

Contents

Preface	XI
Chapter 1. Chondritic meteorites and early solar system solids	1
by IAN S. SANDERS	
1. Introduction	1
1.1. Some essential facts about meteorites	2
1.2. The primitive chemical composition of chondrites	3
1.3. Chondrite classification	4
1.4. Changes to chondrites after their accretion	6
1.5. Differentiated meteorites	6
1.6. The solar system in its galactic context and the origin of elements	7
1.7. The isotopic compositions of elements in meteorites	8
1.8. Summary	10
2. Refractory inclusions	10
2.1. Petrography and formation	11
2.2. Oxygen isotopes	13
2.3. Evidence in CAIs for extinct ²⁶ Al	13
2.4. Dating of CAIs and establishing the age of the solar system	17
2.5. Summary	18
3. Chondrules	18
3.1. Chondrule petrography and chemistry	19
3.2. Oxygen-isotope compositions of chondrules	22
3.3. Chronology of chondrules	23
3.4. Formation of chondrules	24
3.5. Summary and future research	27
Acknowledgements.....	28
References.....	28
Chapter 2. Organics in primitive meteorites	33
by LAURENT REMUSAT	
1. Introduction	33
2. Spatial distribution of the organics: understanding the accretion process	35
3. Soluble organic compounds	37
3.1. Molecular diversity of soluble organic compounds	37
3.2. Linear and aromatic hydrocarbons	39
3.3. Amino and hydroxyl acids	40
3.4. Other molecules of potential biological interest.....	41
3.5. Enantiomeric excesses.....	42
4. The insoluble organic matter: the main organic reservoir in chondrites	43
4.1. Molecular structure of the IOM: a peculiar macromolecule	43
4.2. Diversity among the different types of chondrites: influence of parent-body processes or source effect?	45
4.3. Physical texture at the nanometer scale	47

5. How can we interpret the encrypted isotopic record of organics in chondrites?	49
5.1. Observations	50
5.2. Possible interpretations	52
5.3. C, O and N isotopes in IOM.....	55
6. IDPs, micrometeorites, Stardust: what do we learn from comets?.....	55
7. Conclusion	57
Acknowledgments	57
References.....	57

Chapter 3. Aqueous alteration in chondritic asteroids and comets from the study of carbonaceous chondrites67
 by **JOSEP M. Trigo-Rodríguez**

1. Introduction: searching for Solar-System primordial materials	67
2. Chondrite groups: chemical affinities, equilibration processes and parent bodies.....	70
3. Dating and characterizing aqueous alteration	73
3.1. Evidence of collisional processing of chondritic parent bodies.....	73
3.2. Dating parent-body hydration: formation of carbonates	75
4. Cometary materials: Stardust mission clues on primordial mineralogy	78
5. Discussion.....	80
6. Conclusions.....	82
Acknowledgements.....	83
References.....	83

Chapter 4. Impact metamorphism in terrestrial and experimental cratering events 89
 by **ALEX Deutsch, MICHAEL H. Poelchau and THOMAS Kenkmann**

1. Impacts – a growing field of research in Earth and planetary sciences.....	89
2. Impact metamorphism	91
2.1. Macroscopic shock effects – shatter cones	92
2.2. Microscopic shock effects.....	95
2.2.1. Fracturing, kink bands, mosaicism, twinning	97
2.2.2. Planar fractures.....	98
2.2.3. Planar deformation features	98
2.2.4. Feather features	99
3. Phase transformations to diaplectic glass and high-pressure phases	101
3.1. Diaplectic glass	101
3.2. High-pressure phases.....	101
3.3. Melting in impact events and the occurrence of impact glass.....	102
4. Shocked meteorites as clues to understanding terrestrial impact metamorphism	112
5. The MEMIN project – experimental cratering and its benefits for the understanding of shock metamorphism	113

6. Outlook	117
References.....	117

Chapter 5. Lunar geology129

by **M. ANAND, J.J. BARNES and L.J. HALLIS**

1. Introduction	129
2. Origin of the Moon	133
3. Lunar magma ocean	135
4. Morphology of the lunar surface	136
4.1. Impact crater and basin morphology	137
4.2. Volcanic landforms	137
4.3. Tectonic features	138
4.4. Erosion and degradation by impacts.....	139
5. Lunar stratigraphy and surface ages	140
6. Lunar lithologies/rock types	142
6.1. Lunar highlands.....	142
6.2. Mare basalts and pyroclastic glasses	146
6.3. Pyroclastic glasses.....	146
7. Mineralogy of lunar samples	147
7.1. Pyroxene	148
7.2. Pyroxferroite	150
7.3. Olivine	150
7.4. Feldspar	150
7.5. Ilmenite	150
7.6. Spinel	151
7.7. Armalcolite	151
7.8. Other oxides.....	152
7.9. Sulfides	152
7.10. Phosphates	152
7.11. Silica	153
7.12. FeNi metal	153
8. Lunar impact-related rocks and the regolith	153
9. Volatiles	156
10. Summary.....	158
Acknowledgements.....	158
References.....	159

