

# Contents

|          |                                                            |           |
|----------|------------------------------------------------------------|-----------|
| <b>1</b> | <b>Introduction and General Concepts</b>                   | <b>1</b>  |
| 1.1      | Definitions                                                | 3         |
| 1.2      | Mineral Resources/Reserves Classification: «McKelvey Box»  | 4         |
| 1.3      | A Brief History of Mining                                  | 6         |
| 1.3.1    | Pre-5000 BC                                                | 7         |
| 1.3.2    | Egyptians                                                  | 9         |
| 1.3.3    | Roman Empire                                               | 9         |
| 1.3.4    | China                                                      | 11        |
| 1.3.5    | Middle Ages                                                | 11        |
| 1.3.6    | Industrial Revolution                                      | 12        |
| 1.3.7    | Last Two Centuries                                         | 12        |
| 1.4      | The Mining Cycle                                           | 13        |
| 1.4.1    | Exploration                                                | 14        |
| 1.4.2    | Evaluation                                                 | 16        |
| 1.4.3    | Exploitation                                               | 17        |
| 1.4.4    | Mineral Processing                                         | 18        |
| 1.4.5    | Closure and Reclamation                                    | 20        |
| 1.5      | International Reporting Standards                          | 21        |
| 1.5.1    | CRIRSCO International Reporting Template                   | 22        |
| 1.5.2    | United Nations Framework Classification                    | 24        |
| 1.5.3    | National Codes                                             | 25        |
| 1.6      | Distribution of Mineral Resources in the Earth             | 26        |
| 1.7      | Mineral Resources Consumption                              | 30        |
| 1.8      | Sustainable Development                                    | 33        |
| 1.9      | Critical Raw Materials                                     | 34        |
| 1.10     | Mineral Resource Recycling                                 | 37        |
| 1.10.1   | Construction and Demolition Waste                          | 39        |
| 1.10.2   | Industrial Minerals                                        | 39        |
| 1.10.3   | Metals                                                     | 40        |
| 1.11     | Trade and Markets                                          | 42        |
| 1.12     | Mining as a Business                                       | 44        |
| 1.13     | Questions                                                  | 46        |
|          | References                                                 | 46        |
| <b>2</b> | <b>Mineral Deposits: Types and Geology</b>                 | <b>49</b> |
| 2.1      | Introduction                                               | 50        |
| 2.2      | Basic Vocabulary                                           | 51        |
| 2.3      | Evolutionary Concepts About the Origin of Mineral Deposits | 53        |
| 2.4      | Mineral Deposits and Plate Tectonics                       | 55        |
| 2.5      | Criteria for the Classification of Mineral Deposits        | 58        |
| 2.6      | Ore-Forming Processes                                      | 61        |
| 2.6.1    | Magmatic Processes                                         | 62        |
| 2.6.2    | Metamorphic Processes                                      | 63        |
| 2.6.3    | Sedimentary Processes                                      | 64        |
| 2.6.4    | Hydrothermal Processes                                     | 66        |
| 2.7      | Mineral Resources Commodities                              | 68        |
| 2.7.1    | Energy                                                     | 68        |
| 2.7.2    | Metals                                                     | 76        |

