## Contents

Foreword \( V \)
Preface \( XIX \)
List of Contributors \( XXI \)
Acknowledgements \( XXVII \)
Color Plates \( XXXI \)

1 Drills as Tools for Media Penetration and Sampling \( 1 \)
   Yoseph Bar-Cohen and Kris Zacny
   
1.1 Introduction and Historical Perspective \( 1 \)
1.2 Methods of Drilling and Penetration of Objects \( 9 \)
   1.2.1 Mechanical Techniques \( 9 \)
   1.2.2 Thermal Techniques \( 12 \)
   1.2.3 Chemical Techniques \( 13 \)
1.3 Types of Mechanical Drills \( 14 \)
   1.3.1 Rotary Drill \( 14 \)
   1.3.2 Hammer Drill \( 15 \)
   1.3.3 Rotary-Hammer Drill \( 15 \)
1.4 Bits – the End-Effector of Drills \( 15 \)
   1.4.1 Twist Drill Bits \( 15 \)
   1.4.2 Gun Drill \( 16 \)
   1.4.3 Centering and Spotting Drill Bits \( 17 \)
   1.4.4 Material Makeup of Bits \( 18 \)
1.5 Application of Drilling Techniques \( 19 \)
   1.5.1 Geological Studies and Search for Resources \( 19 \)
   1.5.2 Mining and Tunneling \( 20 \)
   1.5.3 Petroleum and Gas Drilling and Exploration \( 21 \)
   1.5.4 Ocean and Seafloor Drilling \( 23 \)
   1.5.5 Planetary Drilling and Sampling \( 23 \)
   1.5.6 Ice Drilling \( 25 \)
   1.5.7 Dental Drills \( 25 \)
2 Principles of Drilling and Excavation 31
Gang Han, Maurice B. Dusseault, Emmanuel Detournay, Bradley J. Thomson, and Kris Zacny

2.1 Introduction 31
2.2 Physical Properties of Rocks 31
2.2.1 Terrestrial Rocks 31
2.2.2 Extraterrestrial Rocks 48
2.2.3 Influence Factors for Rock Mechanical Properties 52
2.3 Stresses and Energy in Drilling 65
2.3.1 Stress in Sedimentary Basins 65
2.3.2 Stresses Around a Borehole 83
2.4 Theories of Rock Breakage 89
2.4.1 Percussion Drilling 89
2.4.2 Rotary Drilling 104
2.4.3 Percussion–Rotary 118
2.4.4 Other Drilling Methods 118
2.4.5 Drilling Efficiency 119
2.5 Conclusion 126
2.5.1 Underground Rocks and Stresses 126
2.5.2 Drilling Theories 128
2.5.3 Effect of Environment on Drilling 129
References 132

3 Ground Drilling and Excavation 141
Alfred William (Bill) Eustes III, William W. Fleckenstein, Leslie Gertsch, Ning Lu, Michael S. Stoner, and Alfred Tischler

3.1 Background 141
3.1.1 Three Requirements for Any Drilling System 141
3.1.2 Types of Earth Boreholes 143
3.2 Drilling Rigs 144
3.2.1 Percussion Drilling Rigs 144
3.2.2 Rotary Drilling Rigs 149
3.3 Penetrating the Material 162
3.3.1 Basic Rock Destruction Mechanism 163
3.3.2 Specific Energy Comparison of Different Drilling Methods 165
3.4 Cuttings Transport and Disposal 174
3.4.1 Cuttings Transport from Under a Bit in Terrestrial Operations 174
3.4.2 Cuttings Transport Beyond the Bit 175
3.4.3 Cuttings Removal In Situ 178
3.4.4 Recompaction of Cuttings 179
3.4.5 Creation of Disposal Volume 181
3.5 Directional Drilling 183
4.5 Drilling Fluids 291
4.5.1 Main Fluids 293
4.5.2 Densiﬁers 294
4.6 Comments on Encountering the Bed 295
4.7 Drilling to Characterize the Glacier Bed 297
4.7.1 Accessing the Bed 297
4.7.2 Sampling and Characterizing the Bed 299
4.8 Conclusion 300
References 303

