Sedimentary Environments and Facies EDITED BY

H. G. READING

Department of Earth Sciences University of Oxford

SECOND EDITION



BLACKWELL SCIENTIFIC PUBLICATIONS OXFORD LONDON EDINBURGH BOSTON PALO ALTO MELBOURNE

Contents

Authors. x

Preface, xi

1 Introduction, 1

H. G. READING

- 1.1 Development of sedimentology, 1
- Scope and philosophy of this book, 2 1.2
- 1.3 Organization of the book, 2

2 Facies, 4

H.G. READING

2.1 Facies construction, 4

- 2.1.1 Facies definition, 4
- 2.1.2 Facies relationships, 4

2.2 Interpretation of facies, 8

- 2.2.1 Hypotheses, models and theories, 8
- 2.2.2 Normal v catastrophic sedimentation; abundant and rare sediments; exceptional events, 10
- 2.2.3 Preservation potential, 11

Facies in the subsurface, 12 2.3

- 2.3.1 Seismic facies, 12
- 2.3.2 Rocks in the subsurface, 13
- 2.3.3 Wireline logs, 13
- 2.4 Factors controlling the nature and distribution of facies, 15
- 2.4.1 Sedimentary processes, 15
- 2.4.2 Sediment supply, 16
- 2.4.3 Climate, 16
- 2.4.4 Tectonics, 16
- 2.4.5 Sea-level changes, 16
- 2.4.6 Biological activity, 18 2.4.7 Water chemistry, 18
- 2.4.8 Volcanism, 19

- 3.4 3.4.1
 - 3.4.2 3.4.3

Alluvial fans, 29

Meander belts, 35

- 3.6 Inter-channel areas, 41
- Overbank environments, 41 3.6.1
- Areas beyond river influence, 42 3.6.2
- 3.7 Ancient alluvial sediments, 44
- 3.8 Ancient pebbly alluvium, 44
- 3.8.1 Facies, 44
- Lateral facies distributions, 46 3.8.2
- Vertical facies sequences, 48 3.8.3
- Palaeocurrents, 49 3.8.4

3.9 Ancient sandy fluvial systems, 49

- 3.9.1 Introduction, 49
- 3.9.2 Fine member deposits, 49
- Coarse member (channel) deposits, 52 3.9.3
- 3.9.4 Patterns and organization in sandy alluvium, 54

Lakes, 63

- P. A. ALLEN and J. D. COLLINSON
- 4.1 Introduction, 63
- Diversity of present-day lakes, 63 4.2
- 4.3 Properties of lake water, 64

Channel processes, 36 Channel cut-offs, 40

Stream-dominated fans, 30

Present-day meandering rivers, 34

Semi-arid fans, 31

Present-day bedload streams, 20

Pebbly bedforms and processes, 21

Sandy bedforms and processes, 25 Semi-arid ephemeral streams, 29

3.5 Anastomosing channels, 40

3 Alluvial Sediments, 20 J. D. COLLINSON

3.1 Introduction, 20

3.2 3.2.1

3.2.2

3.2.3

3.3

3.3.1

3.3.2

- 4.4 Kinetics of lake water, 66
- 4.5 Chemistry and productivity of lake waters, 68
- 4.6 Sediments of hydrologically open lakes, 69
- 4.6.1 Clastic sedimentation, 69
- 4.6.2 Chemical and biochemical sedimentation, 70
- 4.7 Sediments of hydrologically closed lakes, 72
- 4.7.1 Clastic sedimentation, 72
- 4.7.2 Chemical and biochemical sedimentation, 74
- 4.8 Ancient lake sediments, 76
- 4.8.1 Criteria for recognition of ancient lake sediments, 76
- 4.8.2 Ancient lacustrine facies, 76

4.9 Ancient dilute lakes in hydrologically open basins, 77

- 4.9.1 The Devonian Orcadian basin of NE Britain, 77
- 4.9.2 Other ancient terrigenous lakes, 80
- 4.9.3 Oligocene of the Eastern Ebro basin, Spain, 80
- 4.9.4 Middle Triassic of East Greenland, 82
- 4.9.5 Other ancient lakes with marginal bioherms and coated grain facies, 83

