

# BRIEF CONTENTS

## **PART I Igneous Petrology 1**

- Chapter 1 Some Fundamental Concepts 2
- Chapter 2 Classification and Nomenclature of Igneous Rocks 23
- Chapter 3 Textures of Igneous Rocks 34
- Chapter 4 Igneous Structures and Field Relationships 54
- Chapter 5 An Introduction to Thermodynamics 83
- Chapter 6 The Phase Rule and One- and Two-Component Systems 93
- Chapter 7 Systems with More Than Two Components 113
- Chapter 8 Chemical Petrology I: Major and Minor Elements 135
- Chapter 9 Chemical Petrology II: Trace Elements and Isotopes 158
- Chapter 10 Mantle Melting and the Generation of Basaltic Magma 183
- Chapter 11 Magma Diversity 202
- Chapter 12 Layered Mafic Intrusions 222
- Chapter 13 Mid-Ocean Ridge Volcanism 244
- Chapter 14 Oceanic Intraplate Volcanism 270
- Chapter 15 Continental Flood Basalts 301
- Chapter 16 Subduction-Related Igneous Activity, Part I: Island Arcs 323
- Chapter 17 Subduction-Related Igneous Activity, Part II: Continental Arcs 352
- Chapter 18 Granitoid Rocks 377
- Chapter 19 Continental Alkaline Magmatism 397
- Chapter 20 Anorthosites 436

## **PART II Metamorphic Petrology 445**

- Chapter 21 An Introduction to Metamorphism 446
- Chapter 22 A Classification of Metamorphic Rocks 470
- Chapter 23 Structures and Textures of Metamorphic Rocks 477
- Chapter 24 Stable Mineral Assemblages in Metamorphic Rocks 518
- Chapter 25 Metamorphic Facies and Metamorphosed Mafic Rocks 537
- Chapter 26 Metamorphic Reactions 558
- Chapter 27 Thermodynamics of Metamorphic Reactions 579
- Chapter 28 Metamorphism of Pelitic Sediments 607
- Chapter 29 Metamorphism of Calcareous and Ultramafic Rocks 635
- Chapter 30 Metamorphic Fluids, Mass Transport, and Metasomatism 654

