1 Frontiers of Ultrahigh-Pressure Metamorphism: View from Field and Laboratory

Larissa F. Dobrzhinetskaya and Shah Wali Faryad

1.1 Introduction 1
1.2 Main Achievements: 25 Years On 2
1.2.1 “Deciphering” of New UHP Phases or Their Pseudomorphosis 2
1.2.2 New Discoveries of UHP Terranes 3
1.3 Further Directions 7
1.3.1 Fate of Continental Crust Beyond the “Point of No Return”: Visions and Perspectives 7
1.3.2 Exsolution Lamellae in Minerals from UHPM Terranes 12
1.3.3 Unusual Geological Settings for UHP Minerals/Rocks 19
1.3.4 Advanced State-of-the-Art Analytical Instruments and Facilities 22
1.4 Looking Forward 26

Part I Diamonds—New Studies 41

2 Diamond—Lonsdaleite—Graphite Relations Examined by Raman Mapping of Carbon Microinclusions inside Zircon at Kumdy Kol, Kokchetav, Kazakhstan: Evidence of the Metamictization of Diamond

David C. Smith, Larissa F. Dobrzhinetskaya, Gaston Godard and Harry W. Green

2.1 Introduction 43
2.2 Geological Setting 44
2.3 Analytical Procedures 45
2.4 Results 48
2.4.1 Focus-Track Altitudes 48
2.4.2 Fluorescent Baselines 48
2.4.3 Typical Raman Spectra 50
Diamond and Other Possible Ultradeep Evidence Discovered in the Orogenic Spinel-Garnet Peridotite from the Moldanubian Zone of the Bohemian Massif, Czech Republic

Kosuke Naemura, Daijo Ikuta, Hiroyuki Kagi, Shoko Odake, Tadamasa Ueda, Shugo Ohi, Tomoyuki Kobayashi, Martin Svojtka and Takao Hirajima

3.1 Introduction
3.2 Geological Settings and Some Backgrounds
3.3 Petrography and Mineral Chemistry
3.4 Experimental
  3.4.1 Raman Spectra of Graphitic Carbons
  3.4.2 Fourier Transform Infrared Spectroscopy of Diamond
  3.4.3 Synchrotron Micro-X-Ray Fluorescence and X-Ray Absorption Near Edge Structure Analysis of Diamond Inclusions
  3.4.4 Single Crystal X-Ray Diffraction Experiment of the Inclusion in the Microdiamond
  3.4.5 Electron Backscatter Diffraction Analyses of Pyroxene Lamellae in Cr-spinel
3.5 Varying Crystallinity of Graphite
  3.5.1 Raman Spectra of Graphitic Carbon
  3.5.2 Raman Spectra of Graphitic Carbons in the Plesovice Peridotite
3.6 Diamond
  3.6.1 Infrared Absorption Spectra of Diamond
  3.6.2 Aggregation State of Nitrogen
  3.6.3 Synchrotron Micro-XRF and XANES Analysis of Plešovice Diamond and its Inclusions
  3.6.4 SXD Experiment of the Inclusion in the Microdiamond
3.7 Crystal Orientation Relationship Between Clinopyroxene Lamellae and Host Chromian Spinel
3.8 Discussion
  3.8.1 Origin of Graphitic Carbon in the Plešovice Peridotite
  3.8.2 Diamond—Natural or Contaminant?
  3.8.3 Exsolution Microstructures in Spinel
3.9 Conclusions
6.6 Mineral Composition
6.6.1 Garnet 159
6.6.2 Clinopyroxene and Olivine 161
6.6.3 Oxides 167
6.6.4 Amphibole 167
6.7 Mineral Lamellae in Clinopyroxene and EBSD Patterns 167
6.8 Pressure—Temperature Conditions 171
6.9 Discussion 175
6.9.1 Protoliths and Origin of the Hujianging Garnet Clinopyroxenites 175
6.9.2 Origin of Lamellar Phases 177
6.9.3 Evolution of the Hujianging Clinopyroxenite 178
6.10 Conclusions 180