4.10 Ancient lakes in hydrologically closed basins, 85

- 4.10.1 The Green River Formation of Utah, Wyoming and Colorado, 85
- 4.10.2 Pliocene Ridge Basin Group, California, 89
- 4.10.3 Palaeogene of the Rhône Valley, southern France, 90
- 4.10.4 Other ancient closed basin lakes, 91
- 4.11 Economic importance of lake deposits, 94

5 Deserts, 95

J. D. COLLINSON

- 5.1 Introduction, 95
- 5.2 Present-day deserts, 95
- 5.2.1 Introduction and setting, 95
- 5.2.2. Desert distribution and climate, 95
- 5.2.3 Tectonic setting of deserts, 96
- 5.2.4 Aeolian transport and deposition of sand, 97
- 5.2.5 Aeolian bedforms, 97
- 5.2.6 Interdune and sand sheet areas, 101 5.2.7 Internal dune structures, 102
- 5.2.8 Desert loess, 104
- 5.2.9 Overall desert models, 105

5.3 Ancient desert sediments, 106

- 5.3.1 Introduction, 106
- 5.3.2 Recognition of aeolian sands, 106
- 5.3.3 Types of ancient aeolian dune, 107
- 5.3.4 Interdune deposits, 108
- 5.3.5 Overall desert facies patterns, 110

6 Deltas, 113 T. ELLIOTT

6.1 Introduction, 113

- 6.2 Development of delta studies, 113
- 6.3 A conceptual framework for deltas, 114
- 6.3.1 Hinterland and receiving basin characteristics, 115
- 6.4 Delta models, 116
- 6.5 Facies associations in modern deltas, 117
- 6.5.1 The delta plain, 117
- 6.5.2 The delta front, 124
- 6.6 Delta abandonment, 133

6.7 Ancient deltaic successions, 136

- 6.7.1 Ancient fluvial-dominated deltas, 136
- 6.7.2 Ancient wave-dominated deltas, 145
- 6.7.3 Ancient tide-dominated deltas, 148

6.8 Sediment-induced deformation, 148

- 6.8.1 Deformational processes, 149
- 6.8.2 Deformational features, 150
- 6.8.3 Sediment-induced deformational features in exposed deltaic successions, 154

7 Siliciclastic Shorelines, 155 T. ELLIOTT

7.1 Introduction, 155

- 7.2 Wave-dominated shorelines, 155
- 7.2.1 Nearshore wave processes, 156
- 7.2.2 Beach face sub-environments: processes and products, 160
- 7.2.3 Facies sequences of modern prograding wave-dominated shorelines, 162
- 7.2.4 Wave-dominated, microtidal barrier islands and lagoons, 167
- 7.2.5 Ancient progradational wave-dominated shorelines, 169 7.2.6 Chenier plains, 174
- 7.2.0 Chemier plains, I
- 7.3 Mixed wave-tide shorelines, 175
- 7.3.1 Modern wave-tide influenced shorelines, 175
- 7.3.2 Ancient progradational wave-tidal influenced shorelines, 179
- 7.4 Transgressive wave-dominated and wave-tide influenced shorelines, 179
- 7.4.1 Mechanisms of beach/barrier island migration, 179 7.4.2 Ancient transgressive shorelines, 181

7.5 Tide-dominated shorelines, 182

- 7.5.1 Modern estuaries, 182
- 7.5.2 Modern tidal flats, 186
- 7.5.3 Ancient estuarine and tidal flat facies associations, 187