5 Seafloor Drilling 309
Tim McGinnis
5.1 Introduction 309
5.2 Offshore Drilling 309
5.2.1 Exploration and Production Drill Ship 310
5.2.2 Jack-Up Drill 311
5.2.3 Semi-Submersible Drilling 311
5.3 Geotechnical Drilling 312
5.4 Scientiﬁc Drilling 313
5.4.1 Drilling, Observation and Sampling of the Earth’s Continental Crust (DOSECC) 313
5.4.2 Integrated Ocean Drilling Program (IODP) 315
5.5 Remotely Controlled Robotic Seaﬂoor Drilling 318
5.5.1 Robotic Drilling Techniques – Rod Drilling 320
5.5.2 Robotic Drilling Techniques – Wireline Drilling 325
5.5.3 Robotic Drilling Systems 328
5.6 Non-Rotary Sampling 336
5.6.1 Dredge Sampling 337
5.6.2 Grab Sampling 337
5.6.3 Gravity Coring 338
5.6.4 Push Coring 341
5.7 Vibrocoring 343
5.8 Conclusion 343
References 344

6 Extraterrestrial Drilling and Excavation 347
Kris Zacny, Yoseph Bar-Cohen, Kiel Davis, Pierre Coste, Gale Paulsen,
Stewart Sherrit, Jeffrey George, Brian Derkowski, Steve Gorevan,
Dale Boucher, Jose Guerrero, Takashi Kubota, Bradley J. Thomson,
Scott Stanley, Peter Thomas, Nicholas Lan, Christopher McKay,
Tullis C. Onstot, Carol Stoker, Brian Glass, Sachiko Wakabayashi, Lyle Whyte,
Gianfranco Visentin, Edoardo Re, Lutz Richter, Mircea Badescu, Xiaoqi Bao,
Roger Fincher, Toshiki Hoshino, Piergiorgio Magnani, and Carlo Menon
6.1 Why Subsurface Exploration? 347
6.1.1 Search for Evidence of Existing or Extinct Life 348
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1.2 Science Rationale for Drilling on Mars</td>
<td>349</td>
</tr>
<tr>
<td>6.1.3 Search for Resources and <em>In Situ</em> Resource Utilization to Support Human Exploration</td>
<td>352</td>
</tr>
<tr>
<td>6.2 Methods for Subsurface Access on Extraterrestrial Bodies</td>
<td>352</td>
</tr>
<tr>
<td>6.3 Grinders and Rock Abrasion Tools</td>
<td>355</td>
</tr>
<tr>
<td>6.3.1 Rock Abrasion Tool (RAT)</td>
<td>355</td>
</tr>
<tr>
<td>6.3.2 The Beagle 2 Rock Corer Grinder</td>
<td>356</td>
</tr>
<tr>
<td>6.3.3 Ultrasonic Rock Abrasion Tool (URAT)</td>
<td>356</td>
</tr>
<tr>
<td>6.4 Scoops</td>
<td>358</td>
</tr>
<tr>
<td>6.4.1 Surveyor Scoop</td>
<td>358</td>
</tr>
<tr>
<td>6.4.2 Viking Lander Surface Sampler Acquisition Assembly</td>
<td>360</td>
</tr>
<tr>
<td>6.4.3 Phoenix 2007 Scoop</td>
<td>361</td>
</tr>
<tr>
<td>6.4.4 Micro End-Effecter (MEE)</td>
<td>364</td>
</tr>
<tr>
<td>6.4.5 Percussive Scoop</td>
<td>365</td>
</tr>
<tr>
<td>6.5 Moles</td>
<td>366</td>
</tr>
<tr>
<td>6.5.1 The European Space Agency Mobile Penetrometer</td>
<td>366</td>
</tr>
<tr>
<td>6.5.2 The Moon/Mars Underground Mole (MMUM)</td>
<td>368</td>
</tr>
<tr>
<td>6.5.3 Instrumented Mole System (IMS)</td>
<td>372</td>
</tr>
<tr>
<td>6.5.4 Mole-Type Excavation Robot for Subsurface Exploration</td>
<td>373</td>
</tr>
<tr>
<td>6.6 Ultrasonic and Percussive Actuated Drills</td>
<td>377</td>
</tr>
<tr>
<td>6.6.1 Ultrasonically Assisted Drilling</td>
<td>377</td>
</tr>
<tr>
<td>6.6.2 Ultrasonic/Sonic Driller/Corer (USDC)</td>
<td>379</td>
</tr>
<tr>
<td>6.6.3 Mars Integrated Drilling and Sampling (MIDAS) System</td>
<td>387</td>
</tr>
<tr>
<td>6.6.4 ESA Ultrasonic Rock Corer</td>
<td>390</td>
</tr>
<tr>
<td>6.6.5 ESA Ultrasonic Drill Tool (UDT)</td>
<td>392</td>
</tr>
<tr>
<td>6.6.6 Drill with Hammering Mechanism (DHM)</td>
<td>393</td>
</tr>
<tr>
<td>6.6.7 Percussive Regolith Penetrometer</td>
<td>399</td>
</tr>
<tr>
<td>6.7 Surface Drills</td>
<td>402</td>
</tr>
<tr>
<td>6.7.1 Low-Force Sample Acquisition System (LSAS)</td>
<td>402</td>
</tr>
<tr>
<td>6.7.2 Mini-Corer</td>
<td>405</td>
</tr>
<tr>
<td>6.7.3 Coring and Abrading Tool (CAT)</td>
<td>407</td>
</tr>
<tr>
<td>6.7.4 Small Sample Acquisition and Distribution Tool (SSA/DT)</td>
<td>411</td>
</tr>
<tr>
<td>6.7.5 SENER Touch-and-Go Sampler</td>
<td>412</td>
</tr>
<tr>
<td>6.7.6 Honeybee Robotics Touch-and-Go Sampler</td>
<td>413</td>
</tr>
<tr>
<td>6.7.7 Near-Earth Asteroid Sample Return</td>
<td>416</td>
</tr>
<tr>
<td>6.7.8 Titan Harpoon Sampler</td>
<td>417</td>
</tr>
<tr>
<td>6.8 Shallow Drilling: One Meter Class Drills</td>
<td>421</td>
</tr>
<tr>
<td>6.8.1 CNSR Sample Acquisition System for 1 m (SAS-1m)</td>
<td>422</td>
</tr>
<tr>
<td>6.8.2 Sample Acquisition and Preprocessing System (EBRC)</td>
<td>423</td>
</tr>
<tr>
<td>6.8.3 NORCAT’s SCaD 2 m Drill</td>
<td>438</td>
</tr>
<tr>
<td>6.8.4 ATK’s Segmented Coring Auger Drill (SCAD)</td>
<td>441</td>
</tr>
<tr>
<td>6.8.5 Pneumatic Drill and Excavation System</td>
<td>444</td>
</tr>
<tr>
<td>6.8.6 The Sample Acquisition and Transfer Mechanism (SATM) Drill</td>
<td>449</td>
</tr>
</tbody>
</table>
6.8.7 CNSR Sample Acquisition System for 3 m (SAS-3m) 451
6.8.8 Rover-Based Deep Drill MicroRoSA 452
6.8.9 Construction and Resource Utilization Explorer Drill 453
6.8.10 Subsurface Corer Sampling System 455
6.8.11 Subsurface Telescoping Sampling System 458
6.8.12 Venus Drill 460