|       |                                                         |     |
|-------|---------------------------------------------------------|-----|
| 2.7.3 | Industrial Minerals .....                               | 79  |
| 2.7.4 | Industrial Rocks .....                                  | 84  |
| 2.8   | <b>Genetic Classification of Mineral Deposits</b> ..... | 89  |
| 2.8.1 | Magmatic Ore Deposits .....                             | 89  |
| 2.8.2 | Hydrothermal Ore Deposits .....                         | 97  |
| 2.8.3 | Sedimentary Ore Deposits .....                          | 106 |
| 2.8.4 | Metamorphic and Metamorphosed Mineral Deposits .....    | 116 |
| 2.9   | <b>Questions</b> .....                                  | 117 |
|       | References .....                                        | 117 |
| 3     | <b>Mineral Resource Exploration</b> .....               | 121 |
| 3.1   | <b>Introduction</b> .....                               | 122 |
| 3.2   | <b>Mineral Resource Exploration Stages</b> .....        | 125 |
| 3.2.1 | Program Design .....                                    | 125 |
| 3.2.2 | Reconnaissance Exploration .....                        | 126 |
| 3.2.3 | Detailed Exploration .....                              | 127 |
| 3.2.4 | Pre-feasibility/Feasibility Study .....                 | 129 |
| 3.3   | <b>Mineral Deposit Models</b> .....                     | 130 |
| 3.3.1 | Types of Models .....                                   | 131 |
| 3.3.2 | Maturity of Descriptive-Genetic Models .....            | 136 |
| 3.4   | <b>Exploration Methods</b> .....                        | 137 |
| 3.4.1 | Remote Sensing .....                                    | 137 |
| 3.4.2 | Photogeology .....                                      | 139 |
| 3.4.3 | Geological Mapping .....                                | 141 |
| 3.4.4 | Geophysical Exploration .....                           | 144 |
| 3.4.5 | Geochemical Exploration .....                           | 161 |
| 3.4.6 | Drilling .....                                          | 182 |
| 3.5   | <b>Case Studies</b> .....                               | 197 |
| 3.6   | <b>Questions</b> .....                                  | 219 |
|       | References .....                                        | 220 |
| 4     | <b>Mineral Resource Evaluation</b> .....                | 223 |
| 4.1   | <b>Introduction</b> .....                               | 224 |
| 4.2   | <b>Sampling</b> .....                                   | 224 |
| 4.2.1 | Significance of the Sampling Process .....              | 225 |
| 4.2.2 | Definition of Sample .....                              | 228 |
| 4.2.3 | Steps in Sampling .....                                 | 231 |
| 4.2.4 | Sampling Methods .....                                  | 231 |
| 4.2.5 | Sampling Pattern and Spacing .....                      | 239 |
| 4.2.6 | Sample Weight .....                                     | 240 |
| 4.2.7 | Sample Reduction and Errors .....                       | 241 |
| 4.3   | <b>Determination of Grades</b> .....                    | 245 |
| 4.3.1 | Weighting Techniques .....                              | 245 |
| 4.3.2 | Statistical Estimation of Grades .....                  | 248 |
| 4.3.3 | Outliers .....                                          | 251 |
| 4.3.4 | Coproduct and By-Product .....                          | 253 |
| 4.4   | <b>Cutoff Grade and Grade-Tonnage Curves</b> .....      | 254 |
| 4.4.1 | Cutoff Grade .....                                      | 254 |
| 4.4.2 | Grade-Tonnage Curves .....                              | 257 |
| 4.5   | <b>Estimation Methods</b> .....                         | 258 |
| 4.5.1 | Drillhole Information and Geological Data .....         | 259 |
| 4.5.2 | General Procedure .....                                 | 259 |

