



"This is a splendid compendium of what we know and understand about Quaternary environments, and how we study them. Lowe and Walker are to be congratulated on this fully updated version of their popular textbook. *Reconstructing Quaternary Environments* continues to be a must for Quaternary sciences courses at all university levels and an indispensable reference source for professional geoscientists. This new edition is beautifully illustrated and provides diverse examples from around the world; it is a real *tour de force* of Quaternary studies."

Professor Lewis Owen, *Department of Geology, University of Cincinnati, USA*

"The literature in Quaternary environmental and climatic change has increased exponentially during the last decades and now covers a wide range of archives, proxies and modelling studies. In this revised and updated third edition, Lowe and Walker have successfully integrated the wealth of new data from around the world. The up-to-date information and references, the elegant language, the explanatory notes after each chapter and full-colour illustrations and photos all serve to make this wonderful textbook a treasure trove for students, researchers and anyone else interested in finding out more about the exciting subject of Quaternary climate and environmental change."

Professor Barbara Wohlfarth, *Department of Geological Sciences, Stockholm University, Sweden*

"The third edition of *Reconstructing Quaternary Environments* by John Lowe and Mike Walker continues the impressive standards set by its two predecessor volumes. Well written, extensively referenced and with numerous clear diagrams and colour figures, it sets the standard for textbooks on Quaternary science and the techniques to reconstruct environmental change. It should be essential reading for students and will be an invaluable reference for all those with an interest in the Quaternary."

Professor Colm O'Cofaigh, *Department of Geography, Durham University, UK*



This third edition of *Reconstructing Quaternary Environments* has been completely revised and updated to provide a new account of the history and scale of environmental changes during the Quaternary. The evidence is extremely diverse ranging from landforms and sediments to fossil assemblages and geochemistry, and includes new data from terrestrial, marine and ice-core records. Dating methods are described and evaluated, while the principles and practices of Quaternary stratigraphy are also discussed. The volume concludes with a new chapter which considers some of the key questions about the nature, causes and consequences of global climatic and environmental change over a range of temporal scales. This synthesis builds on the methods and approaches described earlier in the book to show how a number of exciting ideas that have emerged over the last two decades are providing new insights into the operation of the global earth-ocean-atmosphere system, and are now central to many areas of contemporary Quaternary research.

This comprehensive and dynamic textbook is richly illustrated throughout with full-colour figures and photographs. The book will be of interest to undergraduates, postgraduates and professionals in Earth Science, Environmental Science, Physical Geography, Geology, Botany, Zoology, Ecology, Archaeology and Anthropology.

John Lowe is former Gordon Manley Professor and now Emeritus Professor of Quaternary Science in Royal Holloway, University of London, UK.

Mike Walker is Emeritus Professor of Quaternary Science, Trinity Saint David, University of Wales, Lampeter, UK and Honorary Professor, Aberystwyth University, UK.

PHYSICAL GEOGRAPHY / ENVIRONMENTAL SCIENCE

 **Routledge**
Taylor & Francis Group
www.routledge.com



www.routledge.com/books/details/9780131274686/

Routledge titles are available as eBook editions in a range of digital formats

Front cover image: Globe © National Geographic. Back cover: The Joides Resolution research vessel © Arito Sakaguchi; Coring in Lake Suigetsu © Takeshi Nakagawa

ISBN 978-0-13-127468-6



9 780131 274686

an informa business

Contents

<i>List of figures and tables</i>	xxv
<i>Preface to the third edition</i>	xxvii
<i>Acknowledgements</i>	xxix
<i>Cover image details</i>	xxx
1 The Quaternary record	1
1.1 Introduction	1
1.2 Interpreting the Quaternary record	2
1.3 The status of the Quaternary in the geological timescale	2
1.4 The duration of the Quaternary	3
1.5 The development of Quaternary studies	5
1.5.1 <i>Historical developments</i>	5
1.5.2 <i>Recent developments</i>	7
1.6 The framework of the Quaternary	9
1.7 The causes of climatic change	13
1.8 The scope of this book	16
Notes	17
2 Geomorphological evidence	19
2.1 Introduction	19
2.2 Methods	19
2.2.1 <i>Field methods</i>	19
2.2.1.1 Field mapping	19
2.2.1.2 Instrumental levelling	20
2.2.2 <i>Remote sensing</i>	22
2.2.2.1 Aerial photography	22
2.2.2.2 Satellite imagery	22
2.2.2.3 Radar	23
2.2.2.4 Sonar and seismic sensing	24
2.2.2.5 Digital elevation/terrain modelling	24
2.3 Glacial landforms	26
2.3.1 <i>Extent of ice cover</i>	27
2.3.2 <i>Geomorphological evidence and the extent of ice sheets and glaciers during the last cold stage</i>	30
2.3.2.1 Northern Europe	30
2.3.2.2 Britain and Ireland	33

2.3.2.3	North America	35
2.3.3	<i>Direction of ice movement</i>	39
2.3.3.1	Striations	40
2.3.3.2	Friction cracks	40
2.3.3.3	Ice-moulded (streamlined) bedrock	40
2.3.3.4	Streamlined glacial deposits	42
2.3.4	<i>Reconstruction of former ice masses</i>	43
2.3.4.1	Ice sheet modelling	43
2.3.4.2	Ice caps and glaciers	47
2.3.5	<i>Palaeoclimatic inferences using former glacier elevations</i>	50
2.3.5.1	Cirque floor altitude (CFA) and toe-to-headwall (THAR) methods	50
2.3.5.2	ELA/FLA method	51
2.4	Periglacial landforms	53
2.4.1	<i>Palaeoclimatic inferences based on periglacial evidence</i>	55
2.4.1.1	Rock glaciers	55
2.4.1.2	Pingos and palsas	56
2.4.1.3	Pronival ('protalus') ramparts	57
2.5	Sea-level change	58
2.5.1	<i>Relative and 'absolute' sea-level changes</i>	59
2.5.2	<i>Eustatic changes in sea level</i>	59
2.5.2.1	Pre-Quaternary eustatic changes	59
2.5.2.2	Quaternary eustatic changes	60
2.5.3	<i>Tectonic influences</i>	67
2.5.4	<i>Glacio- and hydro-isostasy</i>	68
2.5.5	<i>Shoreline sequences in areas affected by glacio-isostasy</i>	69
2.5.6	<i>Palaeoenvironmental significance of sea-level changes</i>	73
2.6	River terraces	73
2.6.1	<i>Origins of river terraces</i>	75
2.6.1.1	Eustatic changes in sea level	76
2.6.1.2	Climatic change	76
2.6.1.3	Glaciation	77
2.6.1.4	Tectonic changes	77
2.6.1.5	Human activity	77
2.6.2	<i>River terraces and palaeoenvironmental reconstruction</i>	78
2.6.3	<i>The terraces of the River Thames</i>	78
2.7	Quaternary landforms in low latitudes	82
2.7.1	<i>Pluvial lakes</i>	82
2.7.2	<i>Dunefields</i>	86
2.7.3	<i>Fluvial landforms</i>	89
2.7.4	<i>Weathering crusts</i>	90
2.8	Conclusions	91
Notes		91

3 Lithological evidence

3.1	Introduction	93
3.2	Field and laboratory methods	93
3.2.1	<i>Sediment sections</i>	93
3.2.2	<i>Coring</i>	94
3.2.3	<i>Laboratory methods</i>	96

3.2.3.1	Particle size measurements	96
3.2.3.2	Particle shape	97
3.2.3.3	Surface textures of quartz particles	97
3.2.3.4	Organic carbon content	97
3.2.3.5	Metallic elements	98
3.2.3.6	Heavy minerals	98
3.2.3.7	Clay mineralogy	98
3.2.3.8	Mineral magnetic analysis	98
3.2.3.9	Stable isotope analysis	98
3.3.	Glacial sediments	99
3.3.1	<i>Introduction</i>	99
3.3.2	<i>The nature of glacial sediments</i>	99
3.3.2.1	Unstratified and stratified sediments	99
3.3.2.2	Glacigenic facies	100
3.3.3	<i>The classification of tills</i>	102
3.3.3.1	Lodgement, melt-out and 'flow' tills	102
3.3.3.2	Deformation tills	102
3.3.3.3	Paraglacial deposits	105
3.3.4	<i>The influence of the thermal regime of glacier ice</i>	107
3.3.5	<i>Analysis of glacigenic sequences</i>	109
3.3.5.1	Particle size and shape analysis	109
3.3.5.2	Lithofacies interpretations	109
3.3.6	<i>Ice-directional indicators</i>	111
3.3.6.1	Erratics	111
3.3.6.2	Till fabrics	113
3.3.6.3	Properties of the till matrix	115
3.4	Periglacial sediments	115
3.4.1	<i>Introduction</i>	115
3.4.2	<i>Structures associated with permafrost</i>	116
3.4.3	<i>Palaeoclimatic significance of periglacial structures</i>	118
3.5	Palaeosols	122
3.5.1	<i>Introduction</i>	122
3.5.2	<i>The nature of palaeosols</i>	122
3.5.3	<i>Analysis of palaeosols</i>	124
3.5.4	<i>Palaeosols and Quaternary environments</i>	125
3.6	Wind-blown sediments	127
3.6.1	<i>Introduction</i>	127
3.6.2	<i>Loess stratigraphy</i>	127
3.6.3	<i>Mid-latitude sand belts (coversands)</i>	130
3.6.4	<i>Low-latitude 'sand seas'</i>	131
3.6.5	<i>Wind-blown sediments and palaeoenvironmental reconstructions</i>	131
3.7	Lake-level records from low-latitude regions	132
3.7.1	<i>Introduction</i>	132
3.7.2	<i>Pluvial lake sediment sequences</i>	133
3.7.3	<i>Lake-level changes and Quaternary palaeoclimates</i>	135
3.8	Cave sediments and carbonate deposits	140
3.8.1	<i>Introduction</i>	140
3.8.2	<i>Detrital sediment in caves</i>	141
3.8.3	<i>Speleothem</i>	143
3.8.4	<i>Speleothem growth and environmental reconstruction</i>	143
3.8.4.1	Speleothem growth and climatic change	143

3.8.4.2	Stable isotope ratios in cave speleothem	145
3.8.4.3	Trace elements in cave speleothem	148
3.8.4.4	Speleothem formation and sea-level variations	149
3.8.4.5	Speleothem formation and tectonic activity	149
3.8.4.6	Speleothem formation and rates of denudation	149
3.8.5	<i>Other carbonate deposits</i>	149
3.9	Lake, mire and bog sediments	151
3.9.1	<i>Introduction</i>	151
3.9.2	<i>The nature of lake and bog sediments</i>	152
3.9.3	<i>Palaeoenvironmental evidence from lake sediments</i>	154
3.9.3.1	Lake sediments and landscape changes	155
3.9.3.2	Lake-level variations and climatic changes	159
3.9.3.3	Lake sediments and palaeotemperatures	160
3.9.4	<i>Palaeoenvironmental evidence from mire and bog sediments</i>	161
3.9.4.1	Palaeoprecipitation records from ombrotrophic peats	161
3.9.4.2	Stable isotope records from ombrotrophic peats	163
3.9.4.3	Human impact recorded in ombrotrophic peat	165
3.10	The deep-sea sediment record	165
3.10.1	<i>The nature and origin of ocean sediments</i>	165
3.10.2	<i>Oxygen isotope ratios and the ocean sediment record</i>	166
3.10.2.1	General principles	166
3.10.2.2	Glacial ice storage and the marine oxygen isotope record	167
3.10.2.3	Ice volumes, sea level and the marine oxygen isotope record	169
3.10.2.4	Sea-surface temperatures and the marine oxygen isotope record	170
3.10.3	<i>Limitations of oxygen isotope analysis</i>	170
3.10.3.1	Stratigraphic resolution	170
3.10.3.2	Sediment mixing	171
3.10.3.3	Isotopic equilibrium between test carbonate and ocean water	171
3.10.3.4	Carbonate dissolution and diagenesis	171
3.10.4	<i>Carbon isotopes in marine sediments</i>	171
3.11	Ice-core stratigraphy	172
3.11.1	<i>A brief history of deep-ice coring</i>	172
3.11.2	<i>Ice masses as palaeoenvironmental archives</i>	173
3.11.3	<i>Analysis of ice cores</i>	173
3.11.3.1	Annual ice increments	173
3.11.3.2	Dust content	175
3.11.3.3	Chemical content	175
3.11.3.4	Stable isotope records	175
3.11.3.5	Other trace substances	175
3.11.4	<i>Palaeoenvironmental significance of ice cores</i>	175
3.12	Conclusions	178
Notes		179
4	Biological evidence	181
4.1	Introduction	181
4.1.1	<i>The nature of the Quaternary fossil record</i>	181
4.1.2	<i>The taphonomy of Quaternary fossil assemblages</i>	182
4.1.3	<i>The interpretation of Quaternary fossil assemblages</i>	182
4.2	Pollen analysis	183
4.2.1	<i>Introduction</i>	183

4.2.2	<i>The nature of pollen and spores</i>	183
4.2.3	<i>Field and laboratory work</i>	184
4.2.4	<i>Pollen diagrams</i>	185
4.2.5	<i>The interpretation of pollen diagrams</i>	190
4.2.6	<i>Applications of pollen stratigraphy</i>	194
4.2.6.1	Local vegetation reconstructions	194
4.2.6.2	Regional vegetation reconstructions	194
4.2.6.3	Space-time reconstructions	195
4.2.6.4	Human impact on vegetation cover	195
4.2.6.5	Pollen data and climatic reconstructions	197
4.3	<i>Diatom analysis</i>	197
4.3.1	<i>Introduction</i>	197
4.3.2	<i>The nature and ecology of diatoms</i>	198
4.3.3	<i>Field and laboratory methods</i>	200
4.3.4	<i>The interpretation of Quaternary diatom records</i>	202
4.3.5	<i>Applications of diatom analysis</i>	202
4.3.5.1	Diatoms as salinity indicators	202
4.3.5.2	Diatoms and pH	203
4.3.5.3	Diatoms and trophic status	205
4.3.5.4	Diatoms and the archaeological record	205
4.3.5.5	Other environmental applications	206
4.4	<i>Plant macrofossil analysis</i>	207
4.4.1	<i>Introduction</i>	207
4.4.2	<i>The nature of plant macrofossils</i>	207
4.4.3	<i>Field and laboratory work</i>	208
4.4.4	<i>Data presentation</i>	208
4.4.5	<i>The interpretation of plant macrofossil data</i>	209
4.4.6	<i>Palaeoenvironmental applications of plant macrofossil studies</i>	212
4.4.6.1	Palaeoclimatic reconstructions	212
4.4.6.2	Forest history	214
4.4.6.3	Charcoal and fire history	214
4.4.6.4	Archaeological records	215
4.5	<i>Fossil insect remains</i>	215
4.5.1	<i>Introduction</i>	215
4.5.2	<i>Coleoptera</i>	215
4.5.3	<i>Laboratory methods</i>	216
4.5.4	<i>Coleopteran analysis and Quaternary environments</i>	218
4.5.4.1	Habitat preferences	219
4.5.4.2	Palaeoclimatic inferences based on coleopteran assemblages	221
4.5.4.3	Insect fossils and archaeology	225
4.5.5	<i>Chironomidae</i>	225
4.6	<i>Non-marine Mollusca</i>	228
4.6.1	<i>Introduction</i>	228
4.6.2	<i>The nature and distribution of molluscs</i>	229
4.6.3	<i>Field and laboratory work</i>	229
4.6.4	<i>Taphonomy of non-marine molluscan assemblages</i>	231
4.6.5	<i>Interpretation of non-marine molluscan assemblages: habitat groups and indices of species diversity</i>	232
4.6.6	<i>Applications of Quaternary non-marine molluscan records</i>	233
4.6.6.1	Biostratigraphic correlation	233
4.6.6.2	Palaeoclimatic reconstructions	234

4.6.6.3	Archaeological relevance	234
4.7	Marine Mollusca	235
4.7.1	Introduction	235
4.7.2	Analysis of marine molluscan assemblages	235
4.7.3	Marine Mollusca and palaeoclimatic inferences	236
4.7.4	Other applications of fossil marine molluscan records	237
4.8	Ostracod analysis	238
4.8.1	The nature and distribution of ostracods	238
4.8.2	Collection and identification	238
4.8.3	Ostracoda in Quaternary studies	239
4.9	Foraminiferal analysis	241
4.9.1	The nature and distribution of Foraminifera	241
4.9.2	Collection and identification	242
4.9.3	Foraminifera in Quaternary inshore and shelf sediments	242
4.9.3.1	Sea-level change	242
4.9.3.2	Shallow marine water mass and temperature variations	243
4.9.3.3	Other palaeoenvironmental applications	244
4.10	Micropalaeontology of deep-sea sediments	244
4.10.1	Introduction	244
4.10.2	Radiolaria	244
4.10.3	Coccolithophores	245
4.10.4	Dinoflagellates (dinocysts)	246
4.10.5	Marine microfossils in ocean sediments	246
4.10.6	Laboratory separation of marine microfossils	248
4.10.7	Marine palaeoclimatology	248
4.10.8	Marine palaeoproductivity and palaeocirculation	253
4.11	Vertebrate remains	254
4.11.1	Introduction	254
4.11.2	The structure of teeth and bones	254
4.11.3	Fossilization of bone material	256
4.11.4	Field and laboratory techniques	256
4.11.5	The taphonomy of fossil vertebrate assemblages	257
4.11.5.1	Cave and fissure deposits	257
4.11.5.2	Lacustrine sediments	258
4.11.5.3	Fluvial sediments	258
4.11.6	Quaternary vertebrate records	258
4.11.6.1	Vertebrate biostratigraphy	259
4.11.6.2	Vertebrate biogeography	259
4.11.6.3	Vertebrate fossils and Quaternary environments	260
4.11.6.4	Vertebrate fossils and faunal evolution	262
4.12	Other fossil groups	263
4.12.1	Chrysophytes	263
4.12.2	Cladocera	263
4.12.3	Coral polyps	263
4.12.4	Fungal remains	264
4.12.5	Testate amoebae	264
4.12.6	Biomarkers (ancient biomolecules)	265
4.13	Multi-proxy palaeoecological studies	265
4.14	Conclusions	266
	Notes	266

5	Dating methods	267
5.1	Introduction	267
5.2	Precision and accuracy in Quaternary dating	267
5.3	Radiometric dating techniques	268
5.3.1	<i>The nucleus and radioactivity</i>	268
5.3.2	<i>Radiocarbon dating</i>	270
5.3.2.1	General principles	270
5.3.2.2	Measurement of ^{14}C activity	271
5.3.2.3	Quality assurance in radiocarbon dating	275
5.3.2.4	Sources of error in radiocarbon dating	275
5.3.2.5	Radiocarbon dating of soils	279
5.3.2.6	Calibration of the radiocarbon timescale	279
5.3.3	<i>Argon-isotope dating</i>	284
5.3.3.1	Potassium-argon dating	284
5.3.3.2	Argon-argon (Ar/Ar) dating	285
5.3.3.3	Problems and limitations of argon-isotope dating	285
5.3.3.4	Some applications of argon-isotope dating	285
5.3.4	<i>Uranium-series (U-series) dating</i>	286
5.3.4.1	General principles	286
5.3.4.2	Measurement, problems and age range	287
5.3.4.3	Some applications of U-series dating	288
5.3.5	<i>Fission track dating</i>	289
5.3.5.1	General principles	289
5.3.5.2	Measurement and problems	290
5.3.5.3	Some applications of fission track dating	290
5.3.6	<i>Luminescence dating</i>	291
5.3.6.1	General principles	291
5.3.6.2	Measurement and problems	291
5.3.6.3	Developments in luminescence dating	292
5.3.6.4	Age ranges and applications of luminescence dating	293
5.3.7	<i>Electron spin resonance (ESR) dating</i>	293
5.3.7.1	General principles and measurement	293
5.3.7.2	Sources of error in ESR dating	294
5.3.7.3	Some applications of ESR dating	294
5.3.8	<i>Cosmogenic radionuclide (CRN) dating</i>	294
5.3.8.1	General principles	294
5.3.8.2	Measurement and problems	295
5.3.8.3	Some applications of CRN dating	296
5.3.9	<i>Short-lived radioactive isotopes</i>	296
5.3.9.1	Lead-210	297
5.3.9.2	Caesium-137	297
5.3.9.3	Silicon-32	298
5.4	Incremental dating methods	298
5.4.1	<i>Dendrochronology</i>	298
5.4.1.1	General principles	298
5.4.1.2	Measurement and problems	298
5.4.1.3	Dendrochronological records	300
5.4.1.4	Dendroclimatology	302
5.4.2	<i>Varve chronology</i>	304
5.4.2.1	The nature of varved sediments	304

5.4.2.2	Clastic varves	304
5.4.2.3	Organic (biogenic) varves)	305
5.4.2.4	Chemical varves	306
5.4.2.5	Complex varves	306
5.4.2.6	Sources of error in varve counting	306
5.4.2.7	Applications of varve chronologies	307
5.4.3	<i>Annual layers in glacier ice</i>	310
5.4.3.1	General principles	310
5.4.3.2	Errors in ice-core chronologies	312
5.4.3.3	Ice-core chronologies	312
5.4.4	<i>Lichenometry</i>	315
5.4.4.1	General principles	315
5.4.4.2	Sources of error in lichenometric dating	315
5.4.4.3	Some applications of lichenometry	316
5.4.5	<i>Other materials dated by annual increments</i>	316
5.4.5.1	Speleothems	316
5.4.5.2	Sclerochronology	317
5.5	Age-equivalent stratigraphic markers	319
5.5.1	<i>Palaeomagnetism</i>	319
5.5.1.1	Geomagnetic field and remanent magnetism	319
5.5.1.2	Magnetostratigraphy	320
5.5.2	<i>Tephrochronology</i>	325
5.5.2.1	General principles	325
5.5.2.2	Sources of error in tephrochronology	327
5.5.2.3	Applications of tephrochronology	327
5.5.3	<i>Oxygen isotope chronology</i>	330
5.5.4	<i>Biostratigraphy and molecular clocks</i>	331
5.6	Relative chronology based on processes of chemical alteration	332
5.6.1	<i>Amino-acid geochronology</i>	332
5.6.1.1	Chemistry of proteins	332
5.6.1.2	Amino-acid diagenesis	334
5.6.1.3	Aminostratigraphy and age control	334
5.6.1.4	Problems with amino-acid geochronology	334
5.6.1.5	Recent developments in amino-acid geochronology	336
5.6.1.6	Some applications of amino-acid geochronology	336
5.6.2	<i>Fluorine, uranium and nitrogen content of fossil bones</i>	339
5.6.3	<i>Obsidian hydration dating (OHD)</i>	340
5.6.3.1	General principles	340
5.6.3.2	Problems with obsidian hydration dating	340
5.6.3.3	Some applications of obsidian hydration dating	340
5.6.4	<i>Weathering characteristics of rock surfaces</i>	340
5.6.4.1	General principles	340
5.6.4.2	Problems in using surface weathering features as indicators of relative age	341
5.6.4.3	Some applications of surface weathering dating	342
5.6.5	<i>Pedogenesis</i>	342
5.6.5.1	General principles	342
5.6.5.2	Problems in using pedogenesis as a basis for dating	342
5.6.5.3	Some applications of relative dating based on degree of pedogenesis	343
5.7	Stratigraphic and temporal resolution	343
5.8	Conclusions	344
	Notes	345

6	Approaches to Quaternary stratigraphy and correlation	347
6.1	Introduction	347
6.2	Stratigraphic subdivision	347
6.2.1	<i>Principles of Quaternary stratigraphy</i>	347
6.2.2	<i>Stratotypes</i>	349
6.2.3	<i>Elements of Quaternary stratigraphy</i>	349
6.2.3.1	Lithostratigraphy	349
6.2.3.2	Biostratigraphy	353
6.2.3.3	Morphostratigraphy	354
6.2.3.4	Soil stratigraphy	355
6.2.3.5	Oxygen isotope stratigraphy	355
6.2.3.6	Climatostratigraphy	358
6.2.3.7	Chronostratigraphy	361
6.3	Time-stratigraphic correlation	362
6.3.1	<i>Principles of Quaternary correlation</i>	362
6.3.2	<i>Bases for time-stratigraphic correlation</i>	363
6.3.2.1	Palaeomagnetic correlation	363
6.3.2.2	Correlation using tephra layers	364
6.3.2.3	Correlation using palaeosols	364
6.3.2.4	Shoreline correlation	364
6.3.2.5	Correlation on the basis of radiometric dating	365
6.3.2.6	Event stratigraphy and correlation	365
6.3.2.7	Correlation using the marine oxygen isotope record	366
6.3.3	<i>Correlation between continental, marine and ice-core records</i>	366
6.3.3.1	Long-term correlation on Milankovitch timescales	367
6.3.3.2	Correlation on sub-Milankovitch timescales	371
6.3.3.3	Synchronizing records of past environmental change	374
6.4	Conclusions	378
7	Global environmental change during the Quaternary	379
7.1	Introduction	379
7.2	Environmental simulation models (ESMs)	380
7.2.1	<i>Introduction</i>	380
7.2.2	<i>Box models</i>	380
7.2.3	<i>General circulation models (GCMs)</i>	381
7.2.4	<i>Earth system models of intermediate complexity (EMICs)</i>	383
7.2.5	<i>Transient simulations</i>	386
7.2.6	<i>Palaeodata-model comparisons</i>	387
7.2.7	<i>Limitations of ESMs</i>	388
7.2.8	<i>The importance of ESMs in Quaternary research</i>	388
7.3	Climatic change over Milankovitch timescales	389
7.3.1	<i>Introduction</i>	389
7.3.2	<i>The Mid-Pleistocene Transition (MPT)</i>	390
7.3.3	<i>The glacial-interglacial cycles of the last 800 ka</i>	394
7.3.4	<i>Overview</i>	397
7.4	Environmental change over sub-orbital (millennial) timescales	399
7.4.1	<i>Introduction</i>	399
7.4.2	<i>Ice-ocean-climate interplay in the North Atlantic</i>	400
7.4.3	<i>A bipolar teleconnection</i>	405

7.4.4	<i>Global teleconnections: linking mechanisms</i>	407
7.4.5	<i>Overview</i>	412
7.5	<i>The Last Termination</i>	413
7.5.1	<i>Introduction</i>	413
7.5.2	<i>Definition of the Last Termination</i>	413
7.5.3	<i>Onset of the Last Termination</i>	415
7.5.4	<i>Global teleconnections during the Last Termination</i>	418
7.5.5	<i>Synchronizing records of Lateglacial age</i>	419
7.5.5.1	<i>Introduction</i>	419
7.5.5.2	<i>Lateglacial stratigraphy and chronology</i>	419
7.5.5.3	<i>Lateglacial age models and correlation procedures</i>	420
7.5.5.4	<i>Rapid environmental change during the Lateglacial</i>	421
7.6.	<i>Climate and the Holocene</i>	427
7.6.1	<i>Introduction</i>	427
7.6.2	<i>Holocene climate trends</i>	427
7.6.3	<i>Holocene climatic events</i>	428
7.6.3.1	<i>The Pleistocene–Holocene transition</i>	428
7.6.3.2	<i>The 8.2 ka event</i>	429
7.6.3.3	<i>The 4.2 ka event</i>	431
7.6.3.4	<i>The 2.8 ka event</i>	433
7.6.3.5	<i>The Little Ice Age</i>	433
7.6.4	<i>Holocene climatic cycles</i>	434
7.6.4.1	<i>Late Holocene solar cycles</i>	434
7.6.4.2	<i>El Niño–Southern Oscillation (ENSO)</i>	435
7.6.4.3	<i>Late Holocene Atlantic and Pacific Oscillations</i>	435
7.6.5	<i>People and climate</i>	436
7.6.5.1	<i>The greenhouse effect</i>	437
7.6.5.2	<i>Early human impact?</i>	438
7.6.5.3	<i>Delayed glaciation?</i>	439
7.6.6	<i>The Anthropocene</i>	439
7.7	<i>Concluding remarks</i>	440
Notes		443
References		445
Index		523