

## Contents

<b>Foreword</b>	V
<b>Preface</b>	XIX
<b>List of Contributors</b>	XXI
<b>Acknowledgements</b>	XXVII
<b>Color Plates</b>	XXXI

<b>1</b>	<b>Drills as Tools for Media Penetration and Sampling</b>	<b>1</b>
	<i>Yoseph Bar-Cohen and Kris Zacny</i>	
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

1.6	Conclusion	27
	References	28

## 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 <i>In Situ</i>	178
3.4.4	Recompaction of Cuttings	179
3.4.5	Creation of Disposal Volume	181
3.5	Directional Drilling	183

3.5.1	Reference Systems	183
3.5.2	Directional Control Factors	185
3.5.3	Bit Design	188
3.5.4	Bottom Hole Assemblies	191
3.5.5	Directional Mechanics	192
3.5.6	BHA Modeling	193
3.5.7	Planning	196
3.5.8	Survey Techniques	197
3.5.9	Survey Calculations	199
3.6	Sidewall Friction and Unconsolidated Drilling Issues	199
3.6.1	Soil Penetration by Cones	200
3.6.2	Pile Driving Formulas	201
3.6.3	Methods of Cone Resistance Determination	203
3.6.4	Pressure Bubble	209
3.6.5	Permafrost Piling	210
3.6.6	Vibratory Pile Driving	210
3.6.7	Impact on Penetration Resistance	212
3.7	Conclusion	214
	References	215

#### **4 Ice Drilling and Coring 221**

*Charles R. Bentley, Bruce R. Koci, Laurent J.-M. Augustin,  
Robin J. Bolsey, James A. Green, Jay D. Kyne, Donald A. Lebar,  
William P. Mason, Alexander J. Shturmakov,  
Hermann F. Engelhardt, William D. Harrison,  
Michael H. Hecht, and Victor Zagorodnov*

4.1	Introduction	221
4.2	Coring Drills	224
4.2.1	Surface-Driven Rotary Drills	224
4.2.2	Wireline Drill	226
4.2.3	Cable-Suspended Electromechanical Drills	226
4.2.4	Cable-Suspended Electrothermal Drills	248
4.2.5	Hand Augers	257
4.2.6	“Koci Drill” for Debris-Laden Ice	259
4.3	Hole-Only Drills	262
4.3.1	Hot-Water Drilling Systems	262
4.3.2	Flame-Jet Drill	283
4.3.3	Steam Drills	283
4.3.4	Electric Hot Points	284
4.3.5	“Electrochaude”	284
4.3.6	Rapid Air Movement Drill	285
4.3.7	Coiled Tubing Drill for Ice	286
4.4	Autonomous Ice-Melting Drills	286
4.4.1	Cryobot	288
4.4.2	Subsurface Ice Probe	289

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 Sheritt, 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, Xiaohu Bao, Roger Fincher, Takeshi Hoshino, Piergiorgio Magnani, and Carlo Menon*

6.1	Why Subsurface Exploration?	347
6.1.1	Search for Evidence of Existing or Extinct Life	348

6.1.2	Science Rationale for Drilling on Mars	349
6.1.3	Search for Resources and <i>In Situ</i> Resource Utilization to Support Human Exploration	352
6.2	Methods for Subsurface Access on Extraterrestrial Bodies	352
6.3	Grinders and Rock Abrasion Tools	355
6.3.1	Rock Abrasion Tool (RAT)	355
6.3.2	The Beagle 2 Rock Corer Grinder	356
6.3.3	Ultrasonic Rock Abrasion Tool (URAT)	356
6.4	Scoops	358
6.4.1	Surveyor Scoop	358
6.4.2	Viking Lander Surface Sampler Acquisition Assembly	360
6.4.3	Phoenix 2007 Scoop	361
6.4.4	Micro End-Effector (MEE)	364
6.4.5	Percussive Scoop	365
6.5	Moles	366
6.5.1	The European Space Agency Mobile Penetrometer	366
6.5.2	The Moon/Mars Underground Mole (MMUM)	368
6.5.3	Instrumented Mole System (IMS)	372
6.5.4	Mole-Type Excavation Robot for Subsurface Exploration	373
6.6	Ultrasonic and Percussive Actuated Drills	377
6.6.1	Ultrasonically Assisted Drilling	377
6.6.2	Ultrasonic/Sonic Driller/Corer (USDC)	379
6.6.3	Mars Integrated Drilling and Sampling (MIDAS) System	387
6.6.4	ESA Ultrasonic Rock Corer	390
6.6.5	ESA Ultrasonic Drill Tool (UDT)	392
6.6.6	Drill with Hammering Mechanism (DHM)	393
6.6.7	Percussive Regolith Penetrometer	399
6.7	Surface Drills	402
6.7.1	Low-Force Sample Acquisition System (LSAS)	402
6.7.2	Mini-Corer	405
6.7.3	Coring and Abrading Tool (CAT)	407
6.7.4	Small Sample Acquisition and Distribution Tool (SSA/DT)	411
6.7.5	SENER Touch-and-Go Sampler	412
6.7.6	Honeybee Robotics Touch-and-Go Sampler	413
6.7.7	Near-Earth Asteroid Sample Return	416
6.7.8	Titan Harpoon Sampler	417
6.8	Shallow Drilling: One Meter Class Drills	421
6.8.1	CNSR Sample Acquisition System for 1 m (SAS-1m)	422
6.8.2	Sample Acquisition and Preprocessing System (EBRC)	423
6.8.3	NORCAT's SCaD 2 m Drill	438
6.8.4	ATK's Segmented Coring Auger Drill (SCAD)	441
6.8.5	Pneumatic Drill and Excavation System	444
6.8.6	The Sample Acquisition and Transfer Mechanism (SATM) Drill	449

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
6.14.2	Bio-Inspiration from Wood Wasp Digging System	513
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 <i>In Situ</i> 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
<b>7</b>	<b>Planetary Sample Handling and Processing</b>	<b>559</b>
	<i>Kris Zacny, Antonio Diaz-Calderon, Paul G. Backes, Kiel Davis, Chris Leger, Erik Mumm, Edward Tunstel, Jason Herman, Gale Paulsen, and Yoseph Bar-Cohen</i>	
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
<b>8</b>	<b>Instruments for <i>In Situ</i> Sample Analysis</b>	<b>643</b>
	<i>Luther W. Beegle, Sabrina Feldman, Paul V. Johnson, and Christopher B. Dreyer</i>	
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
<b>9</b>	<b>Contamination Control and Planetary Protection</b>	<b>707</b>
	<i>J. Andy Spry</i>	
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
<b>10</b>	<b>Drilling Capabilities, Challenges, and Future Possibilities</b>	<b>741</b>
	<i>Yoseph Bar-Cohen and Kris Zacny</i>	
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	753
	<b>Index</b>	<b>755</b>