*Appendix A: Estimating the Density and Viscosity of Silicate Melts 683*

*Appendix B: The CIPW Norm 686*

*Index 693*

# CONTENTS

Preface xv

## Part I Igneous Petrology 1

### Chapter 1 Some Fundamental Concepts 2

Questions to be Considered in this Chapter 2

1.1 Introduction to Igneous Petrology 2

1.2 The Earth's Interior 4

1.3 Origin of the Solar System and the Earth 6

1.4 Differentiation of the Earth 8

1.5 How Do We Know All This? 9

1.6 Meteorites 11

1.7 Pressure and Temperature Variations with Depth 12

1.7.1 The Pressure Gradient 12

1.7.2 Heat Transfer and the Temperature Gradient 13

1.7.3 Dynamic Cooling of the Earth: Geodynamics and Plate Tectonics 15

1.8 Magma Generation in the Earth 17

*Summary 20 • Key Terms 20 • Important "First Principle" Concepts 20 •*

*Suggested Further Readings 21*

### Chapter 2 Classification and Nomenclature of Igneous Rocks 23

Questions to be Considered in this Chapter 23

2.1 Introduction 23

2.2 Compositional Terms 24

2.3 The IUGS Classification 25

2.3.1 Calculations and Plotting 25

2.3.2 Phaneritic Rocks 26

2.3.3 Modifying Terms 28

2.3.4 Mafic and Ultramafic Rocks 28

2.4 Aphanitic Rocks 28

2.5 Pyroclastic Rocks 30

*Summary 31 • Key Terms 31 • Important "First Principle" Concepts 31 •*

*Suggested Further Readings 31*

### Chapter 3 Textures of Igneous Rocks 34

Questions to be Considered in this Chapter 34

3.1 Primary Textures (Crystal/Melt Interactions) 35

3.1.1 Rates of Nucleation, Growth, and Diffusion 35

3.1.2 Nucleation at Preferred Sites 38

3.1.3 Compositional Zoning 38

3.1.4 Crystallization Sequence 39

3.1.5 Magmatic Reaction and Resorption 41

3.1.6 Differential Movement of Crystals and Melt 41

3.1.7 Cumulate Textures 42

3.1.8 Primary Twinning 43

3.1.9	Volcanic Textures	43
3.1.10	Pyroclastic Textures	44
3.2	Secondary Textures: Postmagmatic Changes	45
3.2.1	Polymorphic Transformation	45
3.2.2	Secondary Twinning	46
3.2.3	Exsolution	47
3.2.4	Secondary Reactions and Replacement	47
3.2.5	Deformation	49
3.3	A Glossary of Igneous Textural Terms	49
	<i>Summary</i>	52 • <i>Key Terms</i>
		53 • <i>Important "First Principle" Concepts</i>
		53 • <i>Suggested Further Readings</i>
		53

## Chapter 4 Igneous Structures and Field Relationships 54

	Questions to be Considered in this Chapter	54
4.1	Extrusive, or Volcanic, Processes, Products, and Landforms	54
4.1.1	Properties of Magma and Eruptive Styles	54
4.1.2	Central Vent Landforms	56
4.1.3	Fissure Eruptions	60
4.1.4	Lava Flow Features	60
4.1.5	Pyroclastic Deposits	63
4.1.5.1	Pyroclastic Fall Deposits	63
4.1.5.2	Pyroclastic Flow Deposits	65
4.1.5.3	Pyroclastic Surge Deposits	66
4.1.5.4	Comparing Pyroclastic Deposits	66
4.2	Intrusive, or Plutonic, Processes and Bodies	67
4.2.1	Tabular Intrusive Bodies	67
4.2.2	Non-Tabular Intrusive Bodies	71
4.2.3	Contact Relationships of Plutons	72
4.2.4	Timing of Intrusion	73
4.2.5	Depth of Intrusion	73
4.2.6	Multiple-Injection and Zoned Plutons	76
4.2.7	The Process of Magma Rise and Emplacement, and the "Room Problem"	77
4.3	Hydrothermal Systems	79
	<i>Summary</i>	80 • <i>Key Terms</i>
		81 • <i>Important "First Principle" Concepts</i>
		82 • <i>Suggested Further Readings</i>
		82

## Chapter 5 An Introduction to Thermodynamics 83

	Questions to be Considered in this Chapter	83
5.1	Energy	83
5.2	Gibbs Free Energy	84
5.3	The Gibbs Free Energy for a Phase	85
5.3.1	Variations in the Gibbs Free Energy for a Phase with Pressure and Temperature	86
5.4	Gibbs Free Energy for a Reaction	88
5.4.1	Variation in the Gibbs Free Energy for a Reaction with Pressure and Temperature	88
5.4.2	The Equilibrium State	89
5.4.3	Thermodynamic Evaluation of Phase Diagrams	90
	<i>Summary</i>	91 • <i>Key Terms</i>
		91 • <i>Important "First Principle" Concepts</i>
		92 • <i>Suggested Further Readings</i>
		92

