

# L · U · N · A · R

s o u r c e b o o k

*a user's guide to the moon*



*edited by Grant H. Heiken, David T. Vaniman,  
and Bevan M. French*

*foreword by Harrison H. Schmitt*

The *Lunar Sourcebook*, a concisely presented collection of data gathered during the American and Soviet missions, is an accessible and complete one-volume reference encyclopedia of current scientific and technical information about the Moon. This book provides a thorough introduction to lunar studies and a summary of current information about the nature of the lunar environment. It explores the formation and evolution of the Moon's surface, the chemical and mineralogical nature of lunar rocks and soils, and the current state of scientific knowledge about the nature, origin, and history of the Moon.

The book is written and edited by scientists active in every field of lunar research, all of whom are veterans of the Apollo program. The contributors are from universities, national laboratories, industry, and NASA.



## Lunar Sourcebook



# LUNAR SOURCEBOOK

A User's Guide to the Moon

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*To those who have been there —  
And to those who will return.*





# CONTENTS

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Contributors	xi
Foreword	xiii
Editor's Preface and Acknowledgments	xv
Units and Abbreviations	xvii
Lunar Databases and Archives	xix
<b>Chapter 1: INTRODUCTION</b>	<b>1</b>
1.1. USING THE MOON: AVAILABLE DATA	1
1.2. THE CONTENTS OF THIS BOOK	2
<b>Chapter 2: EXPLORATION, SAMPLES, AND RECENT CONCEPTS OF THE MOON</b>	<b>5</b>
2.1. LUNAR EXPLORATION	5
2.2. LUNAR SAMPLES	6
2.2.1. The Apollo Collection	6
2.2.2. Lunar Sample Identification	8
2.3. NEW VIEWS OF THE MOON FROM EXPLORATION	10
2.4. NEW CONCEPTS OF THE MOON FOLLOWING EXPLORATION	13
2.4.1. Origin of the Moon	13
2.4.2. Diversity of Lunar Rock Types	13
2.4.3. Differentiation of the Moon and Origin of the Lunar Crust	15
2.4.4. The Present View of Lunar Magmatic Evolution	19
APPENDIX: APOLLO SAMPLE TYPES AND LUNAR SAMPLE CURATION	21
A2.1. Apollo Sample Types	21
A2.2. Lunar Sample Curation	23
A2.3. Curation History	25
<b>Chapter 3: THE LUNAR ENVIRONMENT</b>	<b>27</b>
3.1. EARTH AND MOON COMPARED	27
3.2. THE ASTRONAUT EXPERIENCE	27
3.3. TERRAIN	30
3.3.1. Mare Surfaces	31
3.3.2. Large-scale Ejecta Ridges	31
3.3.3. Lunar Highlands	32
3.3.4. Highlands-Mare Boundaries (Basin Margins)	32
3.3.5. Other Parts of the Moon	34
3.4. DUST	34
3.5. TEMPERATURES ON THE LUNAR SURFACE	34
3.6. LUNAR HEAT FLOW	36
3.6.1. Heat Flow at the Apollo 15 Landing Site	37
3.6.2. Heat Flow at the Apollo 17 Landing Site	37
3.6.3. Conclusions	38
3.7. SEISMIC ACTIVITY	38
3.8. POLAR ENVIRONMENT	39
3.9. ATMOSPHERE	40
3.9.1. Contamination	41
3.9.2. The Real Lunar Atmosphere	42
3.9.3. The Past and Future of the Lunar Atmosphere	43