|       |                                                         |     |
|-------|---------------------------------------------------------|-----|
| 4.5.3 | Bulk Density .....                                      | 260 |
| 4.5.4 | Estimation Procedures .....                             | 262 |
| 4.5.5 | Classical Methods .....                                 | 262 |
| 4.5.6 | Geostatistical Methods .....                            | 272 |
| 4.6   | <b>Mining Project Evaluation</b> .....                  | 288 |
| 4.6.1 | Types of Studies .....                                  | 289 |
| 4.6.2 | Economic Analysis .....                                 | 295 |
| 4.7   | <b>Questions</b> .....                                  | 307 |
|       | References .....                                        | 307 |
| 5     | <b>Mineral Resource Extraction</b> .....                | 311 |
| 5.1   | <b>Introduction</b> .....                               | 312 |
| 5.2   | <b>Surface Mining vs Underground Mining</b> .....       | 313 |
| 5.2.1 | Stripping Ratio .....                                   | 316 |
| 5.2.2 | Dilution .....                                          | 317 |
| 5.3   | <b>Surface Mining</b> .....                             | 319 |
| 5.3.1 | Geotechnical Considerations in Surface Mining .....     | 320 |
| 5.3.2 | Surface Production Cycle .....                          | 325 |
| 5.3.3 | Surface Mining Methods .....                            | 336 |
| 5.4   | <b>Surface Mining to Underground Mining</b> .....       | 356 |
| 5.5   | <b>Underground Mining</b> .....                         | 359 |
| 5.5.1 | Geotechnical Considerations in Underground Mining ..... | 360 |
| 5.5.2 | Underground Infrastructure .....                        | 363 |
| 5.5.3 | Underground Load and Transportation .....               | 367 |
| 5.5.4 | Rock Support .....                                      | 368 |
| 5.5.5 | Underground Methods .....                               | 372 |
| 5.5.6 | Underground Mining Optimization .....                   | 392 |
| 5.6   | <b>Drilling and Blasting</b> .....                      | 392 |
| 5.6.1 | Blasthole Drilling .....                                | 394 |
| 5.6.2 | Explosives .....                                        | 397 |
| 5.6.3 | Surface Blasting .....                                  | 406 |
| 5.6.4 | Underground Blasting .....                              | 412 |
| 5.6.5 | Dangers of Blasting .....                               | 413 |
| 5.7   | <b>Grade Control</b> .....                              | 413 |
| 5.7.1 | Open-Pit Grade Control .....                            | 415 |
| 5.7.2 | Underground Grade Control .....                         | 416 |
| 5.7.3 | Grade Control and Reconciliation .....                  | 417 |
| 5.8   | <b>Questions</b> .....                                  | 419 |
|       | References .....                                        | 419 |
| 6     | <b>Mineral Processing</b> .....                         | 423 |
| 6.1   | <b>Introduction</b> .....                               | 425 |
| 6.2   | <b>Basic Concepts</b> .....                             | 427 |
| 6.2.1 | Concentrates and Penalties .....                        | 427 |
| 6.2.2 | Grade and Recovery .....                                | 429 |
| 6.2.3 | Net Smelter Return .....                                | 430 |
| 6.3   | <b>Steps in Mineral Processing</b> .....                | 431 |
| 6.3.1 | Size Reduction .....                                    | 432 |
| 6.3.2 | Size Separation .....                                   | 432 |
| 6.3.3 | Concentration of Valuable Components .....              | 434 |
| 6.3.4 | Dewatering .....                                        | 436 |

