Contents

Part I. Introduction 1

Chapter 1. Introduction with review of the definition, distribution and geotectonic significance of ultrahigh pressure metamorphism
by **Dennis A. CARSWELL** and **Roberto COMPAGNONI** 3

References 7

Part II. Reviews of representative UHPM terranes 11

Chapter 2. UHPM units in the Western Alps
by **Roberto COMPAGNONI** and **Franco ROLFO** 13

Introduction 13
The Brossasco-Isasca Unit of the Dora-Maira Massif 13
The Polymetamorphic Complex 16
Relics of pre-Alpine metamorphic rocks 17
Variscan paragneiss 17
Relics of Variscan augengneiss 20
Relics of Variscan marble 20
Basement lithologies preserving UHPM mineral assemblages 20
Jadeite-kyanite-almandine-phengite micaschist 21
Phengite-jadeite-almandine-quartz (/coesite) granofels 21
Eclogite 21
Marble 22
Unusual lithologies characterised by UHPM mineral assemblages 23
Kyanite-pyrope talcschist 23
Sodic whiteschist 23
The Monometamorphic Complex 23
UHPM rocks derived from late Variscan intrusives 23
Orthogneiss 23
Relics of metagranitoids 24
Relics of igneous intrusive contacts with basement xenoliths 26
Pyrope-bearing whiteschist 28
Garnet-jadeite-kyanite-quartz (/coesite) granofels 29
The metamorphic evolution of the BIU and its *P–T–t* path 31
The age of the UHP metamorphism 34
Conclusions 34
The Lago di Cignana Unit of the Piemonte zone 36
Geological and structural setting 36
Lithologies 38
Metabasites 38
Metasediments 39
Garnet-phengite-quartz calcschist 40
Piemontite-garnet-phengite-talc-quartz schist 41
Aegirine-augite - garnet - phengite quartzite 41
Metamorphic evolution 42
Geochronology 44
Conclusions 45
Acknowledgements 45
References 45

Chapter 3. Ultrahigh pressure metamorphism in the Western Gneiss Region of Norway
by **Dennis A. CARSWELL** and **Simon J. CUTHBERT** 51

Historical background to UHPM in western Norway 51
Most recent discoveries of UHPM rocks in western Norway 53
The "foreign" versus "*in situ*" eclogite controversy: The influences of differential retrogression and metastability 55
The HPM to UHPM transition 60
The age of the UHPM 65
The occurrence and interpretation of garnet peridotites 66
Acknowledgements 70
References 70

Chapter 4. The Kokchetav massif of Kazakhstan
by **Vladislav S. SHATSKY** and **Nikolai V. SOBOLEV** 75

Introduction 75
Geological outline 76
UHP rocks of the Kumdy-Kol and Barchi locations (Unit I) 76
Eclogites 76
Biotite gneisses and garnet-pyroxene-quartz rocks 80
Metasomatic rocks 82
Garnet-pyroxene rocks 82
Dolomitic marbles 83
Microdiamonds 83
The UHP and HP rocks of Unit II 87
Sulu-Tyube area 87
Enbek-Berlyk area 89
Kulet area 91
P–T path 91
Geochemistry of metamorphic rocks and the age of the UHP metamorphism 94
Exhumation of high pressure rocks of the Kokchetav Massif 98
References 100

Chapter 5. The Dabie Shan–Sulu orogen
by **Takao HIRAJIMA** and **Daisuke NAKAMURA** 105

Geological framework 105
Reconstruction of pre-HP/UHP stage geology 110
Review of the equilibrium temperature of representative UHP rocks at peak stage 117
P–T history of garnet peridotite and associated UHP minerals 117
Peak *P–T* conditions of eclogite 123
The character of Grt–Cpx geothermometer 125
The geobarometry of eclogite 126
Compilation result of the Dabie Shan eclogite 129
Results from the Sulu eclogite 132
Concluding remarks 136
Acknowledgements 139
References 139

Chapter 6. The Bohemian Massif and the NW Himalaya
by **Hans-Joachim MASSONNE** and **Patrick J. O'BRIEN** 145

Introduction 145
Geological setting and geochronological constraints 145
Bohemian Massif 145
Himalaya 148
Petrological information on HP/UHP key areas and rocks 151
Bohemian Massif 151
Metabasites 151
Ultramafic rocks 158
Quartzofeldspathic and related rocks 159
Himalaya 163
Kaghan and Neelum Valleys 165
Tso Morari 169
Indus suture zone, Nanga Parbat–Haramosh Massif 170
Kharta region, east of Mount Everest 172
Geodynamic synthesis 172
Acknowledgements 177
References 177