<b>Chapter 6</b>	<b>The Phase Rule and One- and Two-Component Systems</b>	<b>93</b>
	Questions to be Considered in this Chapter	93
	6.1 Introduction: Crystallization Behavior of Natural Magmas	93
	6.2 Phase Equilibrium and the Phase Rule	95
	6.3 Application of the Phase Rule to the H <sub>2</sub> O System	96
	6.4 One-Component Systems	98
	6.5 Two-Component (Binary) Systems	100
	6.5.1 Binary Systems with Complete Solid Solution	100
	6.5.2 Binary Eutectic Systems	103
	6.5.3 Binary Peritectic Systems	106
	6.5.4 The Alkali Feldspar System	109
	<i>Summary</i>	111 • <i>Key Terms</i> 112 • <i>Important "First Principle" Concepts</i> 112 • <i>Suggested Further Readings</i> 112
<b>Chapter 7</b>	<b>Systems with More Than Two Components</b>	<b>113</b>
	Questions to be Considered in this Chapter	113
	7.1 Three-Component (Ternary) Systems	113
	7.1.1 Ternary Eutectic Systems	113
	7.1.2 Ternary Peritectic Systems	117
	7.1.3 Ternary Systems with Solid Solution	118
	7.2 Systems with More than Three Components	122
	7.3 Reaction Series	124
	7.4 The Effects of Pressure on Melting Behavior	126
	7.5 The Effects of Fluids on Melting Behavior	127
	7.5.1 The Effects of H <sub>2</sub> O	127
	7.5.2 The Effects of CO <sub>2</sub>	132
	<i>Summary</i>	133 • <i>Key Terms</i> 134 • <i>Important "First Principle" Concepts</i> 134 • <i>Suggested Further Readings</i> 134
<b>Chapter 8</b>	<b>Chemical Petrology I: Major and Minor Elements</b>	<b>135</b>
	Questions to be Considered in this Chapter	135
	8.1 Analytical Methods	136
	8.2 Analytical Results	139
	8.3 Major and Minor Elements in the Crust	140
	8.4 Normative Minerals	141
	8.5 Variation Diagrams	142
	8.5.1 Bivariate Plots	143
	8.5.2 Triangular Plots: The AFM Diagram	146
	8.6 Using Variation Diagrams to Model Magmatic Evolution	146
	8.6.1 Pearce Element Ratios (PERs)	146
	8.6.2 Graphical and Mathematical Models of Magmatic Evolution	148
	8.7 Magma Series	152
	<i>Summary</i>	156 • <i>Key Terms</i> 156 • <i>Important "First Principle" Concepts</i> 157 • <i>Suggested Further Readings</i> 157
<b>Chapter 9</b>	<b>Chemical Petrology II: Trace Elements and Isotopes</b>	<b>158</b>
	Questions to be Considered in this Chapter	158
	9.1 Element Distribution	158
	9.2 Models for Solid–Melt Processes	161
	9.2.1 Batch Melting	161
	9.2.2 Rayleigh Fractionation	163

9.3	The Rare Earth Elements: A Special Group of Trace Elements	163
9.4	Normalized Multielement (Spider) Diagrams	166
9.5	Application of Trace Elements to Igneous Systems	167
9.6	Geochemical Criteria for Discriminating Between Tectonic Environments: Discrimination Diagrams	169
9.7	Isotopes	170
9.7.1	Stable Isotopes	171
9.7.2	Radioactive and Radiogenic Isotopes	172
9.7.2.1	The K-Ar System	173
9.7.2.2	The Rb-Sr System	175
9.7.2.3	The Sm-Nd System	177
9.7.2.4	The U-Th-Pb System	179
	<i>Summary</i>	181
	<i>Key Terms</i>	181
	<i>Important "First Principle" Concepts</i>	182
	<i>Suggested Further Readings</i>	182

## **Chapter 10 Mantle Melting and the Generation of Basaltic Magma 183**

Questions to be Considered in this Chapter 183

10.1	Petrology of the Mantle	184
10.2	Melting of the Mantle	187
10.2.1	Raising Temperature	187
10.2.2	Lowering Pressure	188
10.2.3	Adding Volatiles	188
10.2.4	A Brief Summary of Mantle Melting	190
10.3	Generation of Basalts from a Chemically Uniform Mantle	190
10.4	Primary Magmas	194
10.5	A Chemically Heterogeneous Mantle Model	196
	<i>Summary</i>	200
	<i>Key Terms</i>	200
	<i>Important "First Principle" Concepts</i>	201
	<i>Suggested Further Readings</i>	201

## **Chapter 11 Magma Diversity 202**

Questions to be Considered in this Chapter 202

11.1	Partial Melting	202
11.2	Magmatic Differentiation	204
11.2.1	Fractional Crystallization	204
11.2.2	Volatile Transport	209
11.2.3	Liquid Immiscibility	210
11.3	Magma Mixing	211
11.4	Assimilation	213
11.5	Boundary Layers, In Situ Crystallization, and Compositional Convection	215
11.6	Mixed Processes	218
11.7	Tectonic-Igneous Associations	219
	<i>Summary</i>	219
	<i>Key Terms</i>	220
	<i>Important "First Principle" Concepts</i>	220
	<i>Suggested Further Readings</i>	220

