

The Periglacial Environment

Fourth Edition

Hugh M. French

*Professor Emeritus,
University of Ottawa,
Ontario*

*Adjunct Professor,
University of Victoria,
British Columbia*

WILEY Blackwell

Contents

Preface to Fourth Edition	<i>xv</i>
Preface to Third Edition	<i>xvii</i>
Preface to Second Edition	<i>xix</i>
Preface to First Edition	<i>xxi</i>
Acknowledgments	<i>xxiii</i>

Part I The Periglacial Domain 1

1	Introduction	3
1.1	The Periglacial Concept	3
1.2	Diagnostic Criteria	4
1.3	Periglacial Environments	5
1.4	The Periglacial Domain	6
1.5	The Periglacial Domain and the Cryosphere	9
1.6	Disciplinary Considerations	10
1.6.1	The Growth of Geocryology	10
1.6.2	The Challenge of Quaternary Science	11
1.6.3	Periglacial Geomorphology or Cold-Region Geomorphology?	12
1.7	Societal Considerations	12
1.8	The Growth of Periglacial Knowledge	13
2	Periglacial Climates	17
2.1	Boundary Conditions	17
2.2	Cold Deserts	17
2.3	Regional Climates	19
2.3.1	High Arctic Climates	21
2.3.2	Continental Climates	24
2.3.3	Alpine Climates	24
2.3.4	Montane Climates	24
2.3.5	Climates of Low Annual Temperature Range	25
2.3.6	Antarctica: A Special Case	26
2.4	Snow and Ice	26
2.5	Wind	28
2.6	Ground Climates	28
2.6.1	The 'n'-Factor	29

- 2.6.2 The Thermal Offset 30
- 2.6.3 The Ground Temperature Regime 31
- 2.7 Periglacial Climates and Global Climate Change 35
- 2.7.1 Basic Facts 37
- 2.7.2 Why Climate–Cryosphere Interactions Accelerate Climate Warming 38

3 Periglacial Ecosystems 41

- 3.1 General Statement 41
- 3.2 Biogeographic Zonation and Major Vegetation Types 41
- 3.3 Adaptations to Cold, Snow, Wind and Aridity 44
- 3.4 The Effect of Vegetation 44
- 3.5 The Polar Deserts 47
- 3.5.1 The High Arctic Polar Deserts 47
- 3.5.2 The High Arctic Polar Semi-Deserts 47
- 3.6 The Polar Desert–Tundra Transition 49
- 3.7 The Low-Arctic Tundra 49
- 3.8 The Forest–Tundra Bioclimatic Boundary (The Tree Line) 53
- 3.9 The Boreal Forest 56
- 3.10 The Alpine and Montane Ecosystems 58
- 3.11 Antarctica – A Special Case 60
- 3.12 Periglacial Ecosystems and Climate Change 61

Part II Frozen Ground and Permafrost 63

4 Ground Freezing, Permafrost and the Active Layer 65

- 4.1 Introduction 65
- 4.2 Ground Freezing 65
- 4.2.1 Basic Concepts 65
- 4.2.2 Ice Segregation 67
- 4.2.3 ‘The Frozen Fringe’ 69
- 4.2.4 Frost Heave 69
- 4.3 Perennially-Frozen Ground (Permafrost) 70
- 4.4 Moisture and Ice Within Permafrost 72
- 4.5 Thermal and Physical Properties 73
- 4.5.1 The Geothermal Regime 73
- 4.5.2 The TTOP Model 76
- 4.5.3 Physical Properties 77
- 4.5.4 Thermal Properties 78
- 4.6 Permafrost Hydrology 78
- 4.6.1 Aquifers 79
- 4.6.2 Hydrochemistry 80
- 4.6.3 Groundwater Icings 81
- 4.7 The Active Layer 82
- 4.7.1 Terminology 82
- 4.7.2 The Active-Layer Thermal Regime 83
- 4.7.3 The Transient Layer 83
- 4.7.4 The Stefan Equation 84