6.9 Ten-Meter Class Drills 462
6.9.1 Mars Astrobiology Research and Technology Experiment (MARTE) 462
6.9.2 Drilling Automation for Mars Exploration (DAME) 464
6.9.3 NORCAT’s SCaD Deep Drill 469
6.9.4 Subsurface Planetary Exploration Core Extracting System (SPECES) Drill 473
6.9.5 Ultrasonic/Sonic Gopher 475
6.10 Deep Drills (>10 m) 476
6.10.1 Subsurface Explorer (SUBEX) 477
6.10.2 Mars/Arctic Deep Drill 479
6.10.3 Autonomous Tethered Corer 488
6.10.4 Inchworm Deep Drilling System 489
6.10.5 Modular Planetary Drill System (MPDS) 491
6.11 Past and Present Subsurface Access Missions 493
6.11.1 Apollo Drive Tubes and Drill 493
6.11.2 Soviet Luna Drill 497
6.11.3 Venera Drill 498
6.11.4 The Rosetta Lander Drill, Sampler and Distribution System (SD2) 499
6.11.5 The Huygens Penetrometer 501
6.11.6 Sampling Mole PLUTO on Mars Express – Beagle 2 502
6.11.7 The Beagle 2 Rock Corer Grinder (RCG) 503
6.11.8 Asteroid Surface Sampling Device 504
6.12 Future Sampling Missions 504
6.12.1 The Mars Science Laboratory (MSL) Rover Drill 504
6.12.2 The ExoMars Drill 506
6.13 Future European Prospects in Science and Exploration Programs 510
6.13.1 Aurora 510
6.13.2 Cosmic Vision 511
6.14 Bio-Inspired Drilling Systems for Future Space Applications 512
6.14.1 Biomimetics 512
6.14.3 Plant-Inspired Space Probe 514
6.14.4 The Locust as a Model for Inspiring Digging System 515
6.14.5 Descent Mechanism 516
6.14.6 Material Transport System 517
6.14.7 Gecko-Inspired Cuttings Removal 517
6.15 Drilling Automation 520
6.15.1 Background 520
6.15.2 Why Space Drilling Needs Automation 520
6.15.3 Diagnostic Approaches 521
6.16 Testing of Subsurface Systems 521
6.16.1 Reason for Testing in a Relevant Environment 522
6.16.2 Japan Aerospace Exploration Agency (JAXA) 523
6.16.3 Honeybee Robotics Drill Testing Facility 525
6.16.4 ATK Space Subsurface Access Testing Laboratory 527
6.17 Space Analogs on Earth for Field Test Simulations of In Situ Planetary Drilling 528
6.17.1 Arctic Sites 529
6.17.2 Rio Tinto, Spain 532
6.17.3 Atacama Desert, Chile 532
6.17.4 Lonar Crater, India 532
6.17.5 Southwest United States 532
6.17.6 Antarctic Dry Valleys 533
6.18 Drill Evaluation Criteria 534
6.19 Conclusions 541
References 546