## **Chapter 12 Layered Mafic Intrusions 222**

Questions to be Considered in this Chapter 222

12.1	Igneous Layering	223
12.2	Examples of Layered Mafic Intrusions	224
12.2.1	The Bushveld Igneous Complex	224
12.2.2	The Stillwater Complex	228
12.2.3	The Skaergård Intrusion	231

<b>12.3</b>	<b>The Processes of Crystallization, Differentiation, and Layering in LMIs</b>	<b>234</b>
12.3.1	Gravity Settling	235
12.3.2	Recharge and Magma Mixing	235
12.3.3	Oscillations Across the Cotectic	236
12.3.4	Compaction	236
12.3.5	In Situ Crystallization and Convection	236
12.3.6	Preferential Nucleation and Crystallization	237
12.3.7	Density Currents	238
12.3.8	Combined Processes	241
<b>12.4</b>	<b>Conclusion</b>	<b>242</b>
	<i>Summary</i>	242 • <i>Key Terms</i>
		243 • <i>Important "First Principle" Concepts</i>
		243 • <i>Suggested Further Readings</i>
		243

## **Chapter 13 Mid-Ocean Ridge Volcanism 244**

	<b>Questions to be Considered in this Chapter</b>	<b>244</b>
<b>13.1</b>	<b>Volcanism at Constructive Plate Boundaries</b>	<b>244</b>
<b>13.2</b>	<b>The Mid-Ocean Ridges</b>	<b>245</b>
<b>13.3</b>	<b>Structure of the Oceanic Crust and Upper Mantle</b>	<b>248</b>
<b>13.4</b>	<b>MORB Petrography and Major Element Geochemistry</b>	<b>250</b>
<b>13.5</b>	<b>MORB Trace Element and Isotope Geochemistry</b>	<b>254</b>
<b>13.6</b>	<b>Petrogenesis of Mid-Ocean Ridge Basalts</b>	<b>256</b>
13.6.1	Mantle Melting: The Generation of Mid-Ocean Ridge Basalts	256
13.6.2	Magma Chambers and the Creation of Oceanic Lithosphere	259
13.6.3	The Influence of Spreading Rate	264
	<i>Summary</i>	268 • <i>Key Terms</i>
		268 • <i>Important "First Principle" Concepts</i>
		269 • <i>Suggested Further Readings</i>
		269

## **Chapter 14 Oceanic Intraplate Volcanism 270**

	<b>Questions to be Considered in this Chapter</b>	<b>270</b>
<b>14.1</b>	<b>Intraplate Volcanic Activity</b>	<b>270</b>
<b>14.2</b>	<b>Types of OIB Magmas</b>	<b>273</b>
<b>14.3</b>	<b>OIB Petrography and Major Element Geochemistry</b>	<b>274</b>
<b>14.4</b>	<b>OIB Trace Element Geochemistry</b>	<b>277</b>
<b>14.5</b>	<b>OIB Isotope Geochemistry</b>	<b>279</b>
14.5.1	Strontium and Neodymium Isotopes	280
14.5.2	Lead Isotopes	281
14.5.3	Helium Isotopes	282
14.5.4	Osmium and Oxygen Isotopes	285
14.5.5	Other Mantle Isotopic Reservoirs	286
<b>14.6</b>	<b>Nature of the Mantle</b>	<b>287</b>
<b>14.7</b>	<b>Petrogenesis of OIBs</b>	<b>291</b>
	<i>Summary</i>	298 • <i>Key Terms</i>
		298 • <i>Important "First Principle" Concepts</i>
		299 • <i>Suggested Further Readings</i>
		299

## **Chapter 15 Continental Flood Basalts 301**

	<b>Questions to be Considered in this Chapter</b>	<b>301</b>
<b>15.1</b>	<b>Large Igneous Provinces</b>	<b>301</b>
<b>15.2</b>	<b>The Tectonic Setting of CFBs</b>	<b>303</b>
<b>15.3</b>	<b>The Columbia River Basalts</b>	<b>304</b>
15.3.1	The Setting of the Columbia River Basalt Group	304