Part III. Mineralogy, geochemistry and tectonometamorphic evolution of UHPM terranes 189

Chapter 7. Mineral chemistry and mineral reactions in UHPM rocks
by **Christian CHOPIN** and **Giovanni FERRARIS** 191

Introduction 191
Closest- and close packing structures 191
Basic features 191
Polymorphism 193
Filling tetrahedral sites 195
Filling octahedral sites 198
Filling tetrahedral and octahedral sites 202
Rock-forming minerals with a complex structure 203
Garnets 203
Pyroxenes 205
Phengite 207
Magnesiostaurolite 210
Magnesiochloritoid 212
Accessory minerals with a complex structure 212
Zircon 213
Topaz 213
Wagnerite 213
Titanite 214
Hydroxylclinohumite 215
Ellenbergerite group 215
Magnesiodumortierite 216
Bearthite 217
Conclusions 218
Acknowledgements 219
References 219

Chapter 8. Thermobarometric methodologies applicable to eclogites and garnet ultrabasites
by **Erling J. Krogh Ravna** and **Jens Paquin** 229
Introduction 229
Mineral assemblages of interest 229
Practical geothermometers and geobarometers for HP/UHP rocks 230
Some cautionary notes before proceeding 230
Geothermometers 232
Geothermometers based on Fe^{2+}–Mg exchange between garnet and other Fe–Mg minerals 232
Garnet–biotite 232
Garnet–hornblende 232
Garnet–phengite 232
Garnet–clinopyroxene 233
Garnet–olivine 235
Garnet–orthopyroxene 236
Fe-Mg geothermometry and the problem of Fe^{3+} 236
Solvus thermometry 239
Two-pyroxene thermometers 239
Trace element thermometers 241
The Ni-in-garnet thermometer 241
Partitioning of transition elements (Sc, V, Cr, Co and Mn) between orthopyroxene and clinopyroxene in peridotitic and websteritic mantle rocks . . . 241
Ca-Cr system in lherzolitic garnets 242
The clinopyroxene/plagioclase symplectite geothermometer 243
Geobarometers 244
The Al-in-orthopyroxene barometer 244
Effect of Fe^{3+} on the Al-in-orthopyroxene barometer 245
The Cr-in-clinopyroxene barometer 245
Geothermobarometry based on the assemblage garnet–clinopyroxene–phengite–kyanite–quartz/coesite 246
Other, less common geobarometers suitable for HP/UHP rocks 250
Geobarometers involving plagioclase 250
Geobarometers involving zoisite/clinozoisite 251
Ca-Eskola molecule bearing clinopyroxenes at UHP conditions 252
Conclusions 252
References 253

Chapter 9. Coronitic reactions: Constraints to element diffusion during UHP metamorphism
by **Marco Rubbo** and **Marco Bruno** 261
Introduction 261
Kinetic theory 262
Growth of mineral layers 263
Symplectic reaction in olivine 270
Theory of intergrowth spacing 272
An estimate of intergranular diffusion of Al in fluid undersaturated systems 279
The ultrahigh pressure coronitic reactions in a metagranodiorite 283
Geology and petrography 283
Equilibrium thermodynamic modelling 285
Further considerations on the model and the metamorphic evolution of the eclogite facies metagranodiorite 288

Garnet growth model 290
Appendix 294
Some notions of irreversible thermodynamics 294
Diffusion 299
Empirical laws of diffusion 299
Thermodynamic theory 301
Diffusion in garnet 302
Acknowledgements 303
References 303

Chapter 10. Mineral assemblages in ultrahigh pressure metamorphism: A review of experimentally determined phase diagrams
by **Stefano POLI** and **Patrizia FUMAGALLI** 307

Introduction 307
"Fluid" phases at ultrahigh pressure conditions 309
A few definitions 309
How likely is fluid saturation at high pressure? 310
Fluids, melts and the 2nd critical endpoints 314
Ultrahigh pressure rocks: The quartz–coesite transformation and the "internally consistent" thermodynamic databases 318
Ultrahigh pressure rocks: The graphite–diamond transformation 319
Mafic systems 320
Bimineralic mafic eclogites and the relevance of minor and accessory phases 320
Phase relationships in H_2O-bearing systems 321
Phase relationships in a C-O-H-bearing system 324
Ultramafics 327
Peridotite compositions 327
The spinel to garnet transition 328
The peridotite + H_2O system 331
The K-peridotite system 332
Metasedimentary rocks 335
References 336