3.10. METEOROID BOMBARDMENT	45
3.10.1. Meteoroid Velocities and Impact Rates	46
3.10.2. Meteoroid Distributions in Lunar Orbit and on the Lunar Surface	46
3.10.3. Meteoroid Hazards	46
3.11. IONIZING RADIATION	47
3.11.1. Solar Wind	48
3.11.2. Solar-Flare-Associated Particles	49
3.11.3. Galactic Cosmic Rays	52
3.11.4. Modes of Interactions with the Moon	53
3.11.5. Implications of the Lunar Radiation Environment	55
APPENDIX	57
A3.1. Motion of the Earth-Moon System	57
A3.2. Brightness of the Lunar Surface	59
A3.3. Locating Points on the Moon	60
<b>Chapter 4: LUNAR SURFACE PROCESSES</b>	<b>61</b>
4.1. IMPACT PROCESSES	62
4.1.1. The Morphology of Impact Structures	62
4.1.2. The Cratering Process	65
4.1.3. Crater Frequency and Bombardment History	79
4.1.4. Geological Processes	85
4.2. BASALTIC VOLCANISM	94
4.2.1. Volcanic Landforms	95
4.2.2. Filling of the Maria	102
4.2.3. Volume Estimates of Basaltic Mare Fill	105
4.3. TECTONIC ACTIVITY	107
4.3.1. External Forces	108
4.3.2. Internal Forces	111
4.4. LUNAR STRATIGRAPHY	111
<b>Chapter 5: LUNAR MINERALS</b>	<b>121</b>
5.1. SILICATE MINERALS	123
5.1.1. Pyroxene	123
5.1.2. Plagioclase Feldspar	126
5.1.3. Olivine	130
5.1.4. Silica Minerals: Quartz, Cristobalite, and Tridymite	132
5.1.5. Other Silicate Minerals	133
5.1.6. Comparative Silicate Mineralogy: Earth-Moon	135
5.2. OXIDE MINERALS	137
5.2.1. Ilmenite	140
5.2.2. Spinels	143
5.2.3. Armalcolite	147
5.2.4. Other Oxides	149
5.3. SULFIDE MINERALS	150
5.3.1. Troilite	150
5.3.2. Other Sulfides	151
5.4. NATIVE FE	151
5.4.1. Meteoritic Contamination	151
5.4.2. Native Fe in Lunar Rocks	152
5.4.3. Native Fe in Lunar Soil	154
5.5. PHOSPHATE MINERALS	154
APPENDIX: COMPOSITIONS OF LUNAR MINERALS	155

<b>Chapter 6: LUNAR ROCKS</b>	<b>183</b>
6.1. MARE BASALTIC LAVAS AND VOLCANIC GLASSES	186
6.1.1. Chemical Composition, Classification, and Properties of Mare Basalts	186
6.1.2. Mineralogy of Mare Basalts	193
6.1.3. Textures of Mare Basalts	195
6.1.4. Crystallization Experiments on Mare Basalts	198
6.1.5. Cooling Rates of Mare Basalts	201
6.1.6. Vesicles and Nature of the Gas Phase	201
6.1.7. Lunar Pyroclastic Deposits	202
6.1.8. Experimental Petrology and Phase Relations	205
6.1.9. Ages of Mare Basalts	208
6.2. EXTENDED MAPPING OF MARE LAVAS AND PYROCLASTIC DEPOSITS BY REMOTE SPECTRAL OBSERVATIONS	209
6.2.1. Techniques	209
6.2.2. Regional Distribution of Mare Basalts and Pyroclastic Glasses	210
6.3. HIGHLAND PRISTINE ROCKS: IGNEOUS ROCKS AND MONOMICT BRECCIAS	212
6.3.1. Classification of Pristine Igneous Highland Rocks	214
6.3.2. KREEP Rocks	216
6.3.3. Ferroan Anorthosites	220
6.3.4. Mg-rich Rocks	225
6.3.5. Other Pristine Highland Rock Types	228
6.4. HIGHLAND POLYMICT BRECCIAS	232
6.4.1. Nomenclature and Classification	233
6.4.2. Fragmental Breccias	235
6.4.3. Glassy Melt Breccias and Impact Glasses	246
6.4.4. Crystalline Melt Breccias or Impact-Melt Breccias	249
6.4.5. Clast-poor Impact Melts	252
6.4.6. Granulitic Breccias and Granulites	254
6.4.7. Dimict Breccias	256
6.4.8. Regolith Breccias	257
6.5. SPECTRAL PROPERTIES OF HIGHLAND ROCKS	257
APPENDIX: CHEMICAL DATA FOR LUNAR ROCKS	261
<b>Chapter 7: THE LUNAR REGOLITH</b>	<b>285</b>
7.1. LUNAR SOIL	287
7.1.1. General Description	287
7.1.2. Petrography	288
7.1.3. Agglutinates	296
7.1.4. Other Unusual Soil Components	302
7.1.5. Grain Shapes and Surfaces	304
7.1.6. Grain-size Characteristics	304
7.1.7. Chemical Composition of Lunar Soils	306
7.2. SPECTRAL PROPERTIES OF THE LUNAR REGOLITH	307
7.3. REGOLITH EVOLUTION AND MATURITY	307
7.3.1. Maturation by Meteoroid Bombardment	310
7.3.2. Maturation by Ionizing Radiation	315
7.3.3. Maturity Indices and Their Use	317
7.3.4. Regolith Processes and Maturity	321
7.4. VARIATION OF SOILS WITH DEPTH: THE LUNAR CORE SAMPLES	321
7.4.1. General Characteristics of Lunar Regolith Core Samples	321
7.4.2. Variations with Depth in Regolith Core Samples	325
7.4.3. Regolith Stratigraphy	337