Chapter 6. Noble gas chemistry of planetary materials165

by **JULIA. A. Cartwright**

1. Introduction to noble gases and components.....	165
1.1. A brief history of noble gases.....	165
1.2. Noble gas reservoirs	167
1.3. The noble gas budget in the Solar System.....	168

1.4. Components and meteorites	173
1.4.1. In the neighbourhood – the rocky planets and the gas giants	173
1.4.2. Other trapped components	177
1.4.2a. Origins.....	178
1.4.2b. The mysterious Q phase	179
1.4.2c. Presolar graphite and SiC – G, N and R components	181
1.4.2d. Presolar diamond – HL, P3 and P6 components	182
1.4.2e. Solar-System diamond and Ureilite gases	182
1.4.2f. Subsolar gases	183
1.4.3. Components and meteorite groups	183
2. Noble gases as chronometers	183
2.1. System disturbances	184
2.2. The short-lived ^{129}I – ^{129}Xe decay scheme	184
2.2.1. Methodology	185
2.3. ^{40}K – ^{40}Ar and ^{40}Ar – ^{39}Ar dating techniques	187
2.3.1. The curious case of possible excess Ar in shergottite meteorites... ..	189
2.4. U-Th/He and U-Th/Ne dating	191
2.5. Off-shoots of chronometry	192
2.5.1. Noble gases and halogens	192
3. Noble gases from cosmic-ray exposure.....	193
3.1. Caveats of cosmogenic dating	198
3.2. Shielding parameters	199
3.3. Calculating production rates	200
3.3.1. Self-correcting methods	200
3.4. Distribution of cosmic-ray exposure ages of meteorites	201
3.4.1. Stony meteorite CRE ages	201
3.4.2. Iron and stony-iron CRE ages	204
3.4.3. Micrometeorite (MM) and interplanetary dust particle (IDP) CRE ages	204
4. Closing comment	204
Acknowledgements.....	205
References.....	205

Chapter 7. Isotopic analyses of primitive meteorites213

by **JUTTA Zipfel**

1. Introduction	213
2. Isotopic compositions of primitive Solar System materials	215
2.1. Isotope anomalies in presolar grains.....	216
2.2. Oxygen in primitive chondrites	217
2.3 Silicon, iron and minor and trace elements in chondrites.....	219
3. Age constraints on primitive Solar-System materials	222
4. Conclusions.....	223

Acknowledgements.....	223
References.....	223

Chapter 8. Shocked rocks: impacts from the laboratory to the Solar System227

by **MARK J. Burchell**

1. Introduction	227
1.1. Historical recognition of impact origin for terrestrial craters	228
1.2. Hugoniot equations	230
1.3. Linear shock wave speeds.....	230
2. High-speed impacts	230
2.1. Orbital mechanics	231
2.2. Impacts.....	232
2.3. Crater formation	233
3. Calculating peak shock pressures	235
3.1. Planar Impact Approximation (PIA).....	236
3.2. Hydrocode simulations	237
4. Impact experiments	238
4.1. Split bar	238
4.2. Flyer plate	238
4.3. Two-stage light gas guns.....	239
5. Mechanical effects	240
5.1. Shatter cones	240
5.2. Planar microscopic features	241
5.3. Diaplectic glasses	243
6. High-pressure polymorphs	244
7. Melt.....	245
8. Shock barometers	246
9. Conclusions.....	247
References.....	248

Chapter 9. Micrometeorites253

by **LUIGI Folco and CAROLE Cordier**

1. Introduction	253
2. Micrometeoroid sources and orbital evolution	259
3. Micrometeoroid atmospheric entry	260
4. Micrometeorite collections.....	262
5. Classification and mineralogical, textural and bulk compositional properties of micrometeorites.....	264
5.1. Melted micrometeorites.....	264
5.2. Partially melted micrometeorites	272
5.3. Unmelted micrometeorites	276

6. Micrometeorite precursor materials and parent bodies	278
6.1. Melted micrometeorites related to carbonaceous and ordinary chondrite parent bodies	278
6.2. Melted micrometeorites related to Vesta-like parent bodies	281
6.3. Unmelted and partially melted silicate micrometeorites related to carbonaceous and ordinary chondrite parent bodies	283
6.4. Unmelted ultracarbonaceous micrometeorites related to comets.....	283
6.5. Unmelted silicate micrometeorites related to unknown differentiated bodies	284
7. Micrometeorite statistics: flux and the composition of the near-Earth micrometeoroid complex	285
8. Concluding remarks	288
Acknowledgements.....	289
References.....	289
Index.....	299