7 Planetary Sample Handling and Processing 559
Kris Zacny, Antonio Diaz-Calderon, Paul G. Backes, Kiel Davis, Chris Leger, Erik Mumm, Edward Tunstel, Jason Herman, Gale Paulsen, and Yoseph Bar-Cohen
7.1 Introduction 559
7.1.1 Why Sampling? 559
7.1.2 Comminution Requirements for Planetary Applications 562
7.2 Comminution 564
7.2.1 Background to Comminution 564
7.2.2 Theory of Rock Breaking 565
7.2.3 Energy Requirements in Breaking Rock 567
7.2.4 Analysis of Broken Material 568
7.2.5 Sample Caking During Grinding 571
7.2.6 Cryo Grinding 572
7.2.7 Hardness of Material vs Hardness of Crushing/Grinding Surfaces 573
7.3 Classification of Comminution Equipment 573
7.3.1 Classification According to Size of the Product 574
7.3.2 Classification According to Comminution Process 574
7.4 Nipping (Compression) Machines 574
7.4.1 Jaw Crushers 575
7.4.2 Gyratory and Cone Crushers 576
7.4.3 Roll Crusher 577
7.5 Impact Machines 578
7.5.1 Rotary Hammer 580
7.5.2 Vertical Shaft Impactor 580
7.5.3 Pin Mill 580
7.5.4 Stamp Mill 580
7.5.5 Vibration Mill 581
7.5.6 Planetary Mill 582
7.5.7 Cryogenic/Magnetic Hammer Mill 582
7.6 Tumbling Mills 583
7.6.1 Rod Mills 583
7.6.2 Ball Mills 583
7.6.3 Autogenous and Semi-Autogenous Mills 584
7.7 Cutting Machines 585
7.7.1 Knives, Shears, and Wedges 585
7.7.2 Saws 585
7.8 Attrition Machines 585
7.8.1 Disk Attrition Mills 586
7.8.2 Buhrstone 586
7.8.3 Mortar and Pestle Mill 587
7.8.4 Swing Mill 587
7.8.5 Disk Mill (or Colloid Mill) 588
7.8.6 Petit Pulverizer 589
7.9 Other Methods of Comminution 589
7.9.1 Abrasion 589
7.9.2 Thermal Comminution 590
7.9.3 Electrical Comminution 590
7.9.4 Microwave Comminution 590
7.9.5 Ultrasonic Comminution 590
7.9.6 Explosion 591
7.10 Selection of Comminution Equipment for Planetary Sampling 591
7.10.1 Single-Stage Comminution 591
7.10.2 Double-Stage Comminution 594
7.10.3 New Technologies and Innovations 595
7.11 Review of Recent and Current Work on Comminution for Planetary Sampling 595
7.11.1 Jaw Crusher 595
7.11.2 Sample Processing Unit (SPU) 596
7.11.3 Mechanized Sample Handler (MeSH): an Integrated Sample Crushing, Sieving, and Distribution System 600
7.12 Operational Platforms 620
7.12.1 Stationary Platforms 621
7.12.2 Mobile Platforms 621
7.13 Appendages 624
7.13.1 Manipulators 624
7.14 Sample Acquisition from Surface Platforms 628
7.14.1 Terrain Sensing Techniques 628
7.15 Sample Acquisition from Aerial Platforms 632
7.15.1 Small-Body Sampling from Spacecraft 633
7.15.2 Sampling from Aerobots 635
7.16 Conclusion 636
References 638