|        |                                                             |     |
|--------|-------------------------------------------------------------|-----|
| 6.4    | <b>Particle Size and Size Distribution</b>                  | 436 |
| 6.5    | <b>Ore Handling</b>                                         | 439 |
| 6.6    | <b>Comminution</b>                                          | 440 |
| 6.6.1  | Mechanisms of Fracture                                      | 440 |
| 6.6.2  | Energy for Size Reduction                                   | 441 |
| 6.6.3  | Comminution Stages                                          | 443 |
| 6.6.4  | Comminution Equipment                                       | 446 |
| 6.6.5  | Size Reduction Circuits                                     | 456 |
| 6.7    | <b>Size Separation</b>                                      | 458 |
| 6.7.1  | Screening                                                   | 459 |
| 6.7.2  | Classification                                              | 463 |
| 6.8    | <b>Mineral Beneficiation</b>                                | 466 |
| 6.8.1  | Ore Sorting                                                 | 467 |
| 6.8.2  | Gravity Concentration                                       | 473 |
| 6.8.3  | Dense Medium Separation                                     | 481 |
| 6.8.4  | Flotation                                                   | 483 |
| 6.8.5  | Magnetic Separation                                         | 496 |
| 6.8.6  | Electrostatic Separation                                    | 498 |
| 6.8.7  | Pyrometallurgy/Hydrometallurgy                              | 501 |
| 6.9    | <b>Dewatering</b>                                           | 512 |
| 6.9.1  | Sedimentation                                               | 513 |
| 6.9.2  | Filtration                                                  | 515 |
| 6.9.3  | Thermal Dewatering (Drying)                                 | 518 |
| 6.10   | <b>Waste/Tailings Disposal</b>                              | 519 |
| 6.10.1 | Methods of Tailings Disposal                                | 521 |
| 6.11   | <b>Questions</b>                                            | 527 |
|        | References                                                  | 527 |
| 7      | <b>Environment and Sustainability</b>                       | 531 |
| 7.1    | <b>Mining and the Environment</b>                           | 533 |
| 7.1.1  | Introduction                                                | 533 |
| 7.1.2  | Closure and Reclamation: The Final Stage                    | 534 |
| 7.1.3  | Environmental Management System                             | 541 |
| 7.2    | <b>Mining and Sustainable Development</b>                   | 542 |
| 7.3    | <b>Social License to Operate</b>                            | 545 |
| 7.3.1  | Phases of Earning a Social License                          | 547 |
| 7.4    | <b>Potential Environmental Impacts and Their Management</b> | 548 |
| 7.4.1  | Mining Project Phases and Environmental Impacts             | 548 |
| 7.4.2  | Waste Impacts and Their Management                          | 551 |
| 7.4.3  | Water Management                                            | 556 |
| 7.4.4  | Hazardous Materials Management                              | 565 |
| 7.4.5  | Mining and Biodiversity                                     | 567 |
| 7.4.6  | Airborne Contaminants, Noise, and Vibration Management      | 569 |
| 7.4.7  | Other Potential Environmental Impacts                       | 571 |
| 7.4.8  | Revegetation                                                | 574 |
| 7.5    | <b>Potential Social Impacts</b>                             | 579 |
| 7.6    | <b>Environmental Impact Assessment (EIA)</b>                | 581 |
| 7.6.1  | Origin of EIA                                               | 581 |
| 7.6.2  | EIA Phases                                                  | 582 |
| 7.6.3  | Impact Analysis and Prediction                              | 582 |
| 7.6.4  | Methods for Identification of Effects and Impacts           | 582 |
| 7.6.5  | EIA for Mining Projects                                     | 583 |

|       |                                                   |     |
|-------|---------------------------------------------------|-----|
| 7.7   | <b>Social Impact Assessment (SIA)</b> .....       | 587 |
| 7.7.1 | General Overview of SIA.....                      | 587 |
| 7.7.2 | SIA for Mining Projects.....                      | 588 |
| 7.8   | <b>Reclamation Case Studies</b> .....             | 589 |
| 7.9   | <b>Question</b> .....                             | 611 |
|       | References.....                                   | 612 |
| 8     | <b>Mining Software</b> .....                      | 615 |
| 8.1   | <b>Introduction</b> .....                         | 616 |
| 8.2   | <b>Types of Mining Software</b> .....             | 616 |
| 8.2.1 | Inexpensive Software.....                         | 616 |
| 8.2.2 | Commercial Software.....                          | 618 |
| 8.3   | <b>RockWorks</b> .....                            | 619 |
| 8.3.1 | Borehole Manager.....                             | 619 |
| 8.3.2 | Utilities.....                                    | 622 |
| 8.4   | <b>Datamine</b> .....                             | 623 |
| 8.4.1 | Fusion/Geological Database Management System..... | 624 |
| 8.4.2 | Studio RM.....                                    | 625 |
| 8.4.3 | Datamine Studio OP.....                           | 631 |
| 8.4.4 | NPV Scheduler.....                                | 634 |
| 8.5   | <b>Questions</b> .....                            | 637 |
|       | Reference.....                                    | 638 |

## Supplementary Information

|            |     |
|------------|-----|
| Index..... | 641 |
|------------|-----|