15.3.2 CRBG Petrography and Major Element Geochemistry 307

15.3.3 CRBG Trace Element Geochemistry 309

15.3.4 CRBG Isotope Geochemistry 310

15.3.5 Petrogenesis of the Columbia River Basalts 312

15.4 Other Continental Flood Basalt Provinces 314

15.5 Petrogenesis of Continental Flood Basalts and LIPs 316

*Summary* 321 • *Key Terms* 321 • *Important "First Principle" Concepts* 321 •

*Suggested Further Readings* 322

## **Chapter 16 Subduction-Related Igneous Activity, Part I: Island Arcs 323**

Questions to be Considered in this Chapter 323

16.1 Island-Arc Volcanism 324

16.2 Island-Arc Volcanic Rocks and Magma Series 326

16.3 Major Element Geochemistry of Island Arcs 329

16.4 Spatial and Temporal Variations in Island Arcs 332

16.5 Petrography of Island-Arc Volcanics 332

16.6 Island-Arc Trace Element Geochemistry 334

16.7 Island-Arc Isotopes 336

16.8 Petrogenesis of Island-Arc Magmas 339

16.8.1 Thermal Constraints 339

16.8.2 Dehydration and Melting in Subducted Slabs 340

16.8.3 A Possible Model 343

16.8.4 A Panoply of Arc Parental Magmas 346

16.8.5 Mantle Re-enrichment 348

*Summary* 349 • *Key Terms* 350 • *Important "First Principle" Concepts* 351 •

*Suggested Further Readings* 351

## **Chapter 17 Subduction-Related Igneous Activity, Part II: Continental Arcs 352**

Questions to be Considered in this Chapter 352

17.1 Introduction 352

17.2 The Volcanic Andes of South America 353

17.2.1 Petrology and Geochemistry of the Andean Volcanics 354

17.2.2 Petrogenesis of Andean Volcanic Rocks 359

17.3 The Cascades of the Western United States 361

17.4 Plutonic Belts of Continental Arcs 365

17.4.1 Geochemistry of the Peruvian Coastal Batholith 367

17.4.2 Volcanic/Plutonic Equivalence 369

17.4.3 Across-Axis Batholith Variations 370

17.5 Petrogenesis of Continental-Arc Magmas 373

*Summary* 375 • *Key Terms* 376 • *Important "First Principle" Concepts* 376 •

*Suggested Further Readings* 376

## **Chapter 18 Granitoid Rocks 377**

Questions to be Considered in this Chapter 377

18.1 Petrography of Granitoids 378

18.2 Granitoid Geochemistry 379

18.3 Crustal Melting 380

18.4 Granitoid Classification 383

18.4.1 The S-I-A-M Classification of Granitoids 384

18.4.2 A Classification of Granitoids Based on Tectonic Setting 385

18.4.2.1 Oceanic Granitoids	385
18.4.2.2 Continental Orogenic Granitoids	387
18.4.2.3 Transitional Granitoids	388
18.4.2.4 Continental Anorogenic Granitoids	390
18.5 Geochemical Discrimination of Tectonic Granitoids	391
18.6 The Role of the Mantle in Granitoid Genesis	392
18.7 Origin of the Continental Crust	393
<i>Summary</i>	395
<i>Key Terms</i>	395
<i>Important "First Principle" Concepts</i>	396
<i>Suggested Further Readings</i>	396

