Quaternary of Scotland

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Access to the countryside

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

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

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

English Nature,
Northminster House,
Peterborough PE1 1UA.

Foreword

One of the great insights of nineteenth century geology was the recognition that the environmental backdrop against which the drama of human evolution and history had been played was not static, as had been hitherto assumed, but had changed dramatically on relatively short timescales. The young Swiss geologist, Louis Agassiz, who played a major role in bringing about this change in thinking, visited Scotland in 1840 to advocate his new glacial theory, which suggested that the northern continents had suffered widespread glaciation in the recent past. Scottish geologists such as Lyell, Jamieson, MacLaren, Croll and Geikie were quick to pick up his ideas and, seeing ubiquitous evidence of change in their own country's dramatic landscape, led the world in exploring the implications of this revolutionary new concept. These pioneers established the flow patterns of the ice masses which had moulded the rock slabs of the Cuillin of Skye and had dispersed the rocks of Ailsa Craig into England; demonstrated rebound of crust after ice disappearance, which uplifted old shorelines around Oban and Mull high above modern sea level; and showed that great floods of meltwater from the decaying ice masses had produced the hummocky ridges on which many of Scotland's best golf courses are now built. They also showed that there had been rapidly alternating warm and cold periods in the past and that the ultimate drive for climatic change was the Earth's fluctuating orbit around the Sun.

Only recently, however, has the advent of techniques such as pollen analysis, uranium-series dating and radiocarbon dating been able to place a precise timescale on these events. They have revealed the dramatic overlap between an almost unimaginable geological past and a human present as reflected in prehistory and history, showing for example, that 11,000–10,000 years ago, when Jericho was a thriving city, the sites of many modern cities in Scandanavia, and many towns and villages in the Scottish Highlands, were overlain by more than a kilometre of ice.

It is only in the last two decades, with increasing public awareness of the fragility of the ecosystem, of the fact that well-protected botanical reserves appear to 'deteriorate', and of the vulnerability of the Earth's climate itself, that the significance of the geological record of Quaternary environmental change has been generally realised. The record tells us about the frequency and magnitude of natural change in the past, how mean annual temperatures have changed by as much as 5°C in the period of a human lifetime; how floral assemblages have changed rapidly, both in response to climatic change and without any apparent climatic drive; and how the composition of the atmosphere, including its 'greenhouse gases', has varied cyclically and in phase with the climate. The record also tells us about the frequency and magnitude of natural change that long-term dwellers on this Earth should expect, what the consequences of an increased atmospheric greenhouse gas concentration might be, and what processes should be taken into account in theories about future climate and environmental change.

This understanding is drawn from natural geological archives such as those represented by the sites described in this volume. Many of these archives have been well-read and understood: many others, no doubt, await new techniques or new insights before they yield up their secrets. Just as no civilised person would lightly destroy the books in an ancient library, no more should we lightly contemplate the destruction of this record of the past. However, roads need to be built, minerals need to be mined, food must be grown and people need to be housed, and Quaternary sediments are soft and easily destroyed or removed. Moreover, farmers, in their desire to improve their pastures, may wish to drain bogs containing superb records of past climate and ecological change, whilst elsewhere some of our finest surviving eskers are the most readily available source of sand and gravel for building. Clearly there are difficult decisions to be made about the balance between the need to preserve the geological archive and the need for us to use the land. Such decisions as these, which must be made as a result of debate involving the new natural heritage organisations, need information about the extent and nature of our heritage. This splendid volume is of fundamental importance in helping to define that heritage.

The Quaternary of Scotland documents the most important known Quaternary sites in Scotland and provides a basic factual archive, although there are, no doubt, other sites which are known which will prove to be equally important as a result of new insights and new methods, and others as yet undiscovered which will also join these ranks in the future. The site-by-site observational information described in this volume is associated with interpretations, which indicate the significance of each site in adding to our understanding. The site descriptions are incorporated into regional and Scottish syntheses, so that the role of the individual observations in determining the large-scale theoretical framework can be seen. So great is the amount of the data now available that few syntheses are able to go back to the primary observations, but are based on second and third hand sources. John Gordon and Donald Sutherland have not only done a great service to conservation but also to Quaternary geology in relating the facts to the interpretive framework. Much of the speculation may not survive changes in scientific fashion and theory, but the basic observations will.