7 The Correlation Between Raman Spectra and the Mineral Composition of Muscovite and Phengite 187
Huijuan Li, Lifei Zhang and Andrew G. Christy
7.1 Introduction 187
7.2 Experimental Methods 188
7.3 Results 190
7.3.1 Peak Assignment 190
7.3.2 Type I and Type II Raman Spectra 197
7.3.3 Peak Shift with Changing Si Content 198
7.4 Discussion 201
7.4.1 Comparison with Raman Spectra from the RRUFF Project 201
7.4.2 The Influence of Orientation on Raman Spectra 201
7.4.3 The Influence of Polytypic Stacking on Raman Spectra 203
7.4.4 Tetrahedral Peaks 203
7.4.5 Raman Shift and Octahedral Al Content 204
7.4.6 Spectral Variation Due to Si Content 204
7.4.7 OH-Stretching Peaks 205
7.5 Application 206
7.6 Conclusions 210

8 Increasing Chlorinity in Fluids Along the Prograde Metamorphic Path: Evidence of Apatite from Yangkou Eclogite, Sulu, China 213
Jingbo Liu, Lingmin Zhang, Qian Mao and Kai Ye
8.1 Introduction 213
8.2 Geological Setting and Outcrop Description 214
8.3 Descriptions of Samples and Occurrence of Apatite 215
8.3.1 Coronal Metagabbro 215
8.3.2 Coronal Eclogite 216
8.3.3 Coesite-Bearing Eclogite 217
9.8.3 Calculation of Fluid Oxygen Isotopic Composition
273
9.9 Calculation of Fluid Trace Element Composition
274
9.9.1 Garnet—Phengite and Garnet—Quartz Veins
277
9.9.2 Epidote Veins
277
9.10 Discussion
277
  9.10.1 Mass Transfer in HP—LT Polymineralic Garnet—Phengite/Garnet—Quartz Veins
277
  9.10.2 Chemical Exchanges During Prograde Epidote Vein Formation
280
  9.10.3 Origin of Albite and Quartz Veins
281
  9.10.4 Trace Element Mobility
282
  9.10.5 Implications for Vein Formation in Subduction Zones
283
9.11 Conclusions
285

Part III  Geochronological Data of UHPM Terranes
293

10 Geochronology of the Alpine UHP Rhodope Zone: A Review of Isotopic Ages and Constraints on the Geodynamic Evolution
295
  Anthi Liati, Dieter Gebauer and C. Mark Fanning
  10.1 Introduction
  295
  10.2 Overview of the Rhodope Zone
  296
    10.2.1 Geological Setting
    296
    10.2.2 Metamorphism
    298
  10.3 Selection of the Most Relevant Geochronological Data for the Rhodope Zone
  299
  10.4 Geochronological Data on Metamorphism
  301
    10.4.1 Jurassic Metamorphic Ages
    302
    10.4.2 Cretaceous Metamorphic Ages
    303
    10.4.3 Eocene Metamorphic Ages
    310
  10.5 Premetamorphic Geochronological Data
  311
    10.5.1 Detrital Zircon Ages in Metasedimentary Rocks
    311
    10.5.2 Ages of Mafic Rock Protoliths
    312
    10.5.3 Protolith Ages of Orthogneisses
    312
  10.6 Discussion
  313
    10.6.1 Time of UHP and HP Metamorphic Events
    314
    10.6.2 Geodynamic Implications
    316

11 Coherence of the Dabie Shan UHPM Terrane Investigated by Lu—Hf and $^{40}\text{Ar}/^{39}\text{Ar}$ Dating of Eclogites
325
  Fraukje M. Brouwer, Mirek Groen, Oliver Nebel, Jan R. Wijbrans,
  Huaning Qiu, Qijun Yang, Linghao H. Zhao and Yuanbao Wu
  11.1 Introduction
  325
  11.2 Geological Setting and Sample Selection
  328
11.3 Analytical Techniques
  11.3.1 Electron Microprobe
  11.3.2 Thermobarometry
  11.3.3 Mineral Separation
  11.3.4 Lu—Hf Geochronology
  11.3.5 $^{40}\text{Ar}/^{39}\text{Ar}$ Thermochronology

