

Contents

Part I Introduction and General Aspects of Metamorphism

1 Definition, Conditions and Types of Metamorphism	3
1.1 Conditions of Metamorphism	4
1.1.1 Low-Temperature Limit of Metamorphism	4
1.1.2 High-Temperature Limit of Metamorphism	5
1.1.3 Low-Pressure Limit of Metamorphism	7
1.1.4 High-Pressure Limit of Metamorphism	7
1.2 Types of Metamorphism	8
1.2.1 Orogenic Metamorphism	8
1.2.2 Ocean-Floor Metamorphism	11
1.2.3 Other Types of Regional Metamorphism	11
1.2.4 Contact Metamorphism	13
1.2.5 Cataclastic Metamorphism	14
1.2.6 Hydrothermal Metamorphism	14
1.2.7 Other Types of Small-Scale Metamorphism	16
References and Further Reading	17
2 Metamorphic Rocks	21
2.1 Primary Material of Metamorphic Rocks	22
2.1.1 Chemical Composition of Protoliths of Metamorphic Rocks	23
2.1.2 Chemical Composition Classes of Metamorphic Rocks and Their Protoliths	25
2.2 The Structure of Metamorphic Rocks	26
2.3 Classification and Names of Metamorphic Rocks	29
2.3.1 Rock Names Referring to the Structure	31
2.3.2 Names for High-Strain Rocks	32
2.3.3 Special Terms	33
2.3.4 Modal Composition of Rocks	35
2.3.5 Names Related to the Origin of the Protolith	35
2.4 Mineral Assemblages and Mineral Parageneses	36

2.5 Graphical Representation of Metamorphic Mineral Assemblages	39
2.5.1 Mole Numbers, Mole Fractions and the Mole Fraction Line	39
2.5.2 The Mole Fraction Triangle	41
2.5.3 Projections	43
References and Further Reading	55
3 Metamorphic Processes	57
3.1 Principles of Metamorphic Reactions	58
3.2 Pressure and Temperature Changes in Crust and Mantle	65
3.2.1 General Aspects	65
3.2.2 Heat Flow and Geotherms	66
3.2.3 Temperature Changes and Metamorphic Reactions	71
3.2.4 Pressure Changes in Rocks	72
3.3 Gases and Fluids	74
3.4 Time Scale of Metamorphism	76
3.5 Pressure–Temperature–Time Paths and Reaction History	77
3.6 Chemical Reactions in Metamorphic Rocks	81
3.6.1 Reactions Among Solid-Phase Components	82
3.6.2 Reactions Involving Volatiles as Reacting Species	83
3.7 Reaction Progress	99
3.8 Phase Diagrams	102
3.8.1 Phase Diagrams, General Comments and Software	102
3.8.2 The Phase Rule	103
3.8.3 Construction of Phase Diagrams for Multicomponent Systems After the Method of Schreinemakers	105
3.8.4 Use of Phase Diagrams, an Example	109
References and Further Reading	113
4 Metamorphic Grade	119
4.1 General Considerations	119
4.2 Index Minerals and Mineral Zones	120
4.3 Metamorphic Facies	122
4.3.1 Origin of the Facies Concept	122
4.3.2 Metamorphic Facies Scheme	124
4.3.3 Pressure–Temperature Conditions of Metamorphic Facies ...	131
4.4 Isograds	131
4.4.1 The Isograd Concept	131
4.4.2 Zone Boundaries, Isograds and Reaction-Isograds	133
4.4.3 Assessing Isograds, Isobars and Isotherms	135
4.5 Bathozones and Bathograds	139
4.6 Petrogenetic Grid	141
4.6.1 Polymorphic Transitions	142

4.7	Geothermobarometry	146
4.7.1	Concept and General Principle	147
4.7.2	Assumptions and Precautions	149
4.7.3	Exchange Reactions	153
4.7.4	Net-Transfer	158
4.7.5	Miscibility Gaps and Solvus Thermometry	162
4.7.6	Uncertainties in Thermobarometry	166
4.7.7	Thermobarometry Using Multi-equilibrium Calculations (MET)	167
4.8	Gibbs Method	168
4.9	Assemblage Stability Diagrams	170
4.10	More P - T Tools	171
4.10.1	Reactions Involving Fluid Species	171
4.10.2	P - T Tools for Very Low Grade Rocks	173
	References and Further Reading	174

Part II Metamorphism of Specific Rock Types

5	Metamorphism of Ultramafic Rocks	191
5.1	Introduction	191
5.2	Ultramafic Rocks	191
5.2.1	Rock Types	193
5.2.2	Chemical Composition	194
5.3	Metamorphism in the MSH System	196
5.3.1	Chemographic Relations in the MSH System	196
5.3.2	Progressive Metamorphism of Maximum Hydrated Harzburgite	198
5.4	Metamorphism in the CMASH System	202
5.4.1	Progressive Metamorphism of Hydrated Al-Bearing Lherzolite	202
5.4.2	Effects of Rapid Decompression and Uplift Prior to Cooling	204
5.5	Isograds in Ultramafic Rocks	204
5.6	Mineral Assemblages in the Uppermost Mantle	206
5.7	Serpentinization of Peridotite	208
5.8	Ultramafic Rocks at High Temperature	210
5.9	Thermometry and Geobarometry in Ultramafic Rocks	211
5.10	Carbonate-Bearing Ultramafic Rocks	212
5.10.1	Metamorphism of Ophicarbonate Rocks	212
5.10.2	Soapstone and Sagvandite	215
5.11	Open System Reactions in Ultramafic Rocks	219
5.12	Potassium-Bearing Peridotites	221
	References and Further Reading	221

