seismic stratigraphy*, based on the successive geometry of surfaces visible on reflection profiles. To be interpreted correctly, these reflectors must be tied to recorded lithostratigraphy in a borehole. Then, arrays of seismic profiles provide at least a two-dimensional and often a three-dimensional image of stratigraphic relationships. Key surfaces are those that appear to truncate adjacent sets of reflectors. If reflectors are taken to be time-surfaces, these discordant surfaces must be unconformities, marking times of non-deposition or erosion.

Although best visualized in seismic sections, the method of subdividing rock successions using their contained unconformities can be applied to bedded rocks more widely, and forms the basis of *sequence stratigraphy.* A sequence, in this strict sense, is a packet of strata, bounded above and below by unconformities or their laterally continuous surfaces in conformable successions (Fig. 1.4). The unconformities can be due to non-deposition or to a component of erosion. In either case the time-gap (hiatus) is generally taken to represent a relative lowering of sea level. The hypothesis that important changes of sea level may be eustatic and of global extent has provided a basis for inter-regional correlation, and for the construction of global reference curves of sea-level change. Alternatively, the sequence boundaries offer important evidence for regional tectonic events.

Sequence stratigraphy is applied most widely in the weakly deformed Upper Palaeozoic, Mesozoic and Cenozoic successions that can readily be seismically imaged around Britain and Ireland. However, the subdivision of successions along their contained unconformities can be applied to earlier successions too and, on a large scale, forms the basis for the subdivision of this book (see Section 1.7).

## 1.4 LOCATING EVENTS IN SPACE: PALAEOGEOGRAPHY

One of the main challenges of reconstructing geological histories is that rock successions are rarely preserved at the site of their original formation. The latitude, longitude and orientation of the crustal fragment on which the rocks lie will have changed because of global plate motions, and its relationship to adjoining fragments may have altered because of regional tectonic displacements. Proper portrayal of geological history requires palaeogeographic maps, showing the shifting arrangement of the continental crustal pieces that mainly host the preserved geological record.

The most conspicuous indicators of changed palaeolatitude in a sedimentary sequence are lithologies that tend to form in a restricted climatic belt. Most obviously, glacial tillites are deposited in polar and high temperate latitudes (Fig. 1.5). Coals form from the abundant vegetation of both the equatorial and the temperate rainy belts, whereas evaporites need the warmth and low rainfall of the intervening arid subtropical belt. Limestones are most common in the equatorial, subtropical and warm temperate belts where sea-water temperatures are high and sunlight can penetrate effectively. Phosphorites and continental red beds also tend to occur in low latitudes. The northward drift of Britain and Ireland through much of Phanerozoic time is evident from such facies changes. Particularly clear is the transit from the southern arid subtropics, producing Devonian red beds, across the Carboniferous equator, with its abundant coals, to the

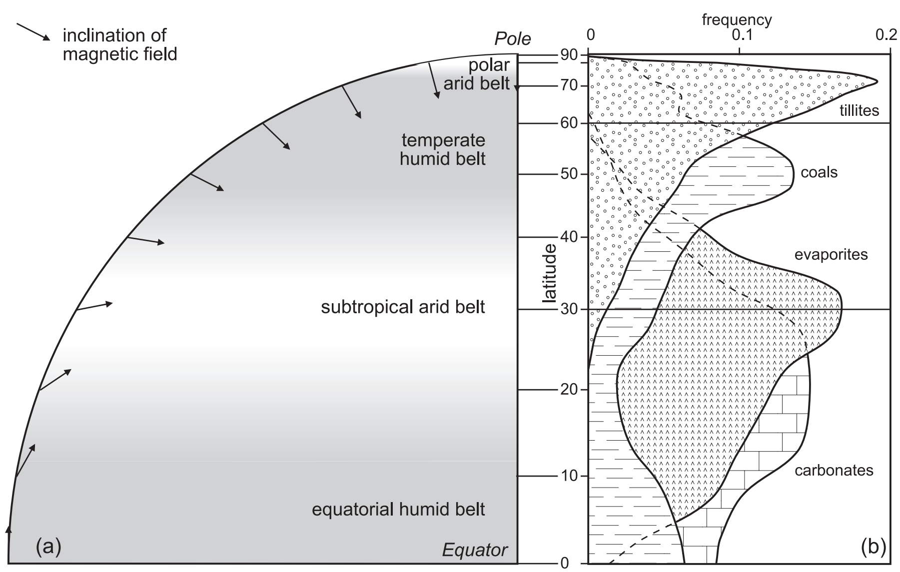


**Fig. 1.5** (a) The main climatic belts of the Earth, with the varying inclination of the magnetic field with latitude. (b) The frequency of climatically sensitive lithofacies formed at different latitudes (Mesozoic and Cenozoic data from Scotese & Barrett 1990).

northern arid belt recorded by Permo–Triassic red beds and evaporites. However, many more subtle latitudinal influences will be noted in this book.

A seemingly more precise measure of palaeolatitude can be obtained from rocks containing mineral grains that align with Earth's magnetic field. Because this field is a dipole, on average centred at the geographical pole, the direction of the measured palaeomagnetic field records the rotation of the site with respect to longitude lines. Because the inclination of the present field varies systematically with latitude (Fig. 1.5), the measured inclination of an old field with respect to a palaeohorizontal, such as sedimentary bedding, yields the palaeolatitude. In deformed rocks, the identification of the appropriate palaeohorizontal datum may be problematical. Errors may also arise by overprinting of one magnetic record by another, typically during metamorphism. However, the main uncertainty in using palaeomagnetic data to make maps is the unconstrained longitude of each crustal fragment. The global palaeogeographic maps in this book should be viewed critically in the knowledge that each fragment could, on palaeomagnetic evidence, lie anywhere along the same latitude band. In practice, geological matches or mismatches between continents can be used to further constrain their positions, but these qualitative criteria often prove to be controversial.

A third way of diagnosing palaeolatitude is from the global distribution of faunal and floral assemblages. Climatic control of present biogeography is particularly evident in land plants, shallow marine benthic organisms, and in the plankton that live high in the marine water column. These groups are more responsive to latitudinal climate change than is the deep-water benthos that occurs on the outboard margins of continents. Distributions of appropriate fossil organisms may therefore reveal biofacies restricted to particular palaeolatitudes. The cold-climate *Glossopteris* flora was one of the first clues that the southern continents once formed a unified Gondwana in high southern latitudes. Latitude-controlled assemblages are now most used to check and refine palaeomagnetically derived continental maps (e.g. Fig. 1.6), particularly in the Palaeozoic where reconstructions are more loosely constrained than for later eras.

More useful even than the control on biofacies by latitude is that by continental separation. In the early Ordovician example (Fig. 1.6), distinct benthic trilobite assemblages occur on different continents in the same equatorial latitudes. Hence Laurentian faunas are distinct from those at the low-latitude end of Gondwana.

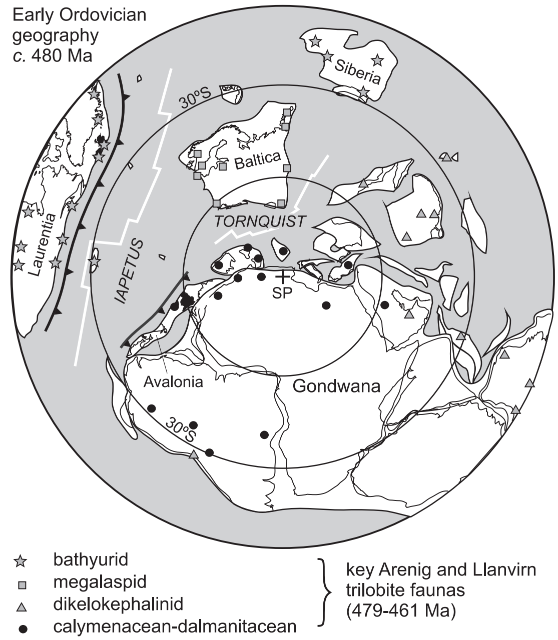


**Fig. 1.6** Early Ordovician (Arenig–Llanvirn) platform trilobite assemblages, showing control both by palaeolatitude and continental separation (modified from Cocks & Torsvik 2002).

However, based on the biofacies evidence alone, Siberia might be arranged closer to Laurentia, which has a similar trilobite fauna. Such arguments depend crucially on knowledge of the palaeoecology of the organisms concerned. For example, early Ordovician pelagic trilobites were not confined by oceanic barriers and show a simple latitudinal control.

Both palaeomagnetic and faunal criteria can identify not only displacement of continents with respect to one other but also mismatches between smaller crustal fragments. Strong contrasts in stratigraphic or tectonic sequences between two areas, now juxtaposed across a major fault, may also suggest that they formed some distance apart. A fault-bounded volume of crust with an internally coherent geological history is called a *tectonostratigraphic terrane*. Britain and Ireland are commonly divided into about 10–15 Neoproterozoic to Early Palaeozoic terranes (see Section 2.3.1), although large separations cannot be proved between all adjacent terranes. The date of amalgamation of two terranes can be recognized from a distinctive event common to both areas (Fig. 1.7). Examples are a shared metamorphic event, a pluton intruded or a sedimen-

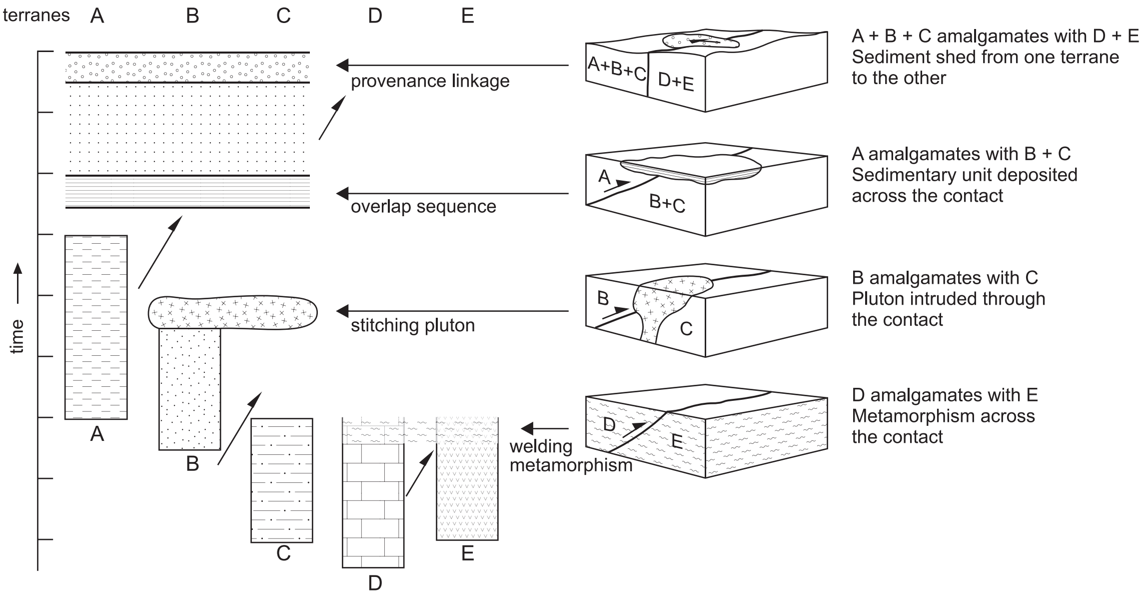


**Fig. 1.7** Hypothetical assembly diagram for five terranes, showing four major ways of recognizing terrane linkage (modified from Howell 1989).

tary sequence deposited across the dormant terrane boundary, or a sedimentary unit on one terrane containing distinctive clasts derived from the other. The sense of displacement on the terrane-bounding faults is a guide to the former relative locations of the terranes, but the magnitude of the original separation may be uncertain.

The palaeogeographic maps of Britain and Ireland in this book try to show the major oceanic separations between continents, although not usually to scale. The maps also indicate known terrane boundaries, although typically not the restored positions of the terranes. All maps up to and including the Variscan Orogeny (latest Carboniferous) must be viewed with the possibility of subsequent terrane displacements in mind. Most maps do not attempt to correct for more local crustal deformation, such as the extension as sedimentary basins form or the shortening or shear across them as they are destroyed. These displacements are on a scale comparable to the sedimentary systems and igneous or metamorphic provinces that form the next level of detail on a palaeogeographic map. By ignoring such local tectonic deformation, the size and shape of geological elements may be distorted on a map, but not their internal topology or their relationship to other elements.

## 1.5 SPECIFYING GEOLOGICAL ENVIRONMENTS

Once geological events are adequately located in space and time, the next stage in reconstructing a history is to identify the proper geological environment for each event. Were the components of a sedimentary rock deposited on a delta or a turbidite fan? Was an intrusive rock formed beneath a continental volcanic arc or within ocean crust? It is the spatial pattern of these environments that provides the detail on a palaeogeographic reconstruction, and it is the changing patterns through successive time intervals that bring geological history to life. This section briefly reviews the sorts of environmental classifications that are useful on the scale of regional geological reconstructions.

### 1.5.1 Sedimentary environments

The first level of interpretation of sedimentary rocks is into *facies*, comprising units with similar specified characteristics; for instance a graded sandstone facies or a laminated mudstone facies. However, individual facies are generally too localized or change too frequently to be useful in describing regional geological history.

Facies typically occur with others in *facies associations*, which can more easily be assigned to a particular depositional environment. Hence, a facies association of massive sandstone, graded sandstone and laminated mudstone might be regionally extensive and diagnosed as the product of a deep-sea turbidite system. This is the scale of environmental system that is useful in regional reconstructions. There is no one definitive classification of depositional environments, but a typical subdivision is shown in Table 1.2a.

Outcrop-scale observations, or their equivalent in cores or downhole log records, are the primary data for diagnosing the environment of deposition of a sedimentary rock. By contrast, petrographical or geochemical observations help to identify the source of the detritus in a sedimentary basin, and to specify its broader tectonic setting. The relative proportions of quartz, feldspar and lithic grains in sandstones have proved to be particularly useful (Table 1.2b). Sand derived from large continents tends to be mineralogically mature, and therefore rich in quartz and poor in rock fragments. By contrast, arc-derived sandstones are immature, and rich in feldspar and volcanic rock fragments. Sandstones derived from active orogenic belts – subduction complexes, collision zones and foreland uplifts – have an intermediate maturity with a mixture of quartz and sedimentary rock fragments.

With modern analytical methods, the ages of some individual sedimentary grains can be found accurately and in abundance. Zircon grains are particularly stable and sufficiently common to provide age distributions for the detritus in a sedimentary unit. These age spectra are often distinctive enough of particular source terranes to discriminate between competing tectonic models for restoring continental geometry.

### 1.5.2 Igneous environments

Igneous rocks are classified into plutonic and volcanic types, and further subdivided on the basis of their mineralogy. However, as for sedimentary rocks, rock type alone is of limited use in reconstructing geological environments because some igneous rocks occur in several different tectonic settings. More usefully, several igneous rock types may occur together in a petrogenetically related *magma series*, diagnostic of a particular tectonic environment (Table 1.3). Magmas of the calc-alkaline series are at present restricted in their occurrence to magmatic arcs above subduction zones. Calc-alkaline geochemistry in ancient igneous rocks is therefore an important indication of their likely tectonic setting. Such sequences tend to include a wide variety of basic, intermediate and acidic rock types, both volcanic and plutonic. By contrast, oceanic ridge

**Table 1.2** Classification schemes for: (a) depositional environments (based on Reading, 1996); (b) provenance of clastic source material (scheme of Dickinson & Suczek 1979).

**(a) Depositional environments**

| Environment | Sub-environment examples |
|---|---|
| Glaciers | Sub- and supra-glacial<br>Glaciofluvial<br>Glaciolacustrine<br>Glaciomarine |
| Alluvial systems | Rivers<br>Levees and floodplains<br>Alluvial fans |
| Lakes | Clastic systems<br>(Bio)chemical systems |
| Desert aeolian systems | Dune fields<br>Sand sheets |
| Clastic coasts | Deltas<br>Non-deltaic coasts |
| Arid shorelines and basins | Sabkhas<br>Evaporite basins |
| Shallow seas | Clastic systems<br>Carbonate systems |
| Deep seas | Clastic systems<br>(Hemi)pelagic systems |
| Volcanoes | Pyroclastic systems |

**(b) Environment of sediment provenance**

| Tectonic setting | Provenance type |
|---|---|
| Continental (quartz + feldspar, low lithics) | Craton interior<br>Transitional<br>Uplifted basement |
| Magmatic arc (feldspar + lithics, low/moderate quartz) | Dissected<br>Transitional<br>Undissected |
| Recycled orogen (quartz + lithics, low/moderate feldspar) | Subduction complex<br>Collisional orogen<br>Foreland uplift |

**Table 1.3** Characteristic magma series associated with specific tectonic settings (based on Wilson 1989).

| Tectonic setting | Plate margin | | Within plate | |
|---|---|---|---|---|
| | Convergent | Divergent | Intra-oceanic | Intracontinental |
| Volcanic feature | Island arc, active continental margin | Mid-ocean ridge, back-arc spreading centre | Oceanic island | Continental rift zone, continental flood-basalt province |
| Characteristic magma series | Tholeiitic<br>Calc-alkaline<br>Alkaline | Tholeiitic | Tholeiitic<br>Alkaline | Tholeiitic<br>Alkaline |
| $SiO_2$ range | Basalts and differentiates | Basalts | Basalts and differentiates | Basalts and differentiates |

**Table 1.4** Classification scheme for metamorphic environments (based on Duff 1993).

| Type of metamorphism | Diagnostic features |
|---|---|
| *Local metamorphism* | |
| Contact metamorphism | Metamorphic rocks are found adjacent to and clearly related to an igneous body |
| Dynamic metamorphism | Metamorphism is associated with a zone of strong deformation (fault or shear zone) |
| Impact metamorphism | Metamorphism is associated with the impact on Earth of an extraterrestrial body |
| *Regional metamorphism* | |
| Orogenic metamorphism | Metamorphic rocks are associated with zones of mountain building |
| Oceanic metamorphism | Metamorphism of ocean crust by injection of basic magmas and circulation of hydrothermal fluids at spreading ridges |
| Burial metamorphism | Metamorphism due to sufficient burial in a thick sedimentary basin succession |

systems have a more restricted range of magma types dominated by the low-potassium, subalkalic basalts known as tholeiites. Tholeiitic basalts are also found in intraplate tectonic settings such as oceanic islands and intracontinental rifts. In these cases, they commonly form part of a bimodal igneous suite together with alkaline types such as trachytes. Detailed study of the nature, relative proportions and geochemistry of ancient magma types may therefore shed light on their likely tectonic setting.

### 1.5.3 Metamorphic environments

Metamorphic mineralogies and textures are controlled by temperature, pressure and deviatoric stress, which in turn are related intimately to tectonic setting. Some specific metamorphic minerals are diagnostic of certain tectonic settings and/or processes. Glaucophane, for example, is invariably found within the low-temperature, high-pressure metamorphic sequences characteristic of subduction zones. Coesite is diagnostic of the ultra-high pressures typical of either the deep roots of mountain belts or impact craters. In general, however, most metamorphic minerals can be found in a number of different tectonic settings. One way of classifying metamorphic rocks is by use of mineral assemblages to define *metamorphic facies*. An alternative and potentially more useful approach from a regional tectonic viewpoint is to use a combination of field mapping and petrological studies to differentiate between the different settings which have led to metamorphism. Broad categories of local and regional metamorphism can be distinguished according to whether the metamorphic rocks are clearly limited in area and related to a localized event, or are of large areal extent. Each of these categories can be subdivided according to setting (Table 1.4).

### 1.5.4 Structural regimes

Structural observations, when integrated over a large area, typically allow a phase of crustal deformation to be assigned to a particular, regionally consistent, structural regime (Table 1.5a). The three end-member regimes are contractional, extensional and transcurrent, although intermediate transpressional and transtensional regimes are common. Certain types of small-scale structures are common in each regime, although heterogeneity of the deformation can give, for instance, locally extensional zones in a regionally contractional regime. The most complex structural settings are orogenic belts, which may display an evolutionary history lasting several tens of millions of years. Studies in young mountain belts, for example the Himalayas, show that the fold and thrust nappes related to contraction during the early stages of collision may be overprinted by transcurrent structures developed during the later 'locking-up' of colliding blocks. Furthermore, the central parts of many mountain belts have undergone a late phase of extensional deformation that results from gravitational instability following the main contraction and crustal thickening. Older mountain belts have typically undergone uplift and erosion, and the orogenic roots so exposed give a valuable insight into the history of the mid-crust.

**Table 1.5** Classification scheme for: (a) regional deformation regimes; (b) plate tectonic settings.

**(a) Tectonic regimes**

| Tectonic regime | Examples of structures |
|---|---|
| Contractional | Reverse faults and thrusts<br>Flexural or fault-related folds<br>Steep low-grade fabrics<br>Reverse ductile shear zones<br>High-grade fabrics |
| Extensional | Planar/listric normal faults<br>Fault-related folds or tilt blocks<br>Low-dip ductile shear zones<br>Low-dip high-grade fabrics |
| Transcurrent | Strike-slip or oblique-slip faults<br>Folds ± oblique fabrics<br>Ductile strike-slip shear zones<br>Steep fabrics and folds |

**(b) Plate tectonic settings**

| Kinematic setting | Examples of components |
|---|---|
| Divergent plate boundary | Ocean ridge/transform<br>Continental rift<br>Aulacogen or failed rift |
| Convergent plate boundary | Trench/subduction complex<br>Fore-arc basin<br>Inter-arc/back-arc<br>Foreland basin |
| Continental collision zone | Foreland basin<br>Hinterland basin |
| Conservative plate boundary | Oceanic transform<br>Continental margin transform<br>Continental transform |
| Intraplate regions | Ocean floor<br>Continental craton |

### 1.5.5 Plate tectonic setting

One large-scale goal of historical geology is to diagnose a particular plate tectonic environment or subenvironment for each chapter of a regional story (Table 1.5b). This diagnosis is only possible from a synthesis of all the available geological evidence. There are a number of problems inherent in such a synthesis. A major difficulty is that plate tectonics operates at a much larger scale than that of even regional geology. This difficulty is strikingly shown by superposing an outline of Britain and Ireland onto a present-day tectonic map of Asia (Fig. 1.8). There, different local tectonic settings – varying from convergence, through strike-slip to extension – all derive from one overall process, which is the collision of India and Asia. By studying only one part of the Asian region we would diagnose only one component of the overall plate tectonic setting. Any plate tectonic analysis of Britain and Ireland must therefore consider the regional context by examining adjacent areas.

A further problem is that some plate tectonic settings are inevitably destined to be destroyed or overprinted. For instance, ancient ocean floor or ridge/transform settings are only likely to be preserved as minor ophiolitic fragments in later orogenic belts. Indeed, the consensus is that most ophiolites are likely to represent back-arc or fore-arc basin crust than oceanic crust *sensu stricto*. Finally, it is apparent that in many mountain belts the original relations between adjacent crustal blocks have been obscured by major

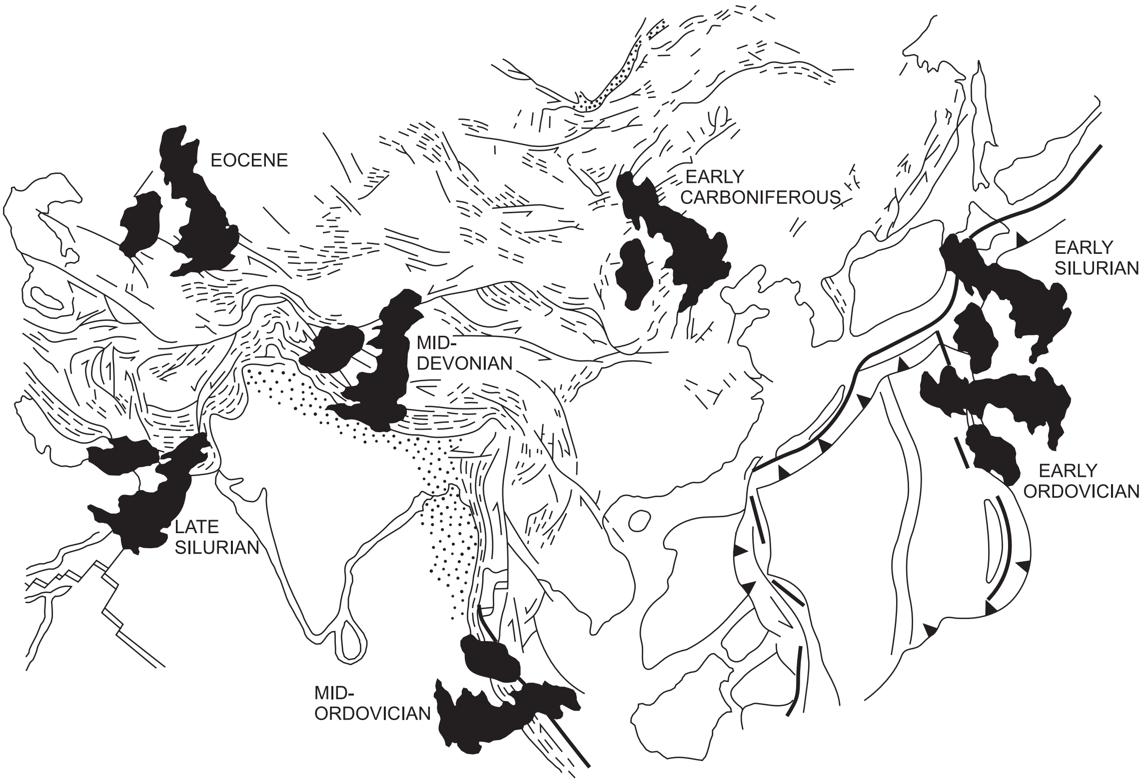


**Fig. 1.8** Structural map of present-day Asia, with Britain and Ireland superimposed in analogous tectonic positions (modified after Dewey 1982) for particular periods of geological time. The juxtaposition highlights the scale problem in diagnosing the plate tectonic setting of small areas.

strike-slip displacements, of the order of hundreds of kilometres, complicating any resulting plate tectonic reassembly.

## 1.6 TELLING THE STORY: ANALOGUES AND MODELS

This book will deploy a number of techniques for illustrating the geological history of Britain and Ireland, particularly regional palaeogeographic maps and crustal-scale cross-sections. At this scale, no interpretation is more than partly constrained by the surviving or accessible evidence. However, any acceptable interpretation must also be geologically realistic in comparison with recent or well-understood ancient analogues and with results of theoretical models.

Examples of appropriate recent analogues are the subduction systems of south-east Asia, which have been used to guide reconstruction of the systems that bordered the Early Palaeozoic Iapetus Ocean. The hypothesis is that the ancient systems would have had an outboard to inboard zonation from subducting ocean floor, through accreted subduction complex and fore-arc basin to active volcanic arc, and perhaps a back-arc basin and extinct arcs. Mismatch of the ancient with the recent systems can promote a search for missing components – perhaps removed further along the system by strike-slip faulting – or focus attention on the need for particular further data.

Theoretical models of geological processes provide a second type of test for regional reconstructions. An influential example is the rift-and-sag model of sedimentary basin formation, in which rapid subsidence due to lithospheric thinning is followed by decaying thermal subsidence as the temperature structure of the lithosphere is re-established. This model has been widely applied to the upper Palaeozoic, Mesozoic and Cenozoic basins of onshore and offshore Britain, so that their basin fill is commonly divided into syn-rift and post-rift phases. Compatibility of a reconstructed geological history with such mechanical models is encouraging. However, given the complexity of many geological processes, a mismatch is just as likely to suggest modification to the theoretical model as it is to the reconstruction.

## 1.7 THE GEOLOGICAL ORGANIZATION OF BRITAIN AND IRELAND

Chapter 2 in the introductory part of this book lays out the historical and spatial framework into which the geology of Britain and Ireland can be fitted. The remainder of the book is divided into six parts, each describing a phase of the region's geological history. The relationship of these phases to the major tectonostratigraphic rock units of Britain and Ireland can be seen on a time-chart (Fig. 1.9a) and geological map (Fig. 1.9b). The boundaries between the units on these diagrams are regional unconformities, major gaps in the geological record each recording the crustal shortening, uplift and erosion associated with an orogenic event. Metamorphism and igneous activity are associated with each orogeny. The periods between the orogenic unconformities are times of net accumulation of rock successions, often because of episodes of crustal extension. Igneous activity and minor unconformities accompany some extensional phases.

Before Silurian time, the wide Iapetus Ocean separated the Laurentian continent – including Scotland and north-west Ireland – from the microcontinent of Eastern Avalonia – including England, Wales and south-east Ireland. These two margins of Iapetus had dissimilar geological histories. The northern, Laurentian, margin had a complex history (described in Part 2) involving Archaean, Proterozoic and Ordovician (Grampian) orogenies. The tectonostratigraphic sequences on this margin differ between discrete fault-bounded terranes assembled late in the margin's history, and the chart simplifies this complex pattern. By comparison, the preserved pre-closure history of the southern Iapetus margin (described in Part 3) is shorter and simpler. The Neoproterozoic rocks of the Cadomian orogenic belt are overlain by Cambrian to lower Devonian successions.

The Iapetus Ocean closed during Silurian time. Remnants are preserved in north-west Scotland of the early Silurian Scandian Orogeny, due to collision of Laurentia with Baltica. Over the rest of Laurentian Britain, Iapetus closure is marked by a mid- to late-Silurian unconformity, but Eastern Avalonian sequences are conformable through the closure period. Part 4 describes the events associated with Iapetus closure, and the subsequent Devonian sedimentation. In mid-Devonian time the amalgamated continents were affected by the Acadian deformation, once thought to be related to Iapetus closure but now ascribed to events related to closure of the Rheic Ocean further south.

The tectonostratigraphic units deformed by the Cambrian to Devonian orogenies together form the Caledonian orogenic belt. It has its deformation fronts in the Welsh borders to the south-east and in the Scottish Highlands to the north-west. Relatively weakly deformed rocks, separately ornamented on Fig. 1.9, survive outside these deformation fronts.

The Acadian deformation was followed by the Variscan cycle of rock accumulation and deformation, described in Part 5. This cycle began in most areas with late Devonian and then Carboniferous deposition over the Acadian unconformity. The exception is in south-west England, where earlier Devonian sedimentation was continuous through the time of the Acadian events. This was the area most affected by the Variscan Orogeny (Fig. 1.9b), whose culminating events resulted in an unconformity spanning late Carboniferous and early Permian time. A Variscan deformation front separates the strongly deformed zone from the area to the north, in which the post-Acadian cover was only gently deformed (Fig. 1.9b).

By early Permian time, the crust of Britain and Ireland had been assembled in more or less its present configuration. The post-Variscan cycle (Part 6) is dominated by sediment accumulation in basins formed by crustal extension, attributable to the marginal effects of the rifting and opening of the Atlantic Ocean. The pulsed nature of extension has produced gentle unconformities (such as the Cimmerian, Fig. 1.9a) and an episode of Jurassic magmatism. The latest geological phase (Part 7) began with the Palaeogene magmatism and unconformities resulting from a mantle plume under north-west Britain. There was gentle Neogene (Alpine) folding in southern England, but

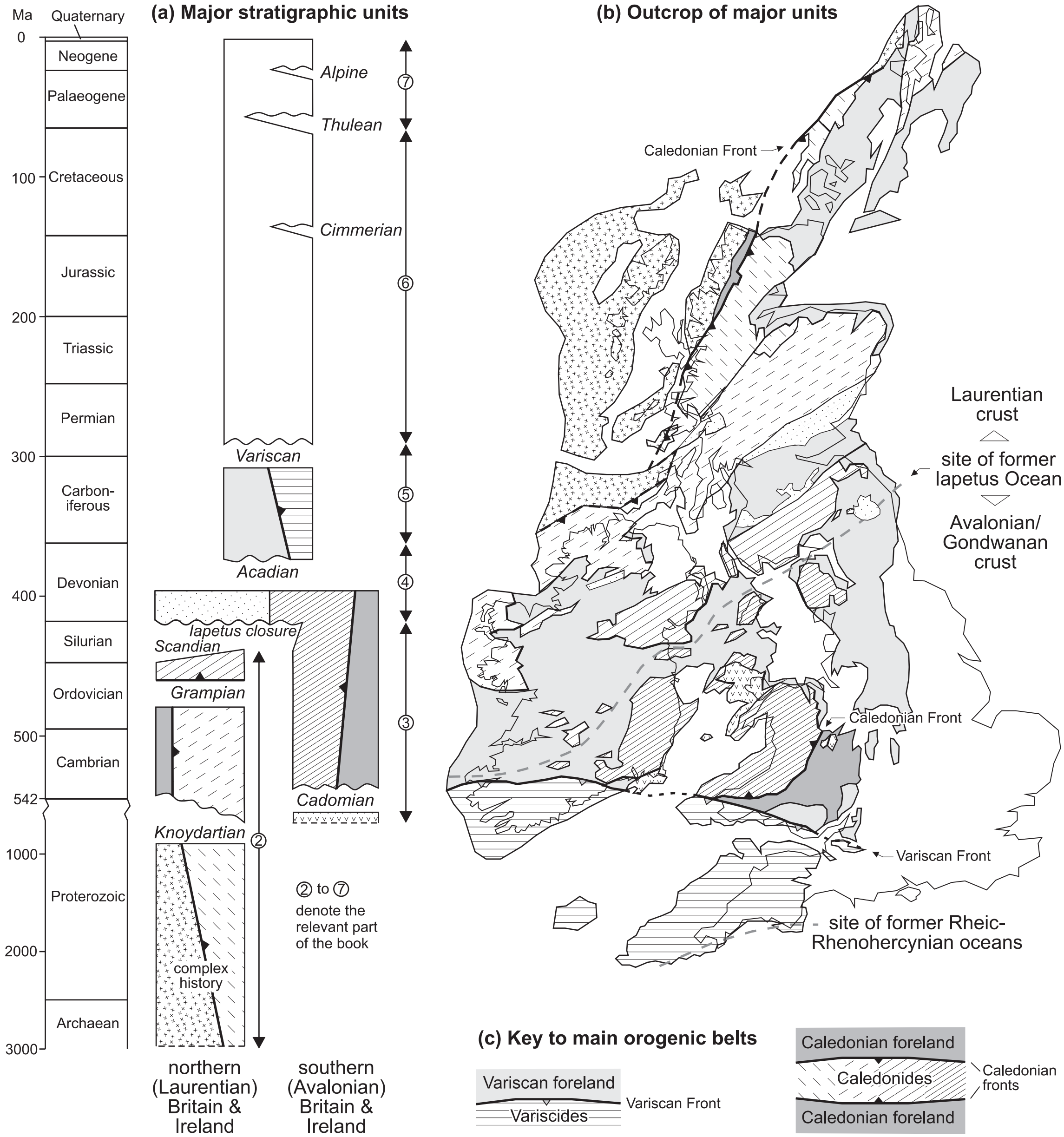


**Fig. 1.9** Major tectonostratigraphic units in Britain and Ireland (a), with their distribution at outcrop (b) and a key to the main orogenic belts (c) (updated from Woodcock 1994). The relevant parts of this book are labelled in (a).

the Cenozoic phase still awaits a culminating regional orogenic event.

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