Chapter 11. Dating UHP metamorphism
by **Daniela RUBATTO, Anthi LIATI** and **Dieter GEBAUER** 341

Introduction 341
The aims and the challenge 341
The problems 342
The method 343
Case studies 344
The Dora-Maira 344
The Kokchetav Massif 348
Other localities 351
Tectonic implications 353
Exhumation rates 353
Duration of UHP metamorphism 355
Age variations within an orogen: The case of the Western Alps 355
The challenge ahead 356
Summary 359
Acknowledgements 360
References 360

Chapter 12. Geochemistry and isotope tracer study of UHP metamorphic rocks
by **Bor-ming JAHN, Douglas RUMBLE** and **Juhn G. LIOU** 365

I. Introduction 365
II. Chemical compositions of eclogites and ultramafic rocks 366
III. Sm–Nd and Rb–Sr isochron ages and Nd–Sr isotope tracers 370
Ranges of Sm and Nd concentrations 373
Equilibrium partition coefficients (*Kd* values) between Cpx and Grt 373
Meaningful Sm–Nd and Rb–Sr isochron ages: Some examples 377
Failure of producing correct ages 377
An example from the Hong'an Block in western Dabieshan 382
Radiogenic isotope tracers 384
IV. Oxygen isotope tracer 389
$\delta^{18}O$ values of eclogites from UHP metamorphic terranes – a summary 389
Limited fluid activity 391
Preservation of equilibrated high-temperature isotope fractionation 393
Conclusions from oxygen isotope tracer studies 395
Coupled Nd and O isotopic disequilibrium 396
V. Application of isotope constraints to tectonic evolution – example of the Dabie orogen . . . 397
Lithological and geochemical characteristics of the NDC and SDC gneisses and Cretaceous intrusions 398
Isotope test of the existing tectonic models 399
Discussion and tectonic implications 403
Acknowledgements 406
References 407

Chapter 13. Three-dimensional mechanics of UHPM terrains and resultant *P–T–t* paths
by **Peter O. KOONS, Phaedra UPTON** and **Michael P. TERRY** 415

Introduction 415
General mechanical considerations 416
Mechanical model: Constraints from natural analogues 418
Natural occurrences: Western Gneiss Region, Norway 419
Tectonic framework 421
Kinematic framework 421
Observations of the modern analogue: Central New Zealand 423
Mechanical framework I: Orogen-scale dynamics 425
Numerical results 426
Role of disequilibrium 427
Influence of surface processes 428
Strain partitioning within the orogen 429
Mechanical framework II: Viscous mixing, local kinematics and nappe formation 429
Thermal and petrological evolution 431
Results of static solutions: Crustal thickening 434
Asthenospheric involvement 434
Dynamic model with thermal results 436
Thermal–mechanical coupling 436
Discussion 436
Acknowledgements 438
References 438

Chapter 14. Metamorphism and textures of dry and hydrous garnet peridotites
by **Lauro MORTEN** and **Volkmar TROMMSDORFF** 443

Central Alpine domain 443
Poikiloblastic and porphyroclastic garnet peridotites in the Central Alps 445
Oriented ilmenite rods in olivine 448
Lattice preferred orientation (LPO) of olivine from AA and CdG 449
Criteria determining the deformation conditions 452
Eastern Alpine domain 453
Nonsberg ultramafic rocks 455
Textures of the Nonsberg peridotites 456
Coarse type 456
Fine type 459
Acknowledgements 461
References 461

Chapter 15. Fluid inclusions in high pressure and ultrahigh pressure metamorphic rocks
by **Jacques L.R. TOURET** and **Maria-Luce FREZZOTTI** 467

Introduction 467
The fluid inclusion approach to HP and UHP rocks: The principles 468
Step 1: Identification of the fluid types 468
Step 2: Chronology of the different fluid types 470
Application of Steps 1 and 2: Micro-mapping at the scale of the thin section on the example of the Shuanghe coesite-bearing eclogite (Fu, 2002) 473
Step 3: Selection of few representative inclusions for each fluid type 476
Step 4: Comparison between fluid inclusion and independent *P–T* mineral data 477
Applications: Some general considerations based on recent studies 480
Which fluids can be expected in HP–UHP rocks? 480
Which fluids are actually found in HP–UHP rocks? 481
High grade metamorphic rocks: Some fundamental differences between high pressure (eclogites and related rocks) and high temperature (granulites) metamorphic rocks 483
Acknowledgements 485
References 485

Name index 489
Subject index 496