

Contents

Part I Basic Principles

1	Definition, Limits and Types of Metamorphism	3
1.1	Limits of Metamorphism	3
1.2	Types of Metamorphism	5
1.2.1	Orogenic Metamorphism	6
1.2.2	Ocean-Floor Metamorphism	8
1.2.3	Other Types of Regional Metamorphism	8
1.2.4	Contact Metamorphism	8
1.2.5	Other Types of Small-Scale Metamorphism	9
	References	10
2	Metamorphic Rocks	13
2.1	Primary Material of Metamorphic Rocks	14
2.1.1	Chemical Composition of Protoliths of Metamorphic Rocks	15
2.1.2	The Seven Chemical Composition Classes of Metamorphic Rocks and Their Protoliths	17
2.2	The Structure of Metamorphic Rocks	18
2.3	Classification and Names of Metamorphic Rocks ..	20
2.3.1	Structurally Defined Rock Names	21
2.3.2	Special Terms	22
2.3.3	The Modal Composition Systematics	24
2.3.4	Names Related to the Origin of the Protolith	25
2.4	Mineral Assemblages and Mineral Parageneses ...	25
2.5	Graphical Representation of Metamorphic Mineral Assemblages	28
2.5.1	Mole Numbers, Mole Fractions and the Mole Fraction Line	28
2.5.2	The Mole Fraction Triangle	30
2.5.3	Projections	32
	References	43
3	Metamorphic Process	45
3.1	Principles of Metamorphic Reactions	46
3.2	Pressure and Temperature Changes in Crust and Mantle	53

3.2.1	General Aspects	53
3.2.2	Heat Flow and Geotherms	54
3.2.2.1	Transient Geotherms	58
3.2.3	Temperature Changes and Metamorphic Reactions	59
3.2.4	Pressure Changes in Rocks	61
3.3	Gases and Fluids	62
3.4	Time Scale of Metamorphism	64
3.5	Pressure-Temperature-Time Paths and Reaction History	65
3.6	Chemical Reactions in Metamorphic Rocks	69
3.6.1	Reactions Among Solid Phase Components	70
3.6.1.1	Phase Transitions, Polymorphic Reactions	70
3.6.1.2	Net-Transfer Reactions	70
3.6.1.3	Exchange Reactions	70
3.6.1.4	Exsolution Reactions/Solvus Reactions	71
3.6.2	Reactions Involving Volatiles as Reacting Species	72
3.6.2.1	Dehydration Reactions	72
3.6.2.2	Decarbonatization Reactions	75
3.6.2.3	Mixed Volatile Reactions	75
3.6.2.4	Oxidation/Reduction Reactions	80
3.6.2.5	Sulfidation Reactions	81
3.6.2.6	Reactions Involving Halogens	82
3.6.2.7	Complex Mixed Volatile Reactions and Fluids ..	82
3.6.2.8	Reactions Involving Minerals and Dissolved Components in Aqueous Solutions	83
3.7	Reactions Progress	85
3.8	Phase Diagrams	88
3.8.1	Significance of Phase Diagrams	88
3.8.2	The Phase Rule	89
3.8.3	Construction of Phase Diagrams for Multicomponent Systems After the Method of Schreinemakers	91
	References and Further Reading	93
4	Metamorphic Grade	99
4.1	General Considerations	99
4.2	Index Minerals and Mineral Zones	99
4.3	Metamorphic Facies	101
4.3.1	Subgreenschist Facies	103
4.3.2	Greenschist Facies	104
4.3.3	Amphibolite Facies	104
4.3.4	Granulite Facies	104
4.3.5	Blueschist Facies	104
4.3.6	Eclogite Facies	105

4.3.7	Pressure-Temperature Conditions of Metamorphic Facies	105
4.4	Isograds and Reaction-Isograds	106
4.5	Bathozones and Bathograds	110
4.6	Pretogenetic Grid	111
4.7	Geothermobarometry	114
4.7.1	Assumptions and Precautions	114
4.7.2	Exchange Reactions	117
4.7.3	Solvus Relations	122
4.7.4	Polymorphic Transitions	125
4.7.5	Net-Transfer Reactions	128
4.7.6	Reactions Involving Fluid Species	133
4.7.7	Thermobarometry Using Multi-Equilibrium Calculations	135
4.7.8	Other Methods	136
4.7.9	Uncertainties in Thermobarometry	137
	References	138

Part II Metamorphism of Different Rock Compositions

5	Metamorphism of Ultramafic Rocks	147
5.1	Introduction	147
5.2	Metamorphic Ultramafic Rocks	147
5.2.1	Rock Types	148
5.2.2	Chemical Composition	148
5.3	Metamorphism in the MSH System	151
5.3.1	Chemographic Relations in the MSH System ..	151
5.3.2	Progressive Metamorphism of Maximum Hydrated Harzburgite	152
5.4	Metamorphism in the CMASH System	154
5.4.1	Progressive Metamorphism of Hydrated Al-Bearing Lherzolites	154
5.4.2	Effects of Rapid Decompression and Uplift Prior to Cooling	157
5.5	Isograds in Ultramafic Rocks	157
5.6	Mineral Assemblages in the Uppermost Mantle ..	158
5.7	Serpentization of Peridotites	159
5.8	Reactions in Ultramafic Rocks at High Temperatures	160
5.9	Thermometry and Geobarometry in Ultramafic Rocks	163
5.10	Carbonate-Bearing Ultramafic Rocks	163
5.10.1	Metamorphism of Ophicarbonate Rocks	164
5.10.2	Soapstones and Sagvandites	166
	References and Further Reading	168