B. C	SCHREIBER (With contributions from M. E. Tucker and R. Till)
8.1	Introduction, 189
8.1.1	Place and time, 189
8.1.2	History of research, 189
8.2	Seawater evaporation, 191
821	Marine precipitates, 191
8.2.2	2 Trace element signature of seawater, 194
8.3	Environments of marine evaporite formation and accumulation, 195
8.4	Modern carbonate-rich sabkhas: The Trucial coast, 195
8.4.1	General setting, 195
8.4.2	2 Reefs, oolite shoals and tidal channels, 197
8.4.3	Lagoons: subtidal to lower intertidal zones, 197
8.4.4	Upper intertidal zone: algal mats, 197
8.4.4	5 Supratidal zone: the sabkha proper, 198
8.4.0	Mediterranean sabkhas: mixed carbonates and
	siliciclastics, 200
8.4.	7 Algal mats of Shark Bay, 201
8.5	Modern siliciclastic sabkhas, 202
8.5	Coastal salinas of Baia California: the ground water
0.5.	chemistry of dolomite gynsum and halite 202
95	Brine page of the Gulf of Flat Sinai 204
85	The sables over an overview 204
0.3	The sabkha cycle. all overview, 204
8.6	Subaqueous evaporites, 205
8.6.	Shallow water facies, 205
8.6.2	2 Coastal salinas of South Australia, 210
8.6.	3 Deep water evaporites, 211
8.7	Some non-marine salt lakes, 212
8.8	Ancient evaporites, 213
8.9	Ancient sabkhas and brine pools, 213
8.9.	1 The Lower Purbeck of Southern England, 214
8.9.	2 Permian Lower Clear Fork of Texas, 216
8.10	Ancient basinal evaporites, 218
8.10	.1 Basin models: criteria for water depth, 218
8.10	2 The Messinian of the Mediterranean, 220
8.10	3 The Zechstein (Upper Permian) of the North Sea, 221
8.10	.4 The Permian Delaware Basin of West Texas and New
	Mexico, 223
8.10	0.5 The Michigan Basin, 225
8.11	Diagenesis of evaporites: A second look, 226
8.11	.1 The gypsum-anhydrite cycle, 226
Sh	allow Siliciclastic Seas, 229
Н.	D. JOHNSON and C. T. BALDWIN
9.1	Introduction, 229
01	General background 229

8 Arid Shorelines and Evaporites, 189

- 9.1.2 Historical development, 229
- 2 Modern siliciclastic shelf models, 231
- 9.3 Main processes controlling shelf sedimentation and facies, 232
- 9.3.1 Rate and type of sediment supply, 232
- 9.3.2 Type and intensity of the shelf hydraulic regime, 233
- 9.3.3 Sea-level fluctuations, 233
- 9.3.4 Climate, 233
- 9.3.5 Animal-sediment interactions, 233
- 9.3.6 Chemical factors, 235

9.4 Physical processes (general), 235

- 9.4.1 Oceanic currents, 236
- 9.4.2 Tidal currents, 236
- 9.4.3 Meteorological currents, 236
- 9.4.4 Density currents, 238

9.5 Tide-dominated shelf sedimentation, 238

- 9.5.1 Sedimentary facies along tidal current transport paths, 238
- 9.5.2 Sediment dispersal patterns, 240
- 9.5.3 Tidal sand ridges, 240

9.6 Storm-dominated (wind- and wave-driven) shelf sedimentation, 242

- 9.6.1 Storm-dominated (wind- and wave-driven)
- sedimentation on the Oregon-Washington shelf, 243
- 9.6.2 Storm-dominated (wind-driven) sedimentation on the NW Atlantic shelf, 245
- 9.6.3 Other storm-dominated shelves: Gulf of Mexico and Bering Sea, 247
- 9.7 Oceanic current-dominated shelf sedimentation, 249

9.8 Modern shelf storm deposits: their nature and origin, 251

- 9.8.1 Characteristics of modern shelf storm deposits, 251
- 9.8.2 Proximal-distal trends in modern shelf storm deposits, 252
- 9.8.3 Origin of modern shelf storm deposits, 253

9.9 Ancient shallow siliciclastic seas, 254

- 9.9.1 Criteria used for recognizing ancient shallow marine siliciclastic deposits, 255
- 9.9.2 Classification of shallow marine siliciclastic facies and their depositional processes, 257

9.10 Tide-dominated offshore facies, 258

- 9.10.1 Sedimentary structures in offshore tidal deposits, 258
- 9.10.2 Tidal sand ridges, 260
- 9.10.3 Palaeocurrents and offshore tidal currents, 264