11.4 Results
  11.4.1 Petrography
  11.4.2 Mineral Chemistry
  11.4.3 Thermobarometry
  11.4.4 Lu—Hf Geochronology
  11.4.5 $^{40}\text{Ar}/^{39}\text{Ar}$ Thermochronology

11.5 Discussion
  11.5.1 Lu—Hf Isochron Relationships
  11.5.2 Ages for UHP Metamorphism
  11.5.3 Comparison with Previous Work
  11.5.4 Interpretation of $^{40}\text{Ar}—^{39}\text{Ar}$ Ages
  11.5.5 Tectonic Significance of the Geochronological Data

11.6 Conclusions

Part IV Ultrahigh-Pressure Metamorphic Belts and Protolith History of Eclogite and Garnet Peridotite

12 Distribution and Geological Position of High-/Ultrahigh-Pressure Units Within the European Variscan Belt: A Review
  Shah Wali Faryad

12.1 Introduction
12.2 Major Suture Zones in the European Variscan Belt
12.3 Bohemian Massif
12.4 Vosges and Schwarzwald
12.5 The French Massif Central
12.6 The Armorican Massif
12.7 Iberian Massif
12.8 Variscan HP Rocks in the External Crystalline Massifs and Occurring in the Alpine Nappe-Thrust Belt

12.9 Summary and Discussion
  12.9.1 Lithology and Occurrences of HP/UHP Rocks Within the European Variscan Belt
  12.9.2 $P—T$ Conditions and $P—T$ Paths of HP/UHP Rocks
  12.9.3 Age Relations and Subduction Polarity for Formation of HP/UHP Rocks
  12.9.4 Further Perspectives and Open Questions
13 Ultramafic Cumulates of Oceanic Affinity in an Intracontinental Subduction Zone: Ultrahigh-Pressure Garnet Peridotites from Pohorje (Eastern Alps, Slovenia)  
Jan C.M. De Hoog, Marian Janák, Mirijam Vrabec and Keiko H. Hattori  
13.1 Introduction  
13.1.1 Tectonic and Geological Background  
13.2 Samples  
13.3 Analytical Techniques  
13.4 Whole-Rock Chemistry  
13.4.1 Major and Minor Elements  
13.4.2 Trace Elements  
13.5 Mineral Chemistry  
13.5.1 Major Elements  
13.5.2 Trace Elements  
13.6 Discussion  
13.6.1 Protoliths  
13.6.2 Geodynamic Implications  
13.7 Conclusions  

14 Very High-Pressure Epidote Eclogite from Ross River Area, Yukon, Canada, Records Deep Subduction  
Edward Ghent and Philippe Erdmer  
14.1 Introduction  
14.2 Tectonic Setting of Eclogites  
14.3 Petrography  
14.4 Analytical Conditions  
14.5 Geothermobarometry  
14.5.1 Geothermobarometry Based on Mineral Equilibria  
14.5.2 Zr in Rutile Geothermometry  
14.5.3 Isochemical Phase Diagram Sections  
14.5.4 Modeling Garnet Zoning Using the Program THERIAK  
14.5.5 Modification of Garnet Zoning by Diffusion  
14.6 Discussion  

15 HP–UHP Metamorphic Belts in the Eastern Tethyan Orogentic System in China  
Jingsui Yang, Zhiqin Xu, Paul T. Robinson, Jianxin Zhang, Zeming Zhang, Fulai Liu and Cailai Wu  
15.1 Introduction  
15.2 HP–UHP Metamorphic Belts of the Eastern Tethyan System in China  
15.3 HP–UHP Metamorphic Belts in the Proto-Tethyan Orogen  
15.3.1 Geologic Background  
15.3.2 HP–UHP Metamorphic Rocks Within the Proto-Tethyan Orogenic Belt
15.4 HP—UHP Metamorphism in the Paleo-Tethyan Orogenic Belt