8 Instruments for In Situ Sample Analysis 643
Luther W. Beegle, Sabrina Feldman, Paul V. Johnson, and Christopher B. Dreyer
8.1 Introduction 643
8.2 Instrument Design Considerations 651
8.3 Instrument Categories 652
8.4 Geological Context 656
8.4.1 Imaging and Spectroscopic Instruments 657
8.5 Mineralogy Identification 666
8.5.1 Mössbauer Spectroscopy 666
8.5.2 Spectrometers (UV/VIS, Near-IR, Mid-IR, Far-IR, etc.) 667
8.5.3 Differential Scanning Calorimetry 669
8.5.4 Raman Spectroscopy 669
8.5.5 Powder X-Ray Diffraction 672
8.5.6 Contact X-Ray Diffraction 673
8.6 Chemistry 674
8.6.1 Laser Spectroscopy 675
8.6.2 Ion- Selective Electrodes, pH, and Redox Meters 677
8.6.3 X-Ray Spectroscopy 679
8.6.4 Gas Chromatography/Mass Spectrometry (GC/MS) 682
8.7 Biology 685
8.7.1 Capillary Electrophoresis 686
8.7.2 Liquid Chromatography and Ion Chromatography 687
8.7.3 Microarrays 689
8.7.4 Colorimetric and Fluorescence Assays in Solution 690
8.7.5 Optical Sensors 690
8.7.6 Non-Traditional Separation Approaches (e.g., Carbon Nanotubes) 691
8.7.7 Ion Mobility 692
8.8 Conclusion 694
References 695

9 Contamination Control and Planetary Protection 707
J. Andy Spry
9.1 Introduction 707
9.2 Contamination Control and Planetary Protection Similarities and Differences 707
9.2.1 Mission Science as a Driver of Contamination Control 708
9.2.2 Planetary Protection as a Mission Compliance Constraint 708
9.3 Contamination Control for Drilling and Excavation Applications 712
9.3.1 Quantifying Molecular Contamination Level Requirements 713
9.3.2 Quantifying Particulate Contamination Level Requirements 714
9.3.3 Contamination Control 716
9.4 Planetary Protection for Drilling and Excavation Applications 719
9.4.1 Forward (Outbound) Planetary Protection – Requirements and Constraints 719
9.4.2 Backward (Sample Return) Planetary Protection – Requirements and Constraints 725
9.4.3 Space Hardware Sterilization and Biodecontamination 726
9.5 Contamination Control and Planetary Protection Case Studies 731
9.5.1 Viking System Sterilization 731
9.5.2 Beagle 2/Mars Express – Extreme Sensitivity 732
9.5.3 Phoenix – a Biobarrier Solution 734
9.6 Contamination Control and Planetary Protection Trends and Future Development 736
References 737

10 Drilling Capabilities, Challenges, and Future Possibilities 741
Yoseph Bar-Cohen and Kris Zacny
10.1 Introduction 741
10.2 Drilling Various Media in Challenging Environments 741
10.2.1 Drilling in Extremely Cold Environments 742
10.2.2 Drilling in Extremely Hot Environments 743
10.2.3 Drilling Through the Seafloor Deep in the Ocean 746
10.2.4 Drilling on Extraterrestrial Bodies 746
10.3 Drilling via Rock Fracture – Sampling Mechanisms 748
10.4 Drilling Tools and Bits 749
10.5 Challenges to Drilling Technologies 750
10.5.1 Challenges to Modeling Drilling Processes 750
10.5.2 Drilling in Planetary Conditions 750
10.5.3 Sampling as the Objective of Planetary Exploration Missions 750
10.5.4 Sample Analyzers and Related Challenges 751
10.5.5 Acquisition of Volatiles 752
10.5.6 Cleaning Drills to Avoid Cross-Contamination 752
10.6 Conclusion 752
References 752

Index 755