6 Metamorphism of Dolomites and Limestones	171
6.1 Introduction	171
6.1.1 General	171
6.1.2 Chemical Composition	171
6.1.3 Chemographic Relationships	172
6.2 Orogenic Metamorphism of Dolomites	174
6.3 Orogenic Metamorphism of Limestones	176
6.4 Contact Metamorphism of Dolomites	178
6.5 Contact Metamorphism of Limestones	180
6.6 Isograds and Zone Boundaries in Marbles	182
6.7 Metamorphic Reactions Along Isothermal Decompression Paths.....	184
6.8 Marbles Beyond the CMS-HC System	185
6.8.1 Fluorine	185
6.8.2 Aluminium	186
6.8.3 Potassium	187
6.8.4 Sodium	187
6.9 Thermobarometry in Marbles	187
6.9.1 Calcite-Aragonite Phase Transition	188
6.9.2 Calcite-Dolomite Miscibility Gap	188
References and Further Reading	188
7 Metamorphism of Pelitic Rocks (Metapelites).....	191
7.1 Metapelitic Rocks	191
7.2 Pelitic Sediments	191
7.2.1 General	191
7.2.2 The Chemical Composition	192
7.2.3 Mineralogy	192
7.3 Pre-Metamorphic Changes in Pelitic Sediments ..	193
7.4 Orogenic Intermediate-Pressure Metamorphism of Pelitic Rocks (\pm Ky-Geotherm)	193
7.4.1 Chemical Composition and Chemographies ..	194
7.4.2 Mineral Assemblages at the Beginning of Metamorphism	194
7.4.3 Phase Relationships in the ASH System	195
7.4.4 Metamorphism in the FASH System	198
7.4.5 Mica-Involving Reactions	201
7.4.6 Metamorphism in the KFMASH System (AFM System)	204
7.5 Low-Pressure Metamorphism of Pelites	209
7.5.1 KFASH System	210
7.5.2 KFMASH System	211
7.5.3 Cordierite-Garnet-Spinel Equilibria	213
7.6 Very High-Temperature Metamorphism of Pelites – Metapelitic Granulites	215
7.6.1 Partial Melting and Migmatites	215

7.6.2	Granulites	218
7.7	Metamorphism of Very Mg-Rich “Pelites”	221
7.8	High-Pressure-Low Temperature Metamorphism	222
7.9	Additional Components in Metapelites.....	226
	References and Further Reading.....	228
8	Metamorphism of Marls	233
8.1	General	233
8.2.	Orogenic Metamorphism of Al-Poor Marls	233
8.2.1	Phase Relationships in the KCMAS-HC System ..	234
8.2.2	Prograde Metamorphism in the KCMAS-HC System at Low X_{CO_2}	236
8.3	Orogenic Metamorphism of Al-Rich Marls	238
8.3.1	Phase Relationships in the CAS-HC System	239
8.3.2	Phase Relationships in the KNCAS-HC System ..	241
8.3.2.1	Prograde Metamorphism at Low X_{CO_2}	244
8.3.2.2	Prograde Metamorphism at Very Low X_{CO_2}	245
	References and Further Reading.....	249
9	Metamorphism of Mafic Rocks.....	251
9.1	Mafic Rocks	251
9.1.1	Geological Occurrence	251
9.1.2	Hydration of Igneous Mafic Rocks	252
9.1.3	Chemical and Mineralogical Composition of Mafic Rocks	253
9.1.4	Chemographic Relationships and the AFC Projection	254
9.2	Overview on the Metamorphism of Mafic Rocks ..	260
9.3	Subgreenschist Facies Metamorphism.....	262
9.3.1	General Aspects and a Field Example.....	262
9.3.2	Metamorphism in the CASH and NCMASH Systems	265
9.3.3	The Transition to the Greenschist Facies	272
9.4	Greenschist Facies Metamorphism	273
9.4.1	Introduction	273
9.4.2	Mineralogical Changes Within the Greenschist Facies	273
9.4.2.1	Reactions in the CMASH-System	273
9.4.2.2	Reactions Including Micas	275
9.4.3	Greenschist-Amphibolite Facies Transition	276
9.5	Amphibolite Facies Metamorphism	278
9.5.1	Introduction	278
9.5.2	Mineralogical Changes Within the Amphibolite Facies	278
9.5.3	Low-Pressure Series Amphibolites.....	280
9.5.4	Amphibolite-Granulite Facies Transition	281

9.6	Granulite Facies and Mafic Granulites	282
9.7	Blueschist Facies Metamorphism	285
9.7.1	Introduction	285
9.7.2	Reactions and Assemblages	286
9.8	Eclogite Facies Metamorphism	289
9.8.1	Eclogites	289
9.8.2	Reactions and Assemblages	291
9.8.2.1	Amphibolite and Granulite to Eclogite Facies Transition	292
9.8.2.2	Reactions in Eclogites	293
9.8.3	Eclogite Facies in Non-Basaltic Mafic Rocks	294
9.8.3.1	Blueschist and Eclogite Facies Metamorphism of an Olivine Gabbro, a Case History from the Central Alps	294
	References	298
10	Metamorphism of Granitoids	303
10.1	Introduction	303
10.2	Presence of Prehnite and Pumpellyite	303
10.3	Quartz Textures	304
10.4	Presence of Stilpnomelane	304
10.5	The Microcline/Sanidine Transformation Isograd ..	304
10.6	Granitoid Rocks in the Eclogite Facies and the Blueschist Facies	306
	References and Further Reading	307
	Appendix: Symbols for Rock-Forming Minerals	309
	Subject Index	311