15.4.1 Dabie UHP Metamorphic Belt

15.4.2 Sulu UHP Metamorphic Belt

15.4.3 Eclogite Facies HP Metamorphic Belt in Qiangtang

15.4.4 Tibetan Sumdo (U?)HP Metamorphic Belt

15.5 HP—UHP Metamorphic Rocks Within the Neo-Tethyan Orogenic Belt

15.5.1 HP—UHP Metamorphic Rocks Within the Western Himalayan Syntaxis

15.5.2 HP—UHP Metamorphic Rocks Within the Eastern Himalayan Syntaxis

15.6 The Formation and Exhumation Dynamics of HP—UHP Metamorphic Belts in the Eastern Tethyan Orogenic Belt in China

15.6.1 Amalgamation of Microcontinental Blocks in the Proto-Tethyan and Paleo-Tethyan Ocean Basins: Subduction of Oceanic Crust and Formation of HP—UHP Metamorphic Belts

15.6.2 The Transition from Deep Subduction of Oceanic Lithosphere to Deep Subduction of Continental Crust

15.6.3 Continental Scissors-Like Collision: Restrictions on Continental Deep Subduction and the Formation of UHP Metamorphic Belts

15.6.4 Deep Subduction of Continent— Continent Collision Horns in Tongue-Shaped Lithospheric Blocks: Examples from the Eastern and Western Himalayan Syntaxes

15.6.5 The Polyphase Partitioning Extrusion and Exhumation Mechanism Along Multiple-Layered Channel Flow

15.6.6 The Role of Strike-Slip Faulting in the Subduction and Exhumation of HP—UHP Terranes

15.7 Conclusions

16 Orogenic Garnet Peridotites: Tools to Reconstruct Paleo-Geodynamic Settings of Fossil Continental Collision Zones

Cong Zhang, Herman van Roermund and Lifei Zhang

16.1 Introduction

16.2 A Conceptual Model Illustrating How Orogenic Garnet Peridotite Can Be Used to Reconstruct Fossil Geodynamic Environments

16.2.1 Mantle Wedge Garnet Peridotite

16.2.2 Subduction Zone Garnet Peridotite

16.3 A Test of the Feasibility of the Model in Scandinavia and China

16.3.1 Orogenic Garnet Peridotites in the Scandinavian Caledonides

16.3.2 Orogenic Garnet Peridotites in Sulu—Dabie and North Qaidam Orogens of China

16.4 Discussion and Conclusions
17 Petrology, Geochemistry, Geochronology, and Metamorphic Evolution of Garnet Peridotites from South Altyn Tagh UHP Terrane, Northwestern China: Records Related to Crustal Slab Subduction and Exhumation History

Chao Wang, Liang Liu, Danling Chen and Yuting Cao

17.1 Introduction 541
17.2 Geologic Background 542
17.3 Petrography
  17.3.1 Spinel—Garnet Peridotite 545
  17.3.2 Amphibole—Garnet Peridotite 547
17.4 Bulk-Rock Composition 547
17.5 Zircon U—Pb Dating and Hf Isotope Compositions 550
17.6 Mineral Chemistry
  17.6.1 Olivine 551
  17.6.2 Garnet 553
  17.6.3 Orthopyroxene 555
  17.6.4 Clinopyroxene 557
  17.6.5 Amphibole 562
  17.6.6 Spinel 562
17.7 Textural and Metamorphic Evolution
  17.7.1 Textural Evolution 563
  17.7.2 Metamorphic Evolution 566
17.8 P—T Estimates and P—T Path
  17.8.1 P—T Estimates 567
  17.8.2 P—T Path 570
17.9 Genesis of the Grt Peridotites and its Tectonic Implications 571
17.10 Conclusions 572

18 Metamorphic Evolution of the Gridino Mafic Dyke Swarm (Belomorian Eclogite Province, Russia)

Ksenia A. Dokukina and Alexander N. Konilov

18.1 Introduction 579
18.2 Geological Setting
  18.2.1 Izbnaya Luda Island 581
  18.2.2 Cape Vargas 584
18.3 Methods 585
18.4 Sample Description
  18.4.1 Mineralogy 588
  18.4.2 Geochemistry 602
  18.4.3 Geochronology 606
18.5 Discussion
  18.5.1 Relative Succession of Events 612
  18.5.2 P—T Evolution of the Gridino Metamorphic Rocks 613
  18.5.3 High-Pressure or Ultrahigh-Pressure? 613
  18.5.4 Time of the High-Pressure Event 614
  18.5.5 Tectonic Implication 616
18.6 Conclusions 616