7.5. MODELS FOR REGOLITH FORMATION	342
7.5.1. Regolith Dynamics	342
7.5.2. Grain-size Distributions	343
7.5.3. Differential Comminution	344
7.5.4. Comparison of Soil Chemistry with Bedrock Chemistry	345
7.5.5. Variation of Soil Chemistry Within Sites	345
7.5.6. Variation of Soil Chemistry Between Sites	351
7.6. REGOLITH BRECCIAS	352
7.7. THE RECORD OF SOLAR HISTORY PRESERVED IN THE LUNAR REGOLITH	354
7.7.1. A Summary of Historical Results	354
7.7.2. Solar-Wind History	355
7.7.3. Solar-Flare History	356
7.7.4. Galactic-Cosmic-Ray History	356
<b>Chapter 8: CHEMISTRY</b>	<b>357</b>
8.1. WHERE TO FIND A PARTICULAR ELEMENT DISCUSSED	359
8.1.1. Organization of the Data	359
8.1.2. Types of Lunar Materials Considered	359
8.1.3. Cautions on Data Use	361
8.2. OVERVIEW OF PLANETARY SEPARATION PROCESSES	361
8.3. MAJOR ELEMENTS	363
8.3.1. Concentrations of Major Elements in the Moon	363
8.3.2. Minerals and Rocks Formed by Major Elements	363
8.3.3. Abundances and Correlations Among Major Elements	366
8.3.4. Ores of Major Elements	371
8.4. INCOMPATIBLE TRACE ELEMENTS	372
8.4.1. Abundances of Incompatible Trace Elements in Lunar Crustal Materials	372
8.4.2. Incompatible Trace Elements in Lunar Highland Materials: KREEP	380
8.4.3. Incompatible Trace Elements in the Lunar Maria	386
8.5. MISCELLANEOUS MINOR ELEMENTS	390
8.5.1. Data Sources	390
8.5.2. Phosphorus, Potassium, and Barium	390
8.5.3. Scandium, Vanadium, Chromium, and Manganese	391
8.5.4. Sulfur, Cobalt, and Nickel	398
8.5.5. Gallium and Strontium	398
8.5.6. Possible Lunar Ores of the Miscellaneous Minor Elements	398
8.6. SIDEROPHILE ELEMENTS	399
8.6.1. Analytical Difficulties	400
8.6.2. Iridium: The "Type" Siderophile Element	404
8.6.3. Other Siderophile Elements	405
8.6.4. Siderophile-Element Fractionations Related to Grain Size in Lunar Soils	413
8.6.5. Possible Lunar Ores of Siderophile Elements	414
8.7. VAPOR-MOBILIZED ELEMENTS	414
8.7.1. Concentration Levels	414
8.7.2. Meteoroid Additions to the Regolith	419
8.7.3. Vapor-Mobilized Elements as Incompatible Trace Elements: Indigenous Concentrations in Lunar Materials	422
8.7.4. Vapor-Phase Transport of Vapor-Mobilized Elements	424
8.7.5. Pyroclastic Volcanic Emissions as an Indigenous Source of Vapor-Mobilized Elements	427
8.7.6. Surface Mobility of Vapor-Mobilized Elements	430
8.7.7. Sulfur	432

