Chapter 1

Introduction

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RATIONALE FOR CONSERVATION AND SELECTION OF QUATERNARY SITES IN SCOTLAND

The most striking feature of the Scottish landscape is the wide variety of landforms represented in a relatively small geographical area. The rugged Highlands with their accentuated relief contrast with the surrounding lowlands and the more rolling hills of the Southern Uplands and the Midland Valley. Further variety is introduced in the distinctive landscapes of the western and northern island groups and in the rich diversity of scenery around Scotland's coasts. This varied topography largely reflects the interplay of geological controls, geomorphological processes and the effects of climatic change, most recently during the Quaternary. When combined with the prevailing climate, the geological legacy has produced a complex natural environment which incorporates a remarkable geographical diversity of plant communities, soils and geomorphological processes. By virtue of Scotland's position on the extreme Atlantic fringe of north-western Europe, allied with its geomorphological diversity, many aspects of the natural environment are unique and demand to be conserved.

Diversity is also a significant theme in a temporal sense: the present landscape is the product of a long history of evolution which reflects the interaction of geology, topography, climate, geomorphological processes and their changes through time. The study of the evolution of the modern Scottish environment during the Quaternary has revealed a fascinating sequence of events that range from the shaping of many of the major elements of the landscape by glacial erosion to the establishment of the present vegetation cover after the last period of glaciation. These events are of considerable intrinsic scientific interest, not only because they are a particularly significant part of recent Earth history, but also because it has been possible to establish that, at various periods during the Quaternary, environments and their accompanying plant communities existed that have no known modern analogues. Knowledge of Quaternary history is important also in that it provides direct evidence for the rate at which natural processes can occur, in particular the response of geomorphological processes and plant communities to both major climatic deteriorations and ameliorations. Such information may become increasingly important as attempts are made to predict the likely effect of future natural or man-induced climatic changes. It is also in this last context that Quaternary science has a unique value, because it is only with a detailed knowledge of the natural environment that had developed prior to human impact that the full extent of that impact can be assessed, whether in terms of prehistoric forest clearance or modern industrial pollution.

Site selection criteria

For the Quaternary scientist concerned about conservation, the wealth of detail present in the Quaternary geological record or preserved in the landforms presents problems as well as opportunities. Decisions as to which sites should be conserved have been made on the basis of a number of guidelines which try to encapsulate the range of scientific interest. These guidelines are: uniqueness; classic examples; representativeness; being part of a site network; providing understanding of present environments; historical importance; and research potential and educational value. Individual sites may fall into one or more of the categories: other things being equal, sites with multiple interests were favoured.

Certain sites are unique. They are either the only known representatives of particular parts of the geological record or they may be known, as part of the landscape, to have no comparable site in Scotland or even internationally. Examples of the former are Fugla Ness, Kirkhill, North-west Coast of Lewis and Tangy Glen. The latter are best exemplified by Glen Roy and the Cairngorms.

Some sites are nationally or internationally recognized as being classic examples of particular features and are quoted in standard textbooks. Examples include Glen Roy, Northern Islay, West Coast of Jura and Carstairs Kames.

Other sites are representative of important aspects of geomorphology, landscape evolution or environmental change during the Quaternary in Scotland. Certain sites have therefore been selected because they are the best studied, are the best preserved and/or have the most complete local representation of phenomena that are quite widespread. They are therefore important reference sites for the particular phenomena or area concerned. Examples are sites concerning glacial deposits or landforms such as end and hummocky moraines, meltwater channels, kames, kettle holes, and eskers; others include representative or informally recognized reference sites for Quaternary stratigraphy.

Where there is a strong geographical component in the scientific interest, a series or network of sites has been chosen to include different aspects of one general type of phenomenon that shows significant regional variations in its characteristics, for example in relation to factors such as geology, climate or relief. Such networks may comprise unique, classic or representative sites. Prime examples are in vegetational change where, for example, the timing of the spread of trees following the climatic amelioration at the end of the Late Devensian varied throughout the country, as did the pattern of vegetation which that spread produced over a period of 3000 to 5000 years. Clearly, no one site in any part of the country can encapsulate such an aspect of the Quaternary history. Examples of the phenomena to which this guideline has been applied are mountain-top periglacial deposits and landforms, Lateglacial and Holocene vegetational and environmental change and Lateglacial and Holocene changes in sea level.