The text has great clarity for such a complex subject and the quality of the illustrations is a reminder of that great lure to field science in Scotland: the beauty of the land.

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Preface

STRUCTURE OF THE VOLUME AND TERMINOLOGY USED

This book contains scientific descriptions of 138 localities of national importance for Quaternary geology, geomorphology and environmental change in Scotland. It consists of two chapters that provide a general overview, followed by 16 regional chapters. The objective of the former chapters is to permit the reader to understand how the details of individual sites fit into the national scheme.

The locations of the regions are shown in Figure 1.1. Each of the regional chapters has a brief introduction which outlines the Quaternary geology and geomorphology and places the individual sites in their regional context. The individual site descriptions form the core of the book. In each chapter they are arranged, broadly, from oldest to youngest, although many of the sites cover significant periods of time. Each site report consists of a description of the evidence; interpretation of that evidence, with correlation, where relevant, with other localities; and assessment of the significance of the site in a regional, national or international context. Where sites form part of a wider network, then cross-reference is made to related sites to provide fuller understanding of the feature or period being discussed. In addition, where sites are of particular historical significance, then the history of study of the site is dealt with in detail.

There is at present no universally accepted system of terminology for the subdivision of Quaternary deposits in Britain. Mitchell *et al.* (1973) proposed a correlation scheme based on standard stages. Since that date, however, not only has there been a great increase in knowledge of the Quaternary succession so that the 1973 system is now incomplete, but also certain of the stage names proposed at that time have been questioned as to their suitability or even existence. To avoid confusion, therefore, Table 1 and Figure 2.7 have been compiled to show the terminology and approximate accompanying chronology that is used in this book; a simplified summary chart showing the position of each site in the chronology is given in Table 2. The basis of the chronology is the oxygen isotope signal recognized in deep-sea sediments. This signal has been shown to be a function of the Earth's orbital parameters (Hays *et al.*, 1976), and astronomical data have been used to 'tune' the geological time-scale (cf. Imbrie *et al.*, 1984; Prell *et al.*, 1986; Ruddiman *et al.*, 1986, 1989; Martinson *et al.*, 1987). For the period back to about 620 ka, the time-scale is that developed by Imbrie *et al.* (1984), which has been substantiated by later work (Prell *et al.*, 1986; Shackleton *et al.*, 1990). For the earlier part of the Quaternary, the revised time-scale of Shackleton *et al.* (1990) is adopted.

Table 1 Terminology used in the subdivision of the Late Pleistocene and Holocene

			Age (years BP)	OI Stage
Holocene (late) (middle) (early)				1
			10,000	
Late Devensian	Lateglacial	Loch Lomond Stadial		
			11,000	
		Lateglacial Interstadial	12,000	
			13,000	
				2
			24,000	
			26,000	
Middle Devensian				3
			59,000	
Early Devensian				4
			71,000	
				5a-5d
			116,000	
Ipswichian				5e
			128,000	

Where radiocarbon 'dates' (age estimates) are cited, they are quoted in radiocarbon years before present (AD 1950). It should be noted that the radiocarbon time-scale diverges from the calendrical one, and although calibration is available back to 9000 years in detail (cf. Pilcher, 1991) and to 30,000 years in outline (Bard *et al.*, 1990), the interpretation of radiocarbon measurements,

Table 2 Summary of stratigraphical positions of sites described in this volume. Sites appear more than once where they have multiple interests or interests of different ages. Sites with features pre-dating the Late Devensian are grouped together because of uncertainties over dating