## **Chapter 19 Continental Alkaline Magmatism 397**

Questions to be Considered in this Chapter 397

19.1 Continental Rift-Associated Alkaline Magmatism	399
19.1.1 The East African Rift System	400
19.1.2 Magma Series of the East African Rift	401
19.1.3 Geochemistry of East African Rift Volcanics	401
19.1.4 Isotopic and Trace Element Characteristics of East African Rift Magmas	402
19.1.5 Mantle Enrichment and Heterogeneity Beneath the East African Rift	404
19.1.6 Trends in East African Rift Magmatism	406
19.1.7 Magma Evolution in the East African Rift	406
19.1.8 A Model for East African Rift Magmatism	407
19.2 Carbonatites	409
19.2.1 Carbonatite Classification and Mineralogy	409
19.2.2 Carbonatite Occurrences	409
19.2.3 Field Characteristics of Carbonatites	411
19.2.4 Carbonatite Geochemistry	412
19.2.5 The Origin of Carbonatites	412
19.2.5.1 Carbonatites as Primary Magmas	414
19.2.5.2 Carbonatites as Differentiation Products of Primary Alkaline Silicate Melts	416
19.2.5.3 Carbonatites as Products of Liquid Immiscibility	417
19.2.5.4 Carbonatite Petrogenesis	418
19.2.6 The Natrocarbonatite Problem	419
19.2.7 The Source of Volatiles in the Mantle	420
19.3 Highly Potassic Rocks	420
19.3.1 Lamproites	421
19.3.2 Lamprophyres	423
19.3.3 Kimberlites	425
19.3.3.1 Petrography of Kimberlites	425
19.3.3.2 Kimberlite–Orangeite Field Relationships	426
19.3.3.3 Kimberlite–Orangeite Geochemistry	427
19.3.3.4 Petrogenesis of Kimberlites and Orangeites	429
19.4 Mantle Metasomatism and Mantle Xenoliths	431
<i>Summary</i>	433
<i>Key Terms</i>	434
<i>Important "First Principle" Concepts</i>	434
<i>Suggested Further Readings</i>	434

## **Chapter 20 Anorthosites 436**

Questions to be Considered in this Chapter 436

20.1 Archean Anorthosites	436
20.1.1 Petrology and Geochemistry of Archean Anorthosites	437

20.1.2	The Parent Liquid of Archean Anorthosites	437
20.1.3	Petrogenesis of Archean Anorthosites	438
20.2	Proterozoic Anorthosites	439
20.2.1	Petrology and Geochemistry of Proterozoic Anorthosites	439
20.2.2	The Parent Liquid of Proterozoic Anorthosites	440
20.2.3	Petrogenesis of Proterozoic Anorthosite Massifs	440
20.2.4	Lunar Anorthosites	442
	<i>Summary</i>	442 • <i>Key Terms</i>
		443 • <i>Important "First Principle" Concepts</i>
		443 • <i>Suggested Further Readings</i>
		443

## Part II Metamorphic Petrology 445

### Chapter 21 An Introduction to Metamorphism 446

Questions to be Considered in this Chapter 446

21.1 The Limits of Metamorphism 447

21.2 Metamorphic Agents and Changes 448

21.2.1 Temperature 448

21.2.2 Pressure 449

21.2.3 Deviatoric Stress 450

21.2.4 Metamorphic Fluids 452

21.3 The Types of Metamorphism 453

21.3.1 Contact Metamorphism 453

21.3.2 Regional Metamorphism 454

21.3.3 Fault-Zone and Impact Metamorphism 457

21.4 The Progressive Nature of Metamorphism 457

21.5 Types of Protolith 458

21.6 Some Examples of Metamorphism 458

21.6.1 Orogenic Regional Metamorphism of the Scottish Highlands 459

21.6.2 Regional Burial Metamorphism, Otago, New Zealand 461

21.6.3 Paired Orogenic Metamorphic Belts of Japan 462

21.6.4 Contact Metamorphism of Pelitic Rocks in the Skiddaw Aureole, United Kingdom 463

21.6.5 Contact Metamorphism and Skarn Formation at Crestmore, California 465

*Summary* 467 • *Key Terms* 468 • *Important "First Principle" Concepts* 469 •

*Suggested Further Readings* 469

### Chapter 22 A Classification of Metamorphic Rocks 470

Questions to be Considered in this Chapter 470

22.1 Foliated and Lineated Rocks 471

22.2 Non-Foliated and Non-Lineated Rocks 471

22.3 Specific Metamorphic Rock Types 472

22.4 Additional Modifying Terms 473

22.5 High-Strain Rocks 473

*Summary* 476 • *Key Terms* 476 • *Important "First Principle" Concept* 476 •

*Suggested Further Readings* 476

### Chapter 23 Structures and Textures of Metamorphic Rocks 477

Questions to be Considered in this Chapter 477

23.1 The Processes of Deformation, Recovery, and Recrystallization 478

23.2 Textures of Contact Metamorphism 483

23.3	High-Strain Metamorphic Textures	486
23.3.1	Shear Sense Indicators	488
23.4	Regional Orogenic Metamorphic Textures	490
23.4.1	Tectonites, Foliations, and Lineations	491
23.4.1.1	Foliations	491
23.4.1.2	Lineations	493
23.4.2	Mechanisms of Tectonite Development	494
23.4.3	Gneissose Structure and Layers	495
23.4.4	Other Regional Metamorphic Textures	496
23.4.5	Deformation Versus Metamorphic Mineral Growth	496
23.4.6	Analysis of Polydeformed and Polymetamorphosed Rocks	503
23.5	Crystallographically Controlled Inclusions	506
23.6	Replacement Textures and Reaction Rims	506
23.7	Textural Geochronology	508
23.7.1	Analytical Techniques and Suitable Minerals	509
23.7.2	Examples of Textural Geochronology	509
	<i>Summary</i>	514
	<i>Key Terms</i>	516
	<i>Important "First Principle" Concepts</i>	517
	<i>Suggested Further Readings</i>	517

## **Chapter 24 Stable Mineral Assemblages in Metamorphic Rocks 518**

	Questions to be Considered in this Chapter	518
24.1	Equilibrium Mineral Assemblages	518
24.2	The Phase Rule in Metamorphic Systems	519
24.3	Chemographic Diagrams	522
24.3.1	Common Chemographic Diagrams for Metamorphic Rocks	524
24.3.1.1	The <i>ACF</i> Diagram	525
24.3.1.2	The <i>AKF</i> Diagram	527
24.3.2	Projections in Chemographic Diagrams	527
24.3.2.1	Projection from Apical Phases	527
24.3.2.2	Projecting from Non-Apical Phases	530
24.3.3	J. B. Thompson's <i>AKFM</i> Diagram	531
24.3.4	Choosing the Appropriate Compatibility Diagram	534
	<i>Summary</i>	535
	<i>Key Terms</i>	535
	<i>Important "First Principle" Concepts</i>	536
	<i>Suggested Further Readings</i>	536

## **Chapter 25 Metamorphic Facies and Metamorphosed Mafic Rocks 537**

	Questions to be Considered in this Chapter	537
25.1	Metamorphic Facies	537
25.2	Facies Series	540
25.3	Metamorphism of Mafic Rocks	542
25.3.1	Mafic Assemblages at Low Grades	542
25.3.2	Mafic Assemblages of the Medium <i>P/T</i> Series: Greenschist, Amphibolite, and Granulite Facies	544
25.3.3	Mafic Assemblages of the Low <i>P/T</i> Series: Albite–Epidote Hornfels, Hornblende Hornfels, Pyroxene Hornfels, and Sanidinite Facies	546
25.3.4	Mafic Assemblages of the High <i>P/T</i> Series: Blueschist and Eclogite Facies	547
25.4	UHP and UHT Metamorphism: The Extremes of Crustal Metamorphism	549
25.5	Pressure–Temperature–Time ( <i>P-T-t</i> ) Paths	551
	<i>Summary</i>	555
	<i>Key Terms</i>	556
	<i>Important "First Principle" Concepts</i>	556
	<i>Suggested Further Readings</i>	556

**Chapter 26 Metamorphic Reactions 558**

Questions to be Considered in this Chapter 558

26.1 Polymorphic Transformations 559

26.2 Exsolution Reactions 560

26.3 Solid–Solid Net-Transfer Reactions 560

26.4 Devolatilization Reactions 560

26.5 Continuous Reactions 565

26.6 Ion Exchange Reactions 567

26.7 Oxidation/Reduction Reactions 568

26.8 Reactions Involving Dissolved Species 569

26.9 Reactions and Chemographics: A Geometric Approach 569

26.10 Phase Diagrams for Multicomponent Systems That Involve Several Reactions 571

26.11 Petrogenetic Grids 574

26.12 Reaction Mechanisms 575

*Summary* 577 • *Key Terms* 578 • *Important “First Principle” Concepts* 578 •*Suggested Further Readings* 578**Chapter 27 Thermodynamics of Metamorphic Reactions 579**

Questions to be Considered in this Chapter 579

27.1 Calculating the Location of a Reaction Equilibrium Curve on a Phase Diagram 580

27.2 Gas Phases 581

27.3 Compositional Variation 582

27.4 Geothermobarometry 587

27.4.1 The Garnet–Biotite Exchange Geothermometer 588

27.4.2 The *GASP* Continuous Net-Transfer Geobarometer 591

27.4.3 Application of Geothermobarometry to Rocks 592

27.4.4 Calculating *P-T-t* Paths from Zoned Crystals 595

27.4.5 Sources of Error in Geothermobarometry 598

27.4.6 Precision and Accuracy in Geothermobarometry 599

27.5 Sources of Data and Programs 600

*Summary* 601 • *Key Terms* 602 • *Important “First Principle” Concepts* 602 •*Suggested Further Readings* 602**Chapter 28 Metamorphism of Pelitic Sediments 607**

Questions to be Considered in this Chapter 607

28.1 Diagenesis and Low-Grade Metamorphism of Pelites 608

28.2 Medium *P/T* Metamorphism of Pelites: The Barrovian Sequence 609

28.2.1 The Chlorite Zone 609

28.2.2 The Biotite Zone 610

28.2.3 The Garnet Zone 613

28.2.4 The Staurolite Zone 614

28.2.5 Pseudosections and High-Variance Reactions in *KFMASH* 615

28.2.6 The Kyanite Zone 620

28.2.7 The Sillimanite Zone 621

28.2.8 Changes Above the Kyanite → Sillimanite Isograd 621

28.2.9 The Effects of Non-*KFMASH* Components 62328.3 Low *P/T* Metamorphism of Pelites 624

28.4 Partial Melting of Pelites 627

28.5 Migmatites 630

**28.6 High P/T Metamorphism of Pelites 631**

*Summary 633 • Key Terms 633 • Important "First Principle" Concepts 634 • Suggested Further Readings 634*

**Chapter 29 Metamorphism of Calcareous and Ultramafic Rocks 635**

Questions to be Considered in this Chapter 635

**29.1 Metamorphism of Calcareous Rocks 635**

**29.1.1 Contact Metamorphism of Siliceous Dolostones 636**

29.1.1.1 Open-System Behavior 637

29.1.1.2 Closed-System Behavior 639

**29.1.2 Regional Metamorphism of Siliceous Dolostones 641**

**29.1.3 Fluid Infiltration in Calcic Rocks 643**

**29.1.4 Metamorphism of Calc-Silicate Rocks 644**

29.1.4.1 Ankerite Zone 645

29.1.4.2 Biotite Zone 645

29.1.4.3 Amphibole Zone 646

29.1.4.4 Zoisite Zone 646

29.1.4.5 Diopside Zone 646

**29.2 Metamorphism of Ultramafic Rocks 647**

**29.2.1 Regional Metamorphism of Ultramafic Rocks in the CMS-H System 647**

**29.2.2 The Effect of Other Components 650**

**29.2.3 The Effect of CO<sub>2</sub> 650**

*Summary 652 • Key Terms 653 • Important "First Principle" Concept 653 • Suggested Further Readings 653*

**Chapter 30 Metamorphic Fluids, Mass Transport, and Metasomatism 654**

Questions to be Considered in this Chapter 654

**30.1 Metamorphic Fluids 654**

**30.1.1 The Nature of Metamorphic Fluids 655**

30.1.1.1 Volatile Species 655

30.1.1.2 Nonvolatile Solutes 656

**30.1.2 The Role of Fluids in Metamorphism 658**

**30.2 Metasomatism 658**

**30.2.1 Metasomatic Processes 659**

30.2.1.1 Diffusion 659

30.2.1.2 Infiltration 660

**30.2.2 J. B. Thompson's Metasomatic Column 662**

**30.2.3 Changes Associated with Metasomatism 667**

**30.2.4 Examples of Metasomatism: Ultramafics 669**

**30.2.5 Examples of Metasomatism: Calcareous Skarns 674**

**30.2.6 Quantitative Models and Experiments of Metasomatism 679**

*Summary 681 • Key Terms 681 • Important "First Principle" Concepts 681 • Suggested Further Readings 682*

*Appendix A: Estimating the Density and Viscosity of Silicate Melts 683*

*Appendix B: The CIPW Norm 686*

*Index 693*