Certain sites are of particular importance because of the light they throw on the development of the present ecological-landscape. An example is the occurrence of the arctic—alpine plant refuges on certain mountains, the nearest neighbours of which may be in Norway. Sites such as Corrie Fee and Morrone demonstrate that these plants have survived on the Scottish mountains during the mild climate of the Holocene since the cold climate of the Late Devensian, when they were much more widespread in their occurrence. A very different example is that of the degradation of the environment by modern pollutants. The full extent of acidification of lochs by industrial emissions can only be known if the pH levels are known prior to the start of the pollution. A further question is the sensitivity of certain parts of the environment to environmental change, including human impact. This is exemplified by upland geomorphological processes and certain sites have provided basic information as to the rates of change that have occurred during the Holocene. Comparison of modern rates and past rates reveals whether the former are anomalous and give cause for concern.

If the above is a justification for conserving sites that preserve specific scientific evidence of certain Quaternary events, then in Scotland the history of the development of Quaternary science is a further important reason for the conservation of many Quaternary sites. The glacial theory was more widely accepted during the middle of the last century by the Earth science community in Scotland than in Britain in general, and over the 50-year period between 1840 (when the glacial theory was introduced by Agassiz) and 1890 many of the concepts related to glacial landforms, sediments and the interaction between solar radiation, climate, ice-sheets and sea-level change were elaborated with respect to the Scottish glacial deposits and landforms. Principal among these ideas may be set the advocacy of glacio-eustasy (MacLaren, 1842a), glacio-isostasy (Jamieson, 1865), multiple ice-sheet glaciation (Croll, 1870b, 1875; Geikie, 1894) controlled principally by variations in the Earth's orbit around the Sun (Croll, 1867, 1875, 1885) and the idea that the ocean currents were the principal agency for transporting heat from the tropics to the polar regions and were hence a fundamental control on the climate of the world (Croll, 1875). In addition, one of the legacies of this period has been the adoption of various Scots words as formal glacial-geological and geomorphological, terms such as 'till', 'kame', 'kettle' and 'drumlin'. Certain of the Quaternary sites in Scotland are therefore of major significance in the history of geology and deserve to be conserved on this basis alone. Other sites have had a long history of research and have played a fundamental role in the development of new ideas and interpretations of Quaternary events, chronology or landscape processes.

A final justification of many sites is the interpretation or interpretations, frequently controversial, that have been placed upon them. Such sites may illustrate the development of scientific thinking on the subject of landscape history and, indeed, the debates, for example about process or chronology, that characterize certain areas of Quaternary science. It is important that such sites continue to be available for further study and to stimulate active scientific debate. Other sites provide fundamental baselines, for example in dating or as stratigraphical markers, and must remain accessible for reference. There are many outstanding questions not yet resolved in the Quaternary of Scotland, as this volume will show, but in many respects this is a strength and not a weakness of the science and will hopefully stimulate further generations to enquire in depth about the evolution of Scotland during the Quaternary. Although new sites will become available, it is important that existing sites are maintained for the application of new research techniques. The long-term research potential of many sites is therefore a key factor in their selection. Finally, the educational importance of many of the sites should not be overlooked, and in total the coverage provides a history of the evolution of the Scottish landscape as recorded in its constituent landforms and sediments.

The present work is a compilation of all the sites in Scotland that merit conservation for their significance to Quaternary science (Figure 1.1). Coastal and fluvial geomorphology, in the sense of modern process studies, and large-scale mass movement features are reviewed in their own thematic volumes of the GCR. Site selection has been based on identifying the minimum number of sites necessary to represent the diverse history and form of the Scottish landscape; direct duplication of interests has therefore been minimized. Extensive consultations on site assessment were carried out with the appropriate specialists in Quaternary science.

Structure of the volume

In the chapters that follow, the sites are arranged in broad geographical areas (Figure 1.1), each with a brief introduction giving an overview of the presently understood Quaternary history of the area and highlighting the particular aspects of that history which are scientifically important. The individual site reports include syntheses of the currently available scientific documentation, and the interpretations of the site. A key part of each report is the assessment, which explains why the site is important. Where sites form part of a wider network, cross-reference is made to related sites to provide a fuller understanding of the event or period being discussed. In addition, where sites are of particular historical significance, the history of study of the site is dealt with in detail. Chapter 2 provides an overview of the Quaternary history of Scotland as understood from the available evidence.