8.7.8. Halogens	434
8.7.9. Possible Lunar Ores of Vapor-Mobilized Elements	435
8.8. SOLAR-WIND-IMPLANTED ELEMENTS	436
8.8.1. The Solar Wind	436
8.8.2. Noble Gases (He, Ne, Ar, Kr, and Xe)	437
8.8.3. Biogenic Elements (H, C, and N)	443
8.8.4. Solar-Wind-Implanted Elements as Lunar Resources	448
APPENDIX: STATISTICAL SUMMARIES OF LUNAR CHEMISTRY	449

**Chapter 9: PHYSICAL PROPERTIES OF THE LUNAR SURFACE** **475**

9.1. GEOTECHNICAL PROPERTIES	475
9.1.1. Particle Size Distribution	477
9.1.2. Particle Shapes	478
9.1.3. Specific Gravity	481
9.1.4. Bulk Density and Porosity	483
9.1.5. Relative Density	494
9.1.6. Compressibility	500
9.1.7. Shear Strength	506
9.1.8. Permeability and Diffusivity	517
9.1.9. Bearing Capacity	517
9.1.10. Slope Stability	521
9.1.11. Trafficability	522
9.2. ELECTRICAL AND ELECTROMAGNETIC PROPERTIES	530
9.2.1. Electrical Conductivity	531
9.2.2. Photoconductivity	532
9.2.3. Electrostatic Charging and Dust Migration	532
9.2.4. Dielectric Permittivity	536
9.2.5. Electromagnetic Sounding	552
9.3. REFLECTION AND EMISSION OF RADIATION FROM THE MOON	558
9.3.1. Optical Astronomy	558
9.3.2. Radar Astronomy	562
9.3.3. Thermal Infrared Astronomy	566
APPENDIX: SUPPLEMENTARY DATA ON LUNAR PHYSICAL PROPERTIES	567

**Chapter 10: GLOBAL AND REGIONAL DATA ABOUT THE MOON** **595**

10.1. GLOBAL AND REGIONAL IMAGERY AND DATA SOURCES	595
10.1.1. Earth-based Telescopic Data	596
10.1.2. Lunar Orbiter Photographic Images	597
10.1.3. Apollo Orbital Photography	597
10.1.4. Coverage and Resolution of Lunar Photography	599
10.2. SURFACE MINERALOGIC AND GEOCHEMICAL DATA	599
10.2.1. Spectral Reflectance Measurements and Multispectral Imagery (Earth-based)	599
10.2.2. Apollo Gamma-ray Spectrometer	602
10.2.3. Apollo X-ray Fluorescence Spectrometer	603
10.3. GEOPHYSICAL DATA	603
10.3.1. Lunar Gravity Field	603
10.3.2. Lunar Surface Magnetic Field	605
10.3.3. Radar Data for the Lunar Nearside	605
10.4. REGIONAL DISTRIBUTION OF LUNAR ROCK TYPES	607
10.4.1. Mare Basalt Lavas	607
10.4.2. Petrologic Map of the Moon from Apollo Gamma-ray Data	608