5	Permafrost Distribution and Stability	87
5.1	Introduction	87
5.2	Controls over Permafrost Distribution	87
5.2.1	Relief and Aspect	87
5.2.2	Rock Type	88
5.2.3	Vegetation	90
5.2.4	Snow Cover	90
5.2.5	Fire	92
5.2.6	Lakes and Surface Water Bodies	92
5.3	Spatial Extent of Permafrost and Frozen Ground	93
5.3.1	Latitudinal Permafrost	93
5.3.2	Alpine (Mountain) Permafrost	95
5.3.3	Montane Permafrost	98
5.3.4	Seasonally-Frozen Ground	100
5.4	Sub-Sea and Relict Permafrost	101
5.4.1	Sub-Sea Permafrost	101
5.4.2	Relict (Terrestrial) Permafrost	101
5.5	Permafrost and Ecosystems	102
5.6	Permafrost Monitoring and Mapping	104
5.6.1	CALM and GTN-P (TSP)	104
5.6.2	BTS and Mountain Permafrost Probability Mapping	106
5.7	Climate Warming and Permafrost	106
5.7.1	Evidence for Warming Permafrost	107
5.7.2	Evidence for Thawing Permafrost	109
6	Ground Ice and Cryostratigraphy	111
6.1	Introduction	111
6.2	Quantitative Parameters	111
6.3	Epigenetic, Syngenetic and Polygenetic Permafrost	112
6.4	Classification	113
6.4.1	The Russian Approach	113
6.4.2	The North American Approach	114
6.5	Main Ground Ice Types	115
6.5.1	Pore Ice	115
6.5.2	Segregated Ice	116
6.5.3	Intrusive Ice	117
6.5.4	Vein Ice	118
6.5.5	Other Types of Ice	118
6.6	Ice Distribution	118
6.6.1	Amounts	118
6.6.2	Distribution with Depth	120
6.6.3	Ice in Bedrock	120
6.6.4	Ice in Poorly-Lithified Sediments	121
6.7	Cryostratigraphy and Cryolithology	124
6.7.1	Cryostructural Analysis	125
6.7.2	Cryostructures of Epigenetic and Syngenetic Permafrost	128
6.7.3	Thaw Unconformities	129
6.7.4	Aggradational Ice	131
6.7.5	Icy Bodies and Ice, Sand and Soil Pseudomorphs	131

- 6.8 Ice Crystallography 132
- 6.9 Ice Geochemistry 133
- 6.10 Massive Ice and Massive-Icy Bodies 133
 - 6.10.1 Nature and Extent 134
 - 6.10.2 Intra-Sedimental Ice 135
 - 6.10.3 Buried Glacier Ice 136
- 6.11 Cryostratigraphy and Past Environments 136

- 7 Aggradational Permafrost Landforms 139**
 - 7.1 Introduction 139
 - 7.2 How Does Permafrost Aggrade? 139
 - 7.2.1 The Illisarvik Drained-Lake Experiment 139
 - 7.3 Thermal-Contraction-Crack Polygons 141
 - 7.3.1 Coefficients of Thermal Expansion and Contraction 141
 - 7.3.2 Ice, Sand and Soil ('Ground') Wedges 142
 - 7.3.3 Development of the Polygon Net 144
 - 7.3.4 Polygon Morphology 145
 - 7.3.5 Controls over Cracking 149
 - 7.3.6 Climatic Significance 149
 - 7.4 Ice and Sand Wedges 151
 - 7.4.1 Epigenetic Wedges 153
 - 7.4.2 Syngenetic Wedges 154
 - 7.4.3 Anti-Syngenetic Wedges 154
 - 7.4.4 Growth and Deformation of Wedges 156
 - 7.5 Organic Terrain 156
 - 7.5.1 Palsas 158
 - 7.5.2 Peat Plateaus 158
 - 7.6 Frost Mounds 159
 - 7.6.1 Perennial-Frost Mounds 159
 - 7.6.2 Hydraulic (Open) System Pingos 159
 - 7.6.3 Hydrostatic (Closed) System Pingos 161
 - 7.6.4 Other Perennial-Frost Mounds 165
 - 7.6.5 Seasonal-Frost Mounds 165
 - 7.6.6 Hydrolaccoliths and Other Frost-Induced Mounds 165

- 8 Thermokarst Processes and Landforms 169**
 - 8.1 Introduction 169
 - 8.2 Thawing Ground 169
 - 8.2.1 Thaw Strain and Thaw Settlement 169
 - 8.2.2 Potential Depths of Soil Freezing and Thawing 170
 - 8.2.3 The Development of Thermokarst 170
 - 8.3 Causes of Thermokarst 171
 - 8.3.1 General Comments 172
 - 8.3.2 Specific Causes 174
 - 8.4 Thaw-Related Processes 176
 - 8.4.1 Thermokarst Subsidence (Thaw Settlement) 176
 - 8.4.2 Thermal Erosion 176
 - 8.4.3 Other Processes 176

- 8.5 Thermokarst Sediments and Structures 177
- 8.5.1 Involuted Structures 177
- 8.5.2 Retrogressive-Thaw-Slumps and Debris-Flow Deposits 178
- 8.5.3 Ice-Wedge Pseudomorphs and Composite-Wedge Casts 179
- 8.5.4 Ice, Silt, Sand and Gravel Pseudomorphs 180
- 8.6 Thermokarst Landscapes 181
- 8.6.1 The Alas-Thermokarst Relief of Central Yakutia 182
- 8.6.2 The Western North American Arctic 185
- 8.6.3 The Ice-Free Areas of Continental Antarctica 185
- 8.7 Ice-Wedge Thermokarst Relief 186
- 8.7.1 Low-Centred Polygons 186
- 8.7.2 High-Centred Polygons 186
- 8.7.3 Badland Thermokarst Relief 186
- 8.8 Thaw Lakes and Depressions 187
- 8.8.1 Lakes and Tálíks 189
- 8.8.2 Morphology 189
- 8.8.3 Growth and Drainage 189
- 8.8.4 Oriented Thaw Lakes 191

Part III Periglacial Geomorphology 193

- 9 Cold-Climate Weathering 195**
- 9.1 Introduction 195
- 9.2 General Weathering Facts 195
- 9.3 Freezing and Thawing Indices 196
- 9.4 Rock (Frost?) Shattering 197
- 9.4.1 Frost Action and Ice Segregation 197
- 9.4.2 Insolation and Thermal Shock 200
- 9.4.3 Perspective 202
- 9.5 Chemical Weathering 204
- 9.5.1 Karkevagge 204
- 9.5.2 Solution and Karstification 205
- 9.5.3 Salt Weathering 208
- 9.6 Cryogenic Weathering 208
- 9.6.1 Cryogenic Disintegration 210
- 9.6.2 The Coefficient of Cryogenic Contrast 210
- 9.6.3 Physico-Chemical Changes 212
- 9.6.4 Problematic Phenomena 212
- 9.7 Cryobiological Weathering 213
- 9.8 Rates of Cold-Climate Bedrock Weathering 214
- 9.9 Cryosols and Cryopedology 215
- 9.9.1 Cryosols 215
- 9.9.2 Classification 216
- 9.9.3 Cryosolic Micromorphology 216
- 10 Mass-Wasting Processes and Active-Layer Phenomena 219**
- 10.1 Introduction 219

10.2	Slow Mass-Wasting Processes	219
10.2.1	Solifluction	219
10.2.2	Frost Creep	221
10.2.3	Gelifluction	223
10.2.4	Solifluction Deposits and Phenomena	223
10.3	Rapid Mass-Wasting Processes	226
10.3.1	Active-Layer-Detachment Slides	226
10.3.2	Debris Flows, Slush Flows and Avalanches	226
10.3.3	Rockfall	230
10.4	Snow Hydrology and Slopewash Processes	232
10.4.1	Snow Hydrology and Snowbanks	233
10.4.2	Surface and Subsurface Wash	233
10.5	Active-Layer Phenomena	235
10.5.1	Frost Heaving	235
10.5.2	Bedrock Heave	235
10.5.3	Upward Heaving of Stones and Objects	235
10.5.4	Stone Tilting	237
10.5.5	Needle Ice	239
10.5.6	Frost Sorting	239
10.5.7	Cryoturbation	240
10.6	Patterned Ground	240
10.6.1	Sorted and Non-Sorted Circles	240
10.6.2	Mud Boils	243
10.6.3	Nets and Stripes	246
11	Azonal Processes and Landforms	247
11.1	Introduction	247
11.2	Fluvial Processes and Landforms	247
11.2.1	Major Rivers	248
11.2.2	Freeze-Up and Break-Up	251
11.2.3	Basin Hydrology	252
11.2.4	Sediment Flow, Surface Transport and Denudation	255
11.2.5	Channel Morphology	256
11.3	Lakes and Lake Ice	259
11.3.1	Lake Ice and Climate Change	259
11.3.2	Perennially-Frozen Lakes	260
11.4	Coastal Processes and Landforms	260
11.4.1	Sea Ice	260
11.4.2	Sea Ice, Wave Generation and Sediment Transport	261
11.4.3	Ice on the Beach and the Near-Shore	262
11.4.4	The Influence of Permafrost	264
11.4.5	Cold-Climate Deltas	266
11.5	Aeolian Processes, Sediments and Landforms	267
11.5.1	Wind Abrasion	268
11.5.2	Wind Deflation	271
11.5.3	Sand Dunes and Sand Sheets	271
11.5.4	Niveo-Aeolian Sediments	273
11.5.5	Loess-Like Silt	274

12	Slope Development and Landscape Evolution	275
12.1	Introduction	275
12.2	Slope Morphology	275
12.2.1	The Free-Face Slope	275
12.2.2	Rectilinear Debris-Mantled Slopes	278
12.2.3	Convexo-Concavo Debris-Mantled Slopes	278
12.2.4	Pediment-Like Slopes and Inselberg-Like Hills	280
12.2.5	Stepped Profiles	281
12.3	Slope and Valley Development	284
12.3.1	Slope Asymmetry	284
12.4	Frozen and Thawing Slopes	287
12.4.1	Frozen Ground (Permafrost) Creep	287
12.4.2	Rock Glaciers	288
12.4.3	Thaw Consolidation and the Stability of Thawing Slopes	290
12.5	Periglacial Slope Evolution	293
12.5.1	The Davisian (Peltier) Model	293
12.5.2	Cryoplanation	295
12.5.3	Richter Denudation Slopes	295
12.6	Landscape Inheritance	296
	Part IV Pleistocene Periglacial Environments	299
13	The Pleistocene Periglacial Domain	301
13.1	Introduction	301
13.2	The Time Scale and Climatic Fluctuations	301
13.3	Global (Eustatic) Considerations	304
13.3.1	Sea-Level Changes	304
13.3.2	Uplift of Qinghai-Xizang (Tibet) Plateau	304
13.4	Past Glaciations, Permafrost and Frozen Ground	305
13.4.1	Extent of Past Glaciations	305
13.4.2	Relict Permafrost	306
13.5	Pleistocene Periglacial Environments	307
13.5.1	General Considerations	307
13.5.2	Problems of Paleo-Environmental Reconstruction	308
13.5.3	Ice Age Mammals and Ecosystems	309
13.6	The Pleistocene Periglacial Domain in the Northern Hemisphere	312
13.6.1	Extent of LPM Permafrost	313
13.6.2	Western, Central and Southern Europe	313
13.6.3	Eastern Europe and Kazakhstan	315
13.6.4	Southern, Central and Northern Siberia	317
13.6.5	Western and North-Eastern China	317
13.6.6	North America	319
13.7	The Pleistocene Periglacial Domain in the Southern Circumpolar Region	321
14	Previously-Frozen Ground	323
14.1	Introduction	323
14.2	Past Permafrost Aggradation	323
14.2.1	The Paleo-Active Layer and Associated Weathering Characteristics	323

- 14.2.2 Fragipans and the Paleo-Permafrost Table 326
- 14.2.3 Secondary Precipitates and Clay Minerals 326
- 14.3 Frost-Fissure Pseudomorphs and Casts 327
- 14.3.1 Terminology Relevant to Pleistocene-Age Structures in Unfrozen Sediments 327
- 14.3.2 Ice-Wedge Pseudomorphs 329
- 14.3.3 Sand Veins, Sand-Wedge Casts and Composite-Wedge Casts 331
- 14.3.4 Frost Cracking: Seasonal or Perennial? 332
- 14.4 Frost-Mound Remnants 333
- 14.5 Past Permafrost Degradation 335
- 14.5.1 Thermokarst Depressions 335
- 14.5.2 Thermokarst Involutions and 'Sediment-Filled Pots' 336
- 14.5.3 Large-Scale Soft-Sediment Deformations 338
- 14.5.4 Non-Diastrophic Structures 339
- 14.6 Summary 341
- 15 Pleistocene Periglaciation 343**
- 15.1 Introduction 343
- 15.2 Intense Frost Action 343
- 15.2.1 Frost-Disturbed Bedrock 343
- 15.2.2 Mountain-Top Detritus ('Blockfields') 344
- 15.2.3 Tors 347
- 15.2.4 Stratified Slope Deposits 347
- 15.2.5 Frost-Disturbed Soils, Periglacial Involutions and Patterned Ground 347
- 15.3 Mass-Wasting and Aeolian-Linked Sediment Deposition 351
- 15.3.1 Geological 'Time Travellers' 351
- 15.3.2 Head or Solifluction Deposits 353
- 15.3.3 'Yedoma' and 'Muck' deposits 353
- 15.3.4 Loess and Aeolian Silt 355
- 15.4 Wind Abrasion and Aeolian Sediment Transport 358
- 15.4.1 Wind-Abraded Rocks 359
- 15.4.2 Aeolian Sand Deposition 360
- 15.5 Drainage Modification 360
- 15.5.1 Ice-Marginal Drainage 361
- 15.5.2 River and Valley Incision in Ice-Free Areas 362
- 15.5.3 Enlargement of the Drainage Network 364
- 15.5.4 Asymmetrical Valley Development 364
- 15.6 Planation and Pedimentation 366
- 15.7 A Perspective on Periglaciation 366

Part V Human Occupation and The Periglacial Environment 371

- 16 Urban and Social Infrastructure 373**
- 16.1 Introduction 373
- 16.2 Human Occupation 373
- 16.3 Human-Induced Thermokarst 375
- 16.3.1 Early Siberian and North American Experience 375
- 16.3.2 The Rapidity of Change 376

16.4	Cold-Regions Engineering	378
16.4.1	General Principles	378
16.4.2	General Solutions	379
16.5	Provision of Municipal Infrastructure in Northern Canada	384
16.5.1	Inuvik, NWT	384
16.5.2	Dawson City, Yukon Territory	384
16.5.3	Yellowknife, NWT	387
16.5.4	Thompson, Northern Manitoba	390
16.6	The Alaskan Experience: The Example of Fairbanks	390
16.7	Water-Supply Problems	392
16.8	Urban Infrastructure and Climate Change	392
16.8.1	The Russian North	392
16.8.2	Other Areas	394
16.8.3	Related Socio-Economic Changes	396
17	Transportation and Resource Development	399
17.1	Introduction	399
17.2	Rivers as Highways	399
17.3	Roads and Highways	401
17.3.1	Winter Roads	401
17.3.2	All-Season Roads	401
17.4	Railways	405
17.4.1	The Hudson Bay Railway, Canada	405
17.4.2	The Qinghai-Tibet Railway (QTR), China	406
17.5	Bridge Construction	406
17.6	Runways and Airstrips	410
17.7	Oil and Gas Development	411
17.7.1	Exploration Problems	411
17.7.2	Drilling and Waste-Drilling-Fluid Disposal Problems	414
17.7.3	Pipelines and Permafrost	415
17.8	Mining Activities	419
17.8.1	Placer Gold Mining	419
17.8.2	Opencast Mining	420
17.8.3	Containment and Waste Disposal	420

References 423

Index 503