INTRODUCTION TO THE QUATERNARY

Character of the Quaternary

The Quaternary is the portion of the late Cenozoic Era of geological time that spans approximately the last 1.6 Ma; the greater part of it is known as the Pleistocene and the last 10 ka as the Holocene. In a strict geological sense the base of the Quaternary, at the Pliocene–Pleistocene boundary, is defined in a section at a type locality at Vrica in Italy and dated at about 1.64 Ma (Aguirre and Pasini, 1985). The terms Pleistocene and Quaternary have often been used synonymously with “Ice Age’. However, it is now known from many parts of the world that glacier advances occurred before the start of the Pleistocene sensu stricto, and recent studies of ocean-floor sediments have indicated significant climatic deterioration and initiation of major Northern Hemisphere glaciation at around 2.4 Ma (Shackleton *et al.*, 1984; Ruddiman and Raymo, 1988). This abrupt onset of the late Cenozoic ice ages is, as yet, unexplained, although changes in insolation associated with orbital periodicities (eccentricity of the Earth’s orbit, tilt of the Earth’s axis and precession of the Earth’s axis) are now established as the driving force of changes in the Earth’s climatic system (Hays *et al.*, 1976; Imbrie *et al.*, 1984; Berger, 1988). The ocean-floor sediments have also revealed that the late Cenozoic was characterized by many fluctuations in climatic conditions, with up to 50 major ‘warm’ and ‘cold’ oscillations recognized during the last 2.4 Ma (Ruddiman and Raymo, 1988). The cold phases are usually described as ice ages or glaciations, and the warmer interludes as interglacials. The ice ages were not unbroken in their frigidity, however, since the exceptionally cold phases (stadials) were interrupted by warmer interludes (interstadials) lasting for a few thousand years.

Factors controlling Quaternary climatic change

Both the duration and the intensity of the climatic cycles have varied through time (Ruddiman and Raymo, 1988; Ruddiman *et al.*, 1989). During the period 2.4–0.9 Ma, the climate was dominated by 41 ka cycles (corresponding to variations in the Earth’s tilt). After

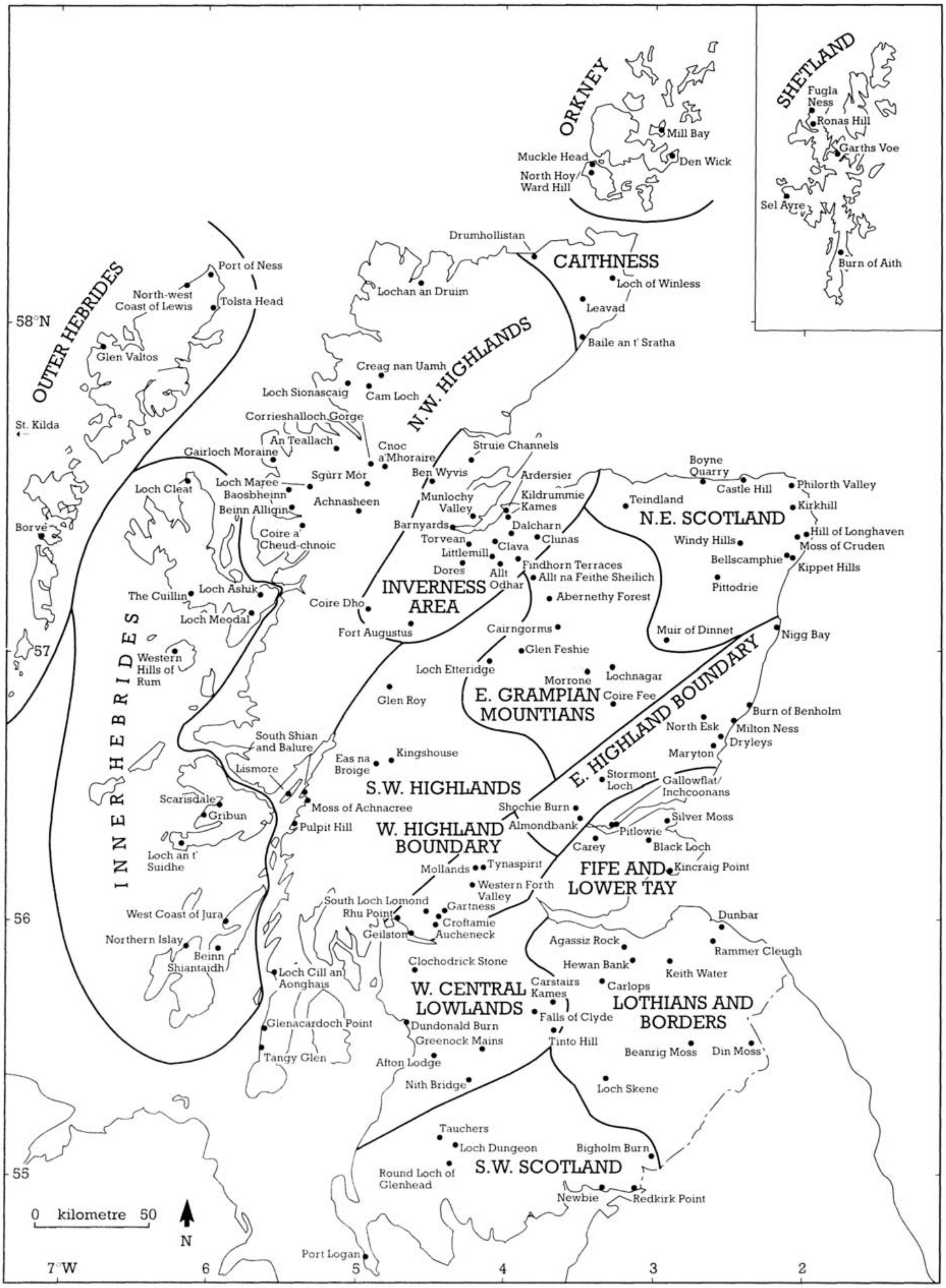

Figure 1.1 Location of sites and areas described.

0.9 Ma, the Northern Hemisphere glaciation intensified, while a 100 ka periodicity (corresponding to variations in orbital eccentricity) became stronger and then dominant after 0.45 Ma. Also, during the last 0.45 Ma, the influence of the 41 ka and 23 ka (corresponding to variations in precession) cycles, superimposed on the longer term fluctuations, has been identified in the geological record. The driving forces for these patterns, linking the relatively small orbitally controlled variations in solar radiation with major climatic change and ice-sheet growth, undoubtedly reflect a complex set of interactions and feedbacks involving the atmosphere, oceans, cryosphere and global tectonics. It is clear that the climatic record is not simply a linear function of astronomical forcing (e.g. Broecker and Denton, 1989; Overpeck *et al.*, 1989; Rind *et al.*, 1989). Several potentially key links have been identified, although a unifying theory awaits further research. The case for global tectonics, particularly the impact of uplift in the American south-west and the Tibetan Plateau on Northern Hemisphere atmospheric circulation patterns, has been argued by Ruddiman and Raymo (1988) and Ruddiman and Kutzbach (1990). In the model of Broecker and Denton (1989, 1990) changes in the world's oceans and their links with the atmosphere provide a potential means of coupling the orbital changes with ice-sheet fluctuations. According to Broecker and Denton, orbitally induced changes in the intensity of the seasons influence water vapour transfer and the salinity structure of the oceans, producing major reorganizations in global ocean circulation and hence in climate. Accompanying changes in the interchange of carbon dioxide between the oceans and atmosphere may provide a means of amplifying the orbital forcing through the ocean–atmosphere system (cf. Saltzman and Maasch, 1990). It has been shown that changes in the atmospheric content of that gas follow the orbital periodicities (e.g. Barnola *et al.*, 1987), but precede changes in ice volume (Shackleton *et al.*, 1983; Shackleton and Psias, 1985). However, it is apparent from modelling experiments that reductions in atmospheric carbon dioxide alone are inadequate to produce the inferred magnitude of global cooling (Broccoli and Manabe, 1987; Broecker and Denton, 1989). In addition, there are other factors which may modulate the growth and decay of ice-sheets, involving non-linear interactions between ice, climate, bedrock and sea level (cf. Sugden, 1987, 1991). Examples proposed have included the inherent instability of marine-based ice-sheets (e.g. Hughes, 1987; van der Veen, 1987; Jones and Keigwin, 1988), the effects of topography on ice-sheet growth (e.g. Payne and Sugden, 1990b), and the combined effects of climatic warming and isostatic depression in producing accelerated ice-sheet melting (Hyde and Peltier, 1985).