		Shetland Western Isles	Orkney Caithness North-west Highlands	Inverness Area North-east Scotland Eastern Grampians	South-west Highlands Inner Hebrides	Western Highland Boundary Eastern Highland Boundary Fife and Lower Tay	Western Central Lowlands Lothians and Borders South-west Scotland
Holocene		Garths Voe Ronas Hill Borve Gleann Mór	Ward Hill Loch of Winless An Teallach Sgùrr Mór Loch Sionascaig Lochan an Druim Loch Maree	Dores Barnyards Munlochy Valley Ben Wyvis Findhorn Terraces Muir of Dinnet Philorth Valley The Cairngorms Abernethy Forest Loch Etteridge Allt na Feithe Sheilich Coire Fee Glen Feshie Morrone	Glenacardoch Point Kingshouse Pulpit Hill Loch Cill an Aonghais Eas na Broige Western Hills of Rum West Coast of Jura Gribun Loch an t-Suidhe Loch Ashik Loch Cleat Loch Meodal	South Loch Lomond Rhu Point Western Forth Valley Mollands Tynaspirit Dryleys Maryton Milton Ness Stormont Loch Carey Silver Moss Pitlowie Kincraig Point Black Loch	Dundonald Burn Tinto Hill Din Moss Newbie Loch Dungeon Round Loch of Glenhead
Late Devensian	Loch Lomond Stadial	Burn of Aith Ronas Hill	Ward Hill Loch of Winless Achnasheen An Teallach Baosbheinn Beinn Alligin Cnoc a'Mhoraire Coire a'Cheud-chnoic Creag nan Uamh Cam Loch Lochan an Druim	Coire Dho Fort Augustus Dores Barnyards Munlochy Valley Ben Wyvis Muir of Dinnet The Cairngorms Lochnagar Loch Etteridge Morrone Glen Feshie Coire Fee	Isle of Lismore Moss of Achnacree South Shian Glen Roy Pulpit Hill The Cuillin Beinn Shiantaidh Western Hills of Rum Northern Islay? West Coast of Jura? Loch an t-Suidhe Loch Ashik	Aucheneck Croftamie Gartness South Loch Lomond Rhu Point Western Forth Valley Tynaspirit Stormont Loch Black Loch	Loch Skene Beanrig Moss Dunbar Tauchers Bigholm Burn Redkirk Point
	Lateglacial Interstadial	Burn of Aith	Loch of Winless Cam Loch Lochan an Druim	Ardersier Findhorn Terraces The Cairngorms Lochnagar Loch Etteridge Abernethy Forest Morrone Glen Feshie	Glenacardoch Point South Shian Pulpit Hill West Coast of Jura Loch an t-Suidhe Loch Ashik	Croftamie Gartness South Loch Lomond Geilston Rhu Point Tynaspirit Dryleys Milton Ness North Esk & West Water Stormont Loch Inchcoonans & Gallowflat Kincraig Point Black Loch	Beanrig Moss Bigholm Burn Redkirk Point
		North-west Coast of Lewis Port of Ness Tolsta Head Glen Valtos	Den Wick? Mill Bay? Baile an t-Sratha? Drumhollistan? Leavad? Gairloch Moraine An Teallach Corrieshalloch Gorge	Clava Ardersier Struie Channels Kildrummie Kames Littlemill Torvean Findhorn Terraces Boyne Quarry Teindland Castle Hill Kippet Hills Muir of Dinnet Kirkhill Bellscamphie The Cairngorms Loch Etteridge Glen Feshie	The Cuillin Scarisdale Beinn Shiantaidh? Northern Islay West Coast of Jura	Croftamie Gartness Geilston Nigg Bay Burn of Benholm Almondbank Shochie Burn North Esk & West Water	Afton Lodge Nith Bridge Greenock Mains Carstairs Kames Clochodrick Stone Falls of Clyde Agassiz Rock Hewan Bank Keith Water Carlops Rammer Cleugh Port Logan Bigholm Burn
Pre-Late Devensian		Fugla Ness Sel Ayre North-west Coast of Lewis Tolsta Head	Den Wick? Mill Bay? Muckle Head & Selwick Baile an t-Sratha? Drumhollistan ? Leavad? Corrieshalloch Gorge? Creag nan Uamh	Clunas Dalcharn Allt Odhar Clava Windy Hills Moss of Cruden Pittodrie Hill of Longhaven Kirkhill Bellscamphie Boyne Quarry? Teindland Castle Hill? The Cairngorms	Tangy Glen Glenacardoch Point Isle of Lismore? Northern Islay West Coast of Jura	Nigg Bay Burn of Benholm Milton Ness Kincraig Point	Afton Lodge Dunbar

particularly during parts of the Late Devensian is additionally complicated (cf. Ammann and Lotter, 1989; Zbinden *et al.*, 1989).

The informal term 'Lateglacial' (equivalent to Devensian late-glacial) is well established in the Scottish Quaternary literature and is used throughout this volume following the definitions of Gray and Lowe (1977a). The terms Lateglacial Interstadial and Loch Lomond Stadial are also used. These are climate-stratigraphic, or climatostratigraphic, terms, and as such differ from chronostratigraphic, or time-stratigraphic terms. The latter are intervals of time based on a definition tied to a particular rock-sequence. Climate-stratigraphic terms, however, are based on climatic inferences drawn from rocks, either at a site, or from several sites. The terms Lateglacial Interstadial and Loch Lomond Stadial describe the inferred nature of the climate towards the end of the Devensian Stage. In general terms, the former relates to the time between approximately 13,000 and 11,000 years ago, a time of overall climatic improvement, whereas the latter refers to the time between approximately 11,000 and 10,000 years ago, which corresponds to a time of climatic deterioration.