6	Metamorphism of Dolomites and Limestones	225
6.1	Introduction	225
6.1.1	Rocks	225
6.1.2	Minerals and Rock Composition	227
6.1.3	Chemographic Relationships	228
6.2	Orogenic Metamorphism of Siliceous Dolomite	230
6.2.1	Modal Evolution Model	232
6.3	Orogenic Metamorphism of Limestone	233
6.4	Contact Metamorphism of Dolomites	235
6.4.1	Modal Evolution Model	238
6.5	Contact Metamorphism of Limestones	239
6.6	Isograds and Zone Boundaries in Marbles	243
6.7	Metamorphic Reactions Along Isothermal Decompression Paths	244
6.8	Marbles Beyond the CMS-HC System	246
6.8.1	Fluorine	247
6.8.2	Aluminium	248
6.8.3	Potassium	248
6.8.4	Sodium	251
6.9	Thermobarometry of Marbles	251
6.9.1	Calcite–Dolomite Miscibility Gap	252
6.10	High-Pressure and Ultrahigh-Pressure Metamorphism of Carbonate Rocks	252
	References and Further Reading	253
7	Metamorphism of Pelitic Rocks (Metapelites)	257
7.1	Metapelitic Rocks	257
7.2	Pelitic Sediments	257
7.2.1	General	257
7.2.2	Chemical Composition	258
7.2.3	Mineralogy	258
7.3	Pre-metamorphic Changes in Pelitic Sediments	258
7.4	Intermediate-Pressure Metamorphism of Pelitic Rocks	259
7.4.1	Chemical Composition and Chemography	259
7.4.2	Mineral Assemblages at the Beginning of Metamorphism	260
7.4.3	The ASH System	262
7.4.4	Metamorphism in the FASH System	264
7.4.5	Mica-Involving Reactions	267
7.4.6	Metamorphism in the KFMASH System (AFM System)	269
7.5	Low-Pressure Metamorphism of Pelites	278
7.5.1	FASH System	278
7.5.2	KFMASH System	280
7.6	High-Temperature Metamorphism of Pelites: Metapelitic Granulites	284

7.6.1	Cordierite–Garnet–Opx–Spinel–Olivine Equilibria	285
7.6.2	The Excess Quartz Condition	286
7.6.3	Partial Melting and Migmatite	288
7.6.4	More About Granulites	292
7.7	Metamorphism of Mg-rich “Pelites”	296
7.8	High Pressure: Low Temperature Metamorphism of Pelites	298
7.9	Additional Components in Metapelites	302
	References and Further Reading	306
8	Metamorphism of Marls	315
8.1	General	315
8.2	Orogenic Metamorphism of Al-Poor Marls	316
8.2.1	Phase Relationships in the KCMAS-HC System	317
8.2.2	Prograde Metamorphism in the KCMAS-HC System at Low X_{CO_2}	319
8.3	Orogenic Metamorphism of Al-Rich Marls	321
8.3.1	Phase Relationships in the CAS-HC System	323
8.3.2	Phase Relationships in the KNCAS-HC System	325
8.4	Increasing Complexity of Metamarls	332
8.5	Low Pressure Metamorphism of Marls	333
	References and Further Reading	336
9	Metamorphism of Mafic Rocks	339
9.1	Mafic Rocks	339
9.1.1	Hydration of Mafic Rocks	340
9.1.2	Chemical and Mineralogical Composition of Mafic Rocks	342
9.1.3	Chemographic Relationships and ACF Projection	343
9.2	Overview of Metamorphism of Mafic Rocks	348
9.2.1	Plagioclase in Mafic Rocks, Equilibria in the Labradorite System (NCASH System)	352
9.3	Subgreenschist Facies Metamorphism	353
9.3.1	General Aspects	353
9.3.2	Metamorphism in the CMASH and NCMASH Systems	356
9.3.3	Transition to Greenschist Facies	362
9.4	Greenschist Facies Metamorphism	363
9.4.1	Introduction	363
9.4.2	Mineralogical Changes Within the Greenschist Facies	363
9.4.3	Greenschist–Amphibolite Facies Transition	365
9.5	Amphibolite Facies Metamorphism	367
9.5.1	Introduction	367
9.5.2	Mineralogical Changes Within the Amphibolite Facies	367
9.5.3	Low-Pressure Series Amphibolites	368
9.5.4	Amphibolite–Granulite Facies Transition	370
9.6	Granulite Facies and Mafic Granulites	371

9.7 Blueschist Facies Metamorphism	374
9.7.1 Introduction	374
9.7.2 Reactions and Assemblages	374
9.8 Eclogite Facies Metamorphism	378
9.8.1 Eclogites	378
9.8.2 Reactions and Assemblages	380
9.8.3 Eclogite Facies in Gabbroic Rocks	383
References and Further Reading	387
10 Metamorphism of Quartzofeldspathic Rocks	395
10.1 Quartzofeldspathic Rocks	395
10.2 Metagraywackes	395
10.2.1 Introduction	395
10.2.2 Metamorphism of Metagraywacke (Metaspanmitic) Compositions	397
10.2.3 Orogenic Metamorphism of Metagraywackes	398
10.2.4 Contact Metamorphism of Metagraywackes and Metaspanmites	400
10.3 Granitoids	406
10.3.1 Prehnite and Pumpellyite	406
10.3.2 Stilpnomelane	406
10.3.3 The Microcline–Sanidine Isograd	407
10.3.4 Eclogite and Blueschist Facies Granitoids	408
10.3.5 Migmatitic Granitoids and Charnockite	409
References and Further Reading	411
Appendix: Symbols for rock forming minerals	415
Index	419