9.11 Wave- and storm-dominated offshore facies, 265

- 9.11.1 Wave ripples and wave ripple cross-lamination, 265
- 9.11.2 Hummocky cross-stratification, 265
- 9.11.3 Characteristics of ancient offshore storm sand layers, 266

9.12 Mud-dominated offshore facies, 268

- 9.12.1 Palaeoecological aspects, 268
- 9.12.2 Sedimentological aspects, 270

viii CONTENTS

- 9.13 Ancient offshore shallow marine siliciclastic facies models, 270
 9.13.1 Tide-dominated systems, 270
 9.13.2 Tide/storm interactive systems, 271
 9.13.3 Wave/storm (non-tidal) interactive systems, 273
- 9.13.4 Storm/current interactive systems, 277
- 9.14 Sand supply models to ancient shelf seas, 280
 9.14.1 Sand supply to Precambrian tidal shelves, 281
 9.14.2 Sand supply to the Cretaceous Western Interior seaway, 282
- 10 Shallow-marine Carbonate Environments, 283 B. W. SELLWOOD

10.1 Introduction, 283

10.2 **Carbonate ingredients and controls on production and distribution**, 284

10.2.1 Ingredients, 284 10.2.2 Controls, 286

10.2.2 Controls, 280

10.3 Modern subtropical carbonate shelves, 288

- 10.3.1 General settings, 288
- 10.3.2 Environments and facies in 'warm-water' carbonate systems, 289
- 10.3.3 Examples of open shelves, 301
- 10.3.4 Examples of rimmed shelves, 305

10.4 Facies models in ancient warm-water shelf carbonates, 315

- 10.4.1 Stable isotopes of Oxygen and Carbon in facies interpretation, 316
- 10.4.2 Sequence evaluation, 318
- 10.4.3 Muddy sequences, 321
- 10.4.4 Grainy sequences, 324

10.5 Carbonate buildups through time, 327

10.6 Temperate water carbonates, 338

10.6.1 Modern temperate marginal shelves, 339 10.6.2 Modern temperate isolated platforms, 339

- 10.6.3 Ancient temperate marginal shelf facies and rocky shoreline associations, 340
- 10.6.4 Carbonate tillite associations, 341

11 Pelagic Environments, 343 H. C. JENKYNS

11.1 Historical Introduction, 343

11.1.1 Pelagic sediments in the oceans, 343 11.1.2 Pelagic sediments on land, 344

11.2 Definitions and classifications, 344

11.3 Pelagic sediments in the oceans, 345 11.3.1 Introduction to pelagic sedimentation, 345

11.3.2 Spreading ridges, 349

- 11.3.3 Aseismic volcanic structures, 354
 11.3.4 Deep ocean basins, 358
 11.3.5 Small ocean basins, 359
 11.3.6 Continental-margin seamounts, banks, plateaus and basins, 362
- 11.4 Pelagic sediments on land, 365
 11.4.1 Introduction, 365
 11.4.2 Pelagic sediments with inferred oceanic basement, 366
 11.4.3 Deposits of small pelagic basins, 374
 11.4.4 Continental-margin facies, 376
 11.4.5 Deposits of epeiric seas, 385
 11.4.6 Palaeoceanography and the pelagic record, 390

11.5 Conclusions, 396

12 Deep Clastic Seas, 399 DORRIK A. V. STOW

12.1Introduction, 39912.1.1Historical outline, 39912.1.2Geological controls, 400

12.2 Processes, 400
12.2.1 Erosion-transport-deposition, 400
12.2.2 Process continuum, 401
12.2.3 Residimentation processes, 402
12.2.4 Normal bottom currents, 408
12.2.5 Surface currents and pelagic settling, 410

12.3 Facies: Modern and ancient, 411 12.3.1 Facies characteristics, 411 12.3.2 Facies classification, 411 12.3.3 Facies models (general), 413 12.3.4 Resedimented facies models (clastics), 413 12.3.5 Resedimented facies models (biogenics), 417 12.3.6 Bottom current facies models, 418