10.4.3. Mineralogy of Highland Rock Types Inferred from Near-Infrared Reflectance Spectra	608
10.5. STRATIGRAPHY AND RELATIVE AGES	609
10.6. GEOLOGY OF THE APOLLO AND LUNA LANDING SITES	609
10.6.1. Apollo 11	609
10.6.2. Apollo 12	610
10.6.3. Apollo 14	610
10.6.4. Apollo 15	610
10.6.5. Apollo 16	631
10.6.6. Apollo 17	631
10.6.7. The Luna Landing Sites	631
<b>Chapter 11: AFTERWORD</b>	<b>633</b>
11.1. RETURN TO THE MOON	633
11.2. CURRENT UNDERSTANDING OF THE MOON: A BASE FOR PLANNING	633
11.2.1. The Post-Apollo Moon	633
11.2.2. Environmental Impacts	635
11.3. GOALS FOR FUTURE LUNAR EXPLORATION	636
11.3.1. Science	636
11.3.2. Transportation	636
11.3.3. Resources	636
11.3.4. Benefits to Future Astronauts: <i>Terra Firma Nova</i>	637
11.4. UNANSWERED QUESTIONS ABOUT THE MOON	637
11.4.1. The Lunar Environment	638
11.4.2. Lunar Surface Processes and Evolution	638
11.4.3. Lunar Minerals, Rocks, and Soils	638
11.4.4. Lunar Chemistry	639
11.4.5. Lunar Physical Properties	639
11.4.6. Global Lunar Data and Future Mapping	639
11.5. THE NEXT STEPS	639
11.6. A PERMANENT PRESENCE	640
APPENDIX A11.1: STUDIES IN LUNAR UTILIZATION	644
APPENDIX A11.2: LUNAR RESOURCES	647
A11.2.1. Aluminum	647
A11.2.2. Helium-3	647
A11.2.3. Hydrogen	647
A11.2.4. Iron	648
A11.2.5. Oxygen	648
A11.2.6. Regolith	649
APPENDIX A11.3: SUMMARY OF UNANSWERED QUESTIONS ABOUT THE MOON	650
References	655
Sample Index	717
Subject Index	721

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## FOREWORD

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Humankind sought and attained greatness with the first field explorations of the Moon between 1966 and 1976. Apollo spacecraft and the various automated probes launched by the U.S. and the U.S.S.R., which successfully collected samples and information from the Moon during this period, pushed the species along its first clear steps of evolution into the solar system and eventually into the galaxy. A sense of reality began to surround a lesson taught to the Pueblo Indians by their ancestors: “We walk on the Earth, but we live in the sky.”

Early explorers of the sky took their eyes and minds into space and became the eyes and minds of billions of other explorers on the starship Earth. They also began the long process of transplanting civilization into space. This fundamental change in the course of history has occurred as humans have also gained new insight into themselves and their first planetary home. With the conclusion of the Apollo 17 mission and the Apollo program in December 1972, humankind had reached the “end of the beginning” of its movement into the universe.

Human evolution into the universe began with the 1968 Christmas Eve mission of Apollo 8. The presence of Frank Borman, Jim Lovell, and Bill Anders in orbit around the Moon, and the words and pictures they shared with us, gave human beings a new awareness not only of the Moon but of the Earth’s own place as a lonesome, lovely, and potentially fragile life-bearing planet in the black void of space. Hundreds of millions of human beings throughout the world simultaneously thought new thoughts about a familiar object in the night sky—the Moon. The men of Apollo 8 were there, and the Moon would never be the same for anyone.

Now we should realize that the Earth will also never be the same. Through new communication, information, and space technologies, solutions can be found to the age-old problems of the human condition on Earth—ignorance, poverty, hunger, and disease. Opportunities have been created to realize the more modem dream of living permanently in space. Such solutions and opportunities exist, however, only *if* we are wise enough to reach out and grasp them.

President George Bush’s statement on the occasion of the 20th anniversary of Apollo 11’s landing on the Moon provides a vision of human beings as a perpetual spacefaring species. The President’s words implied a commitment to protect the Earth, settle the solar system, and move toward the stars.

The Moon’s proximity to the Earth, lack of atmosphere, gravity (only one-sixth that of the Earth), planetary position as the smallest of the terrestrial planets, and potential resources almost certainly assure a role for lunar activities in support of human exploration and utilization of space.

Proximity, one-sixth gravity, and potential resