Contents

Preface xv

1 Dating Methods and the Quaternary 1
  1.1 Introduction 1
  1.2 The Development of Quaternary Dating 2
  1.3 Precision and Accuracy in Dating 5
  1.4 Atomic Structure, Radioactivity and Radiometric Dating 7
  1.5 The Quaternary: Stratigraphic Framework and Terminology 9
  1.6 The Scope and Content of the Book 12
Notes 15

2 Radiometric Dating 1: Radiocarbon Dating 17
  2.1 Introduction 17
  2.2 Basic Principles 18
  2.3 Radiocarbon Measurement 19
    2.3.1 Beta Counting 20
    2.3.2 Accelerator Mass Spectrometry 20
    2.3.3 Extending the Radiocarbon Timescale 23
    2.3.4 Laboratory Intercomparisons 24
  2.4 Sources of Error in Radiocarbon Dating 24
    2.4.1 Contamination 24
    2.4.2 Isotopic Fractionation 25
    2.4.3 Marine Reservoir Effects 26
    2.4.4 Long-Term Variations in $^{14}$C Production 27
  2.5 Some Problematic Dating Materials 29
    2.5.1 Lake Sediments 29
    2.5.2 Shell 30
    2.5.3 Bone 31
    2.5.4 Soil 31
  2.6 Calibration of the Radiocarbon Timescale 32
    2.6.1 Dendrochronological Calibration 32
    2.6.2 The INTCAL Calibration 32
    2.6.3 Extending the Radiocarbon Calibration Curve 34
2.6.4 Bayesian Analysis and Radiocarbon Calibration 35
2.6.5 Wiggle-Match Dating 37

2.7 Applications of Radiocarbon Dating 37
2.7.1 Radiocarbon Dating: Some Routine Applications 37

2.7.1.1 Dating of plant macrofossils: Lateglacial cereal cultivation in the valley of the Euphrates 38
2.7.1.2 Dating of charcoal: a Holocene palaeoenvironmental record from western Germany 38
2.7.1.3 Dating of peat: a Holocene palaeoclimatic record from northern England 41
2.7.1.4 Dating of organic lake mud: a multi-proxy palaeoenvironmental record from Lake Rutundu, East Africa 41
2.7.1.5 Dating of marine micropalaeontological records: an example of a problem from the North Atlantic 43
2.7.1.6 Dating of marine shell: a Holocene aeolianite from Mexico 45
2.7.1.7 Dating of bone: the earliest humans in the Americas 47

2.7.2 Radiocarbon Dating of Other Materials 47
2.7.2.1 Dating of textiles: the ‘Shroud of Turin’ 48
2.7.2.2 Dating of old documents: the Vinland Map 49
2.7.2.3 Dating of lime mortar: medieval churches in Finland 51
2.7.2.4 Dating of hair: radiocarbon dates and DNA from individual animal hairs 51
2.7.2.5 Dating of iron artefacts: the Himeji nail and the Damascus sword 52
2.7.2.6 Dating of pottery: the earliest pottery in Japan 52
2.7.2.7 Dating of rock art: Palaeolithic cave paintings in Spain and France 53

Notes 54

3 Radiometric Dating 2: Dating Using Long-Lived and Short-Lived Radioactive Isotopes 57
3.1 Introduction 57
3.2 Argon-Isotope Dating 58
3.2.1 Principles of Potassium–Argon Dating 58
3.2.2 Principles of Argon–Argon Dating 59
3.2.3 Some Assumptions and Problems Associated with Potassium–Argon and Argon–Argon Dating 59
3.2.4 Some Applications of Potassium–Argon and Argon–Argon Dating 61
3.2.4.1 Potassium–argon and argon–argon dating of the dispersal of Early Pleistocene hominids 62
3.2.4.2 $^{40}$Ar/$^{39}$Ar dating of anatomically modern Homo sapiens from Ethiopia 62

Notes 54
Contents ix

3.2.4.3 $^{40}$Ar/$^{39}$Ar dating of historical materials: the eruption of Vesuvius in AD 79 65
3.2.4.4 $^{40}$Ar/$^{39}$Ar dating and geological provenancing of a stone axe from Stonehenge, England 66

3.3 Uranium-Series Dating 66
3.3.1 Principles of U-Series Dating 67
3.3.2 Some Problems Associated with U-Series Dating 69
3.3.3 Some Applications of U-Series Dating 71
3.3.3.1 Dating the Last Interglacial high sea-level stand in Hawaii 71
3.3.3.2 Dating of early hominid remains from China 72
3.3.3.3 Dating of a speleothem from northern Norway 74
3.3.3.4 Dating of fluvial terraces in Wyoming, USA 74

3.4 Cosmogenic Nuclide Dating 77
3.4.1 Principles of Cosmogenic Nuclide (CN) Dating 77
3.4.2 Sources of Error in CN Dating 79
3.4.3 Some Applications of CN Dating 80
3.4.3.1 Cosmogenic dating of two Late Pleistocene glacial advances in Alaska 80
3.4.3.2 Cosmogenic dating of the Salpausselkä I formation in Finland 82
3.4.3.3 Cosmogenic dating of Holocene landsliding, The Storr, Isle of Skye, Scotland 82
3.4.3.4 Cosmogenic dating of alluvial deposits, Ajo Mountains, southern Arizona, USA 84

3.5 Dating Using Short-Lived Isotopes 84
3.5.1 Lead-210 ($^{210}$Pb) 85
3.5.2 Caesium-137 ($^{137}$Cs) 86
3.5.3 Silicon-32 ($^{32}$Si) 86
3.5.4 Some Problems in Using Short-Lived Isotopes 87
3.5.5 Some Dating Applications Using Short-Lived Isotopes 87
3.5.5.1 Dating a record of human impact in a lake sequence in northern England 88
3.5.5.2 Dating a 500-year lake sediment/temperature record from Baffin Island, Canada 88
3.5.5.3 $^{32}$Si dating of marine sediments from Bangladesh 91

Notes 92

4 Radiometric Dating 3: Radiation Exposure Dating 93

4.1 Introduction 93
4.2 Luminescence Dating 94
4.2.1 Thermoluminescence (TL) 94
4.2.2 Optically Stimulated Luminescence (OSL) 96
4.2.3 Sources of Error in Luminescence Dating 99
4.2.4 Some Applications of Luminescence Dating 100
4.2.4.1 TL dating of Early Iron Age iron smelting in Ghana 100
4.2.4.2 TL and AMS radiocarbon dating of pottery from the Russian Far East 101
4.2.4.3 TL dating of burnt flint from a cave site in France 102
4.2.4.4 TL dating of the first humans in South America 103
4.2.4.5 OSL dating of young coastal dunes in the northern Netherlands 104
4.2.4.6 OSL dating of dune sands from Blombos Cave, South Africa: single and multiple grain data 104
4.2.4.7 OSL dating of fluvial deposits in the lower Mississippi Valley, USA 107
4.2.4.8 OSL dating of marine deposits in Denmark 108

4.3 Electron Spin Resonance Dating 109
4.3.1 Principles of ESR Dating 109
4.3.2 Sources of Error in ESR Dating 110
4.3.3 Some Applications of ESR Dating 110
4.3.3.1 ESR dating of teeth from the Hoxnian Interglacial type locality, England 111
4.3.3.2 ESR dating of mollusc shells from the Northern Caucasus and the earliest humans in eastern Europe 112
4.3.3.3 ESR dating of Holocene coral: an experimental approach 113
4.3.3.4 ESR dating of quartz: the Toba super-eruption 113

4.4 Fission Track Dating 114
4.4.1 Principles of Fission Track Dating 115
4.4.2 Some Problems Associated with Fission Track Dating 116
4.4.3 Some Applications of Fission Track Dating 116
4.4.3.1 Fission track dating of glacial events in Argentina 116
4.4.3.2 Fission track dating of a Middle Pleistocene fossiliferous sequence from central Italy 117
4.4.3.3 Dating of obsidian in the Andes, South America, and the sourcing of artefacts 117

Notes 119

5 Dating Using Annually Banded Records 121
5.1 Introduction 121
5.2 Dendrochronology 122
5.2.1 Principles of Dendrochronology 122
5.2.2 Problems Associated with Dendrochronology 123
5.2.3 Dendrochronological Series 125
5.2.4 Applications of Dendrochronology 127
5.2.4.1 Dating a 2000-year temperature record for the northern hemisphere 128
5.2.4.2 Dating historical precipitation records 128
5.2.4.3 Dating volcanic events
5.2.4.4 Dating archaeological evidence

5.3 Varve Chronology
5.3.1 The Nature of Varved Sediments
5.3.2 Sources of Error in Varve Chronologies
5.3.3 Applications of Varve Chronologies
5.3.3.1 Dating regional patterns of deglaciation in Scandinavia
5.3.3.2 Dating prehistoric land-use changes
5.3.3.3 Dating long-term climatic and environmental changes
5.3.3.4 Varve sequences and the radiocarbon timescale

5.4 Lichenometry
5.4.1 Principles of Lichenometric Dating
5.4.2 Problems Associated with Lichenometric Dating
5.4.3 Lichenometry and Late Holocene Environments
5.4.3.1 Dating post-Little Ice Age glacier recession in Norway
5.4.3.2 Dating rock glaciers and Little Ice Age moraines in the Sierra Nevada, western USA
5.4.3.3 Dating Late Holocene rockfall activity on a Norwegian talus slope
5.4.3.4 Dating archaeological features on raised shorelines in northern Sweden

5.5 Annual Layers in Glacier Ice
5.5.1 Ice-Core Chronologies
5.5.2 Errors in Ice-Core Chronologies
5.5.3 Ice Cores and the Quaternary Palaeoenvironmental Record
5.5.3.1 Dating climatic instability as revealed in the Greenland ice cores
5.5.3.2 Dating rapid climate change: the end of the Younger Dryas in Greenland
5.5.3.3 Dating long-term variations in atmospheric Greenhouse Trace Gases
5.5.3.4 Dating human impact on climate as reflected in ice-core records

5.6 Other Media Dated by Annual Banding
5.6.1 Speleothems
5.6.1.1 Dating a proxy record for twentieth-century precipitation from Poole’s Cavern, England
5.6.1.2 Dating climate variability in central China over the last 1270 years
5.6.2 Corals
5.6.2.1 Dating a 420-year-coral-based palaeoenvironmental record from the southwestern Pacific
5.6.2.2 Dating a 240-year palaeoprecipitation record from Florida, USA
Contents

5.6.3 Molluscs 160

5.6.3.1 The development of a sclerochronology using the long-lived bivalve *Arctica islandica* 160

5.6.3.2 The development of a ‘clam-ring’ master chronology from a short-lived bivalve mollusc and its palaeoenvironmental significance 162

Notes 162

6 Relative Dating Methods 165

6.1 Introduction 165

6.2 Rock Surface Weathering 166

6.2.1 Surface Weathering Features 166

6.2.2 Problems in Using Surface Weathering Features to Establish Relative Chronologies 167

6.2.3 Applications of Surface Weathering Dating 168

6.2.3.1 Relative dating of Holocene glacier fluctuations in the Nepal Himalaya 168

6.2.3.2 Relative dating of periglacial trimlines in northwest Scotland 168

6.2.3.3 Relative dating of archaeological features by Lake Superior, Canada 170

6.3 Obsidian Hydration Dating 172

6.3.1 The Hydration Layer 173

6.3.2 Problems with Obsidian Hydration Dating 173

6.3.3 Some Applications of Obsidian Hydration Dating 174

6.3.3.1 Dating of a Pleistocene age site, Manus Island, Papua New Guinea 174

6.3.3.2 Dating of fluvially reworked sediment in Montana, USA 176

6.4 Pedogenesis 176

6.4.1 Soil Development Indices 176

6.4.2 Problems in Using Pedogenesis as a Basis for Dating 177

6.4.3 Some Applications of Dating Based on Pedogenesis 178

6.4.3.1 Relative dating of moraines in the Sierra Nevada, California 178

6.4.3.2 Dating glacial events in southeastern Peru 178

6.5 Relative Dating of Fossil Bone 180

6.5.1 Post-Burial Changes in Fossil Bone 181

6.5.2 Problems in the Relative Dating of Bone 181

6.5.3 Some Applications of the Relative Dating of Bone 182

6.5.3.1 Fluoride dating of mastodon bone from an early palaeoindian site, eastern USA 182

6.5.3.2 Chemical dating of animal bones from Sweden 182

6.6 Amino Acid Geochronology 184

6.6.1 Proteins and Amino Acids 185

6.6.2 Amino Acid Diagenesis 186

6.6.3 Problems with Amino Acid Geochronology 187
6.6.4 Applications of Amino Acid Geochronology 188
6.6.4.1 Dating and correlation of the last interglacial shoreline (~MOI substage 5e) in Australia using aminostratigraphy 189
6.6.4.2 Quaternary aminostratigraphy in northwestern France based on non-marine molluscs 189
6.6.4.3 Dating the earliest modern humans in southern Africa using amino acid ratios in ostrich eggshell 191
6.6.4.4 Dating sea-level change in the Bahamas over the last half million years 192

Notes 195

7 Techniques for Establishing Age Equivalence 197
7.1 Introduction 197
7.2 Oxygen Isotope Chronostratigraphy 198
7.2.1 Marine Oxygen Isotope Stages 199
7.2.2 Dating the Marine Oxygen Isotope Record 199
7.2.3 Problems with the Marine Oxygen Isotope Record 201
7.3 Tephrochronology 202
7.3.1 Tephras in Quaternary Sediments 202
7.3.2 Dating of Tephra Horizons 204
7.3.3 Problems with Tephrochronology 205
7.3.4 Applications of Tephrochronology 207
7.3.4.1 Dating the first human impact in New Zealand using tephrochronology 207
7.3.4.2 Dating and correlating events in the North Atlantic region during the Last Glacial–Interglacial transition using tephrochronology 209
7.3.4.3 Dating Middle Pleistocene artefacts and cultural traditions in East Africa using tephrostratigraphy 209
7.3.4.4 Dating Early and Middle Pleistocene glaciations in Yukon by tephrochronology 211
7.4 Palaeomagnetism 213
7.4.1 The Earth’s Magnetic Field 214
7.4.2 The Palaeomagnetic Record in Rocks and Sediments 215
7.4.3 Magnetostatigraphy 216
7.4.3.1 Polarity changes and the palaeomagnetic timescale 216
7.4.3.2 Secular variations 216
7.4.3.3 Mineral magnetic potential 219
7.4.4 Some Problems with Palaeomagnetic Dating 220
7.4.5 Applications of Palaeomagnetic Dating 221
7.4.5.1 Dating lake sediments using palaeosecular variations 221
7.4.5.2 Palaeomagnetic correlations between Scandinavian Ice Sheet fluctuations and Greenland ice-core records 222
7.4.5.3 Palaeomagnetic dating of the earliest humans in Europe 223
7.4.5.4 Palaeomagnetic dating of the Sterkfontein hominid, South Africa 224
7.5 Palaeosols 225
7.5.1 The Nature of Palaeosols 227
7.5.2 Palaeosols as Soil-Stratigraphic Units 228
7.5.3 Some Problems with Using Palaeosols to Establish Age Equivalence 229
7.5.4 Applications of Palaeosols in the Establishment of Age Equivalence 230
7.5.4.1 Buried palaeosols on the Avonmouth Level, southwest England: stratigraphic markers in Holocene intertidal sediments 230
7.5.4.2 The Valley Farm and Barham Soils: key stratigraphic marker horizons in southeast England 231
7.5.4.3 Correlation between the Chinese loess–palaeosol sequence and the deep-ocean core record for the past 2.5 million years 233

Notes 235

8 Dating the Future 237
8.1 Introduction 237
8.2 Radiometric Dating 237
8.3 Annually Banded Records 240
8.4 Age Equivalence 242
8.5 Biomolecular Dating 243
Notes 244

References 245
Index 279