Comparison with the nomenclature used in Europe shows that the Lateglacial Interstadial corresponds with the Oldest Dryas, Bølling, Older Dryas and Allerød events. The Loch Lomond Stadial corresponds with the Younger Dryas. Attention is drawn to the latter in particular, in view of its importance as an international term in studies seeking to understand the Earth's climate system.

Finally, where the usage of certain local terms for particular landforms or deposits is widely accepted in the literature, these have been retained in the present volume; for example, corrie (cirque) and carse (estuarine silts and clays). Where possible, modern names of marine mollusca are used, following Smith and Heppell (1991).

Chapter 1

Introduction

J. E. Gordon and D. G. Sutherland

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 guidelines

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 counterparts 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 Coire 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.

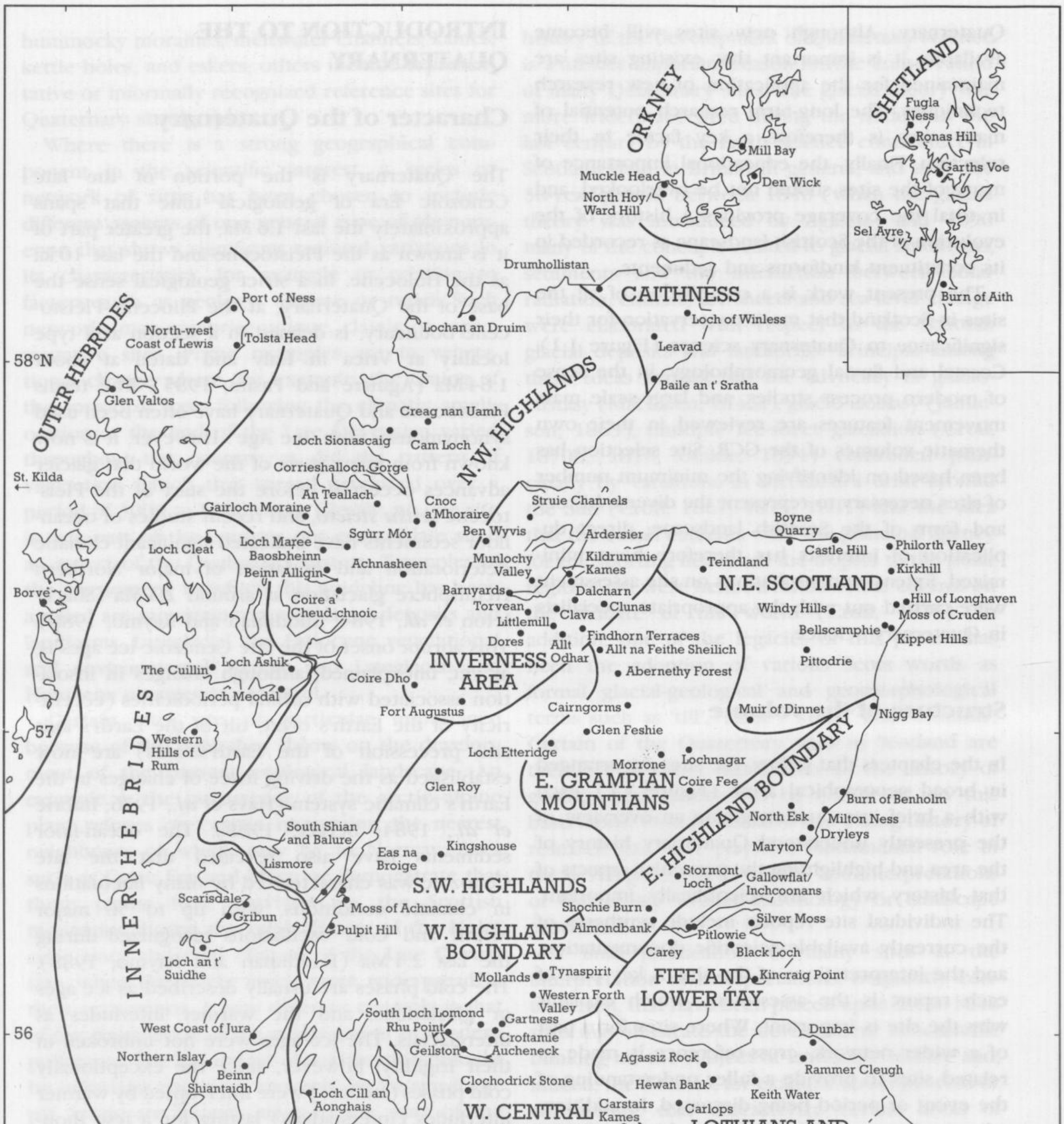
INTRODUCTION TO THE QUATERNARY

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


SHETLAND
Fugla Ness
Ronas Hill
Garths Voe
Sel Ayre
Burn of Aith
ORKNEY
Mill Bay
Den Wick
Muckle Head
North Hoy/ Ward Hill
Drumhollistan
CAITHNESS
Loch of Winless
Leavad
Baile an t' Sratha
OUTER HEBRIDES
Port of Ness
North-west Coast of Lewis
Tolsta Head
Lochan an Druim
58°N
Glen Valtos
N.W. HIGHLANDS
Creag nan Uamh
Loch Sionascaig
Cam Loch
St. Kilda
Corrieshalloch Gorge
An Teallach
Cnoc a'Mhoraire
Gairloch Moraine
Struie Channels
Sgùrr Mór
Ben Wyvis
Ardersier
Loch Cleat
Loch Maree
Baosbheinn
Beinn Alligin
Achnasheen
Munlochy Valley
Kildrummie Kames
Teindland
Boyne Quarry
Castle Hill
Philorth Valley
Kirkhill
N.E. SCOTLAND
Borve
Coire a' Cheud-chnoic
Barnyards
Torvean
Littlemill
Dalcharn
Clava
Clunas
Windy Hills
Hill of Longhaven
Moss of Cruden
Bellscamphie
Kippet Hills
Dores
Findhorn Terraces
Allt Odhar
Allt na Feithe Sheilich
The Cuillin
Loch Ashik
Coire Dho
INVERNESS AREA
Abernethy Forest
Pittodrie
Loch Meodal
Fort Augustus
Cairngorms
Muir of Dinnet
Nigg Bay
57
Western Hills of Rum
INNER HEBRIDES
Glen Feshie
Loch Etteridge
Morrone
Lochnagar
E. HIGHLAND BOUNDARY
E. GRAMPIAN MOUNTIANS
Coire Fee
Glen Roy
Burn of Benholm
North Esk
Milton Ness
Dryleys
Maryton
South Shian and Balure
Kingshouse
Eas na Broige
Lismore
S.W. HIGHLANDS
Stormont Loch
Gallowflat/ Inchcoonans
Scarisdale
Gribun
Moss of Achnacree
Shochie Burn
Silver Moss
Pulpit Hill
W. HIGHLAND BOUNDARY
Almondbank
Pitlowie
Carey
Black Loch
Loch an t' Suidhe
Mollands
Tynaspirit
FIFE AND LOWER TAY
Kincraig Point
Western Forth Valley
South Loch Lomond
Gartness
Rhu Point
Croftamie
West Coast of Jura
56
Geilston
Aucheneck
Dunbar
Northern Islay
Beinn Shiantaidh
Agassiz Rock
Rammer Cleugh
Clochodrick Stone
Hewan Bank
Keith Water
Loch Cill an Aonghais
W. CENTRAL LOWLANDS
Carstairs Kames
Carlops
LOTHIANS AND BORDERS
Falls of Clyde
Glenacardoch Point
Dundonald Burn
Greenock Mains
Tinto Hill
Beanrig Moss
Din Moss
Tangy Glen
Afton Lodge
Nith Bridge
Loch Skene
Tauchers
Loch Dungeon
Bigholm Burn
55
Round Loch of Glenhead
S.W. SCOTLAND
Newbie
Redkirk Point
0 kilometre 50
N
Port Logan
7°W
6
5
4
3
2

variations in the Earth's tilt). After 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 Pisias, 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).

Figure 1.1 Location of sites and areas described.

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 2.7), 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 water-lain 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, allowing climatic and environmental conditions to be inferred. 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.