12.3.7 Hemipelagite and pelagite facies models, 420

12.4 Modern deep-sea environments, 420

12.4.1 Environmental models and their components, 42012.4.2 Slope-aprons, 42012.4.3 Submarine fans, 42512.4.4 Basin plains, 428

- **12.5** Ancient deep-sea systems: recognition, 430 12.5.1 Scale, preservation and bathymetry, 431
- 12.5.2 Horizontal facies distribution, 432
 12.5.3 Palaeocurrents and palaeoslopes, 434
 12.5.4 Vertical facies sequences, 434
 12.5.5 Environmental facies association, 436

12.6 Ancient deep-sea systems: examples and controls, 438
12.6.1 Sediment supply and related controls, 438
12.6.2 Tectonic controls, 440
12.6.3 Sea-level fluctuations, 443

13 Glacial Environments, 445 M. EDWARDS

13.1 Historical background, 445

13.2 Present-day glaciers, 445 13.2.1 Glacier flow, 446 13.2.2 Thermal balance, 446

13.2.3 Mass balance, 447

13.3 Modern glacial environments and facies, 447

13.3.1 The basal zone, 449
13.3.2 The supraglacial and ice-contact proglacial zone, 449
13.3.3 Glaciofluvial environment, 451
13.3.4 Aeolian environment, 451
13.3.5 Pedogenic environment, 451
13.3.6 Glaciolacustrine environment, 451
13.3.7 Glaciomarine environment, 452

13.4 Glacial sedimentary facies, 454

13.4.1 Subglacial facies, 45513.4.2 Supraglacial facies, 45813.4.3 Proglacial outwash facies, 45913.4.4 Glaciomarine and glaciolacustrine facies, 461

13.5 Glacial facies associations and sequences, 463

13.5.1 Terrestrial glacial facies zones, 464
13.5.2 Examples of ancient terrestrial glacial facies associations, 465
13.5.3 Marine glacial facies zones, 467
13.5.4 Examples of ancient marine glacial facies associations, 469

13.6 Conclusion, 469

14 Sedimentation and Tectonics, 471 A. H. G. MITCHELL and H. G. READING

14.1 Introduction, 471

14.2 The geosynclinal theory, 471 14.2.1 Early American and European views 1859–1920, 471 14.2.2 Concepts and classification of geosynclines in Europe, 471

14.2.3 Concepts and classification of geosynclines in North America, 474

- 14.2.4 Concepts of geosynclines and metallogenesis in the USSR, 475
- 14.2.5 Geosynclinal facies and cycles of sedimentation, 476 14.2.6 Plate tectonics and geosynclines, 477

14.3 Global tectonic settings and sedimentation, 478

14.4 Interior basins, rifts and aulacogens, 478 14.4.1 Continental interior basins, 478

- 14.4.2 Thermally initiated rifts, failed rifts and aulacogens, 480
- 14.4.3 Collision-related rifts, 485

14.5 Passive continental margins, 486

14.5.1 Modern shelves, slopes and rises, 486

14.5.2 Ancient passive margins, 489

14.6 Ocean basins and rises, 491

14.6.1 Early stages of ocean rise basin development, 491 14.6.2 Later stages of ocean rise basin development, 491

14.7 Subduction-related settings, 493

14.7.1 Deep-sea trenches and outer arcs, 49414.7.2 Volcanic arcs, 49714.7.3 Fore-arc basins, 49914.7.4 Back-arc marginal basins, 500

14.8 Strike-slip/transform fault-related settings, 502

14.8.1 Modern strike-slip basins, 504

14.8.2 Ancient strike-slip basins, 508

14.9 Collision-related settings, 512

14.9.1 Remnant basins, 513

- 14.9.2 Foreland basins, 514
- 14.9.3 Supra-arc troughs, 516
- 14.9.4 Intramontane basins, troughs and graben, 516

14.10 Geosynchial evolution and global tectonics, 51714.10.1 The Wilson cycle, 51714.10.2 Strike-slip cycle, 518

15 Problems and Perspectives, 520 H. G. READING

References, 525

Index, 593