Evidence for subdivision of the Quaternary

One of the major developments in Quaternary studies in the last 20 years has been the recovery of sediment cores from the floors of the world's oceans and the resolution of the climatic and other environmental records which they contain (Bowen, 1978; Imbrie and Imbrie, 1979). In contrast to the fragmentary terrestrial records, those from the ocean floors have a major advantage in being longer and more continuous, and for the first time have allowed a comprehensive picture of climatic variation during the Quaternary. Three indices have been employed to reconstruct this climatic record: variations in oxygen isotope ratios in the shells of marine microfossils (which in large part reflect changes in ice-sheet volume (Shackleton and Opdyke, 1973)), variations in sea-surface temperatures inferred from assemblages of these microfossils, and variations in the percentages of $CaCO_3$ (higher during warmer episodes) and ice-rafted or wind-blown continental detritus (higher during colder episodes) (Ruddiman *et al.*, 1986). Complementary records of climatic fluctuations have been obtained from studies of the oxygen isotope ratios in polar ice-sheets (Johnsen *et al.*, 1972; Robin, 1983; Jouzel *et al.*, 1987, 1990; Oeschger and Langway, 1989). Although these latter relate to relatively short time-scales, over the last 160 ka, and their interpretation may be subject to more constraints (see Paterson, 1981), they are nevertheless a key data source for Quaternary scientists. One particularly important conclusion to emerge is the rapidity of climatic change; for example, Greenland ice-cores indicate a warming of 7°C in about 50 years at the end of the Younger Dryas (Dansgaard *et al.*, 1989).

The deep-sea sediments, and in particular the variations in oxygen isotope ratios with depth which they contain, have also provided the foundation for a subdivision of Quaternary time that has global applicability (see Bowen, 1978). This subdivision is based on the recognition of a series of oxygen isotope stages (cf. Figure 2.1), beginning with the Holocene (Stage 1) and numbered back in time with even numbers for glacial periods and odd numbers for interglacials. These stages are dated in relation to the established boundaries defining changes in the direction of polarity of the Earth's magnetic field and tuned according to the time-scale of orbital periodicities (Imbrie *et al.*, 1984; Martinson *et al.*, 1987; Shackleton *et al.*, 1990). The problem remains, however, to relate the fragmentary terrestrial sedimentary record to the oxygen isotope time-scale, particularly back beyond the last interglacial.

In Britain the extent of the area covered by ice varied during different glaciations. During the last (Late Devensian) glaciation ice extended as far south as the north Midlands and just impinged on the north coast of East Anglia. During some earlier glaciations ice extended farther south but probably never beyond the Thames Valley. However, the sedimentary record of the Quaternary in Britain is incomplete. The most comprehensive sequences of deposits occur in East Anglia and the Midlands, where a series of glacials and interglacials has been recognized. These are individually named, sometimes after particular reference localities, and provide the type sites (stratotypes) for stratigraphic correlation in Britain. Over the remainder of the country, the period during and since the last (Ipswichian) interglacial has been reconstructed in greatest detail, reflecting the more widespread preservation of younger sediments.

Quaternary environments

A fundamental feature of the Quaternary is the predominance of extreme climatic change, and as the climate fluctuated, so too did environmental conditions. Particular types of environmental change have left a strong imprint in the landforms, fossils and recent sedimentary deposits of Britain. By studying these features and by making comparisons with modern analogues, Quaternary scientists have made considerable progress in unravelling the past. They have shown that a wide range of landforms and sediments produced by ice erosion and deposition distinguish the glaciations. During the melting of the ice-sheets the liberation of vast volumes of meltwater produced an equally characteristic suite of waterlain glaciofluvial landforms and deposits. In the areas that lay beyond the ice-sheets, and also during less severe cold phases when glaciers were either restricted in their distribution or absent altogether, periglacial conditions prevailed. These are characterized by frost-assisted processes and by a range of frost and ground-ice generated landforms and deposits. Mass wasting (downslope movement of soil on both large and small scales) and increased wind action were prevalent and also produced a range of diagnostic features. In parts of upland Britain periglacial processes are still active today. As reflected in the fossil record, the flora and fauna of the cold periods show restricted diversity of species and, not surprisingly, the predominance of cold-tolerant types.

Interglacials have a sedimentary record characterized by the absence of glacial, periglacial and glaciofluvial features. They are often distinguished by periods of chemical weathering, soil formation or the accumulation of organic material. Changes in the amounts and types of pollen grains preserved in organic deposits have been used to define systems of pollen zones, each zone being characterized by particular vegetation types, and which climatic conditions have been inferred from these. Progressive changes in vegetation through time can be summarized by sequences of pollen zones. In addition, environmental conditions were different in different interglacials, and hence the presence of particular types of pollen can be diagnostic of particular interglacials. Similarly, different mammal faunas occurred in different glacials and interglacials, and some species are diagnostic of particular glacials or interglacials. Both terrestrial and marine molluscs and Coleoptera (beetles) are also useful in reconstructing past environmental conditions by analogy with their present-day environmental tolerances and geographic ranges.

Running parallel with the growth and decay of ice-sheets, significant changes have occurred in the coastal zone of Britain associated with a complex interplay of changing land and sea levels. World sea level has varied according to the volume of water locked up within the ice-sheets, being lower during glacials than interglacials. The level of the land has also varied, sinking under the weight of advancing ice-sheets and rising up again when they melted. Such changes are evident in beaches, shore platforms and marine sediments now raised above present sea level. Some of the more important examples have been given particular names, and some have been dated or assigned to particular subdivisions of the Quaternary. Submerged shoreline features and drowned valleys also point to relatively lower sea levels in the past. Changes in river courses and channel patterns have followed changes in discharge, sediment supply and sea level. There have been times when rivers built up large thicknesses of glacially derived debris on their floodplains, and others when they eroded down into their floodplains. The resulting effects on the landscape are "staircases' of terraces in many river valleys. In some cases the more important terraces have been individually named and dated with reference to a range of fossil materials.

Change through time is a fundamental aspect of Quaternary studies. Very often traces of successive environments are recorded in layers of sediment preserved on top of one another; for example, glacial deposits may overlie interglacial beach deposits and in turn be succeeded by periglacial slope deposits and later sand dunes. Sites with such sequences can provide particularly revealing perspectives on the Quaternary. Although a temporal theme has been emphasized, it is also the case that Quaternary environmental changes and associated processes have not been uniform in their operation throughout Britain, and allied with the variety of the geology, this has produced a remarkable regional diversity in surface landforms and deposits. This has been a key factor in compiling the national network of GCR sites representing the Quaternary.

Approaches to Quaternary science

The fundamentals of Quaternary science are explained in a range of texts (for example, West, 1977; Bowen, 1978; Birks and Birks, 1980; Lowe and Walker, 1984; Bradley, 1985; Dawson, 1992). In brief, key aims are (1) to establish the stratigraphy of the deposits and to effect their correlation and classification, and (2) to interpret and explain the evolution of the landscape during the Quaternary, the history of geomorphological events and processes, climatic and environmental change, and the development of the flora and fauna. It is also important to understand the relationships between each of these aspects and how they have varied both geographically and through time. Quaternary science is therefore multidisciplinary, involving the combined efforts of geologists, geographers, geomorphologists, botanists, zoologists and archaeologists. The basis of the geological approach is stratigraphy, that is correlating between individual localities using sediments or fossils. Other approaches can involve reconstruction of environmental change or spatial analysis, for example of landforms, ice movements or vegetation patterns. Certain sites are recognized, either formally or informally, to be important reference localities because they demonstrate, for example, particular events, sequences of environmental changes, types of sediment, or contain datable materials. Such sites provide the standards for future studies. Sites with organic or fossil remains are also highly valued as rich sources of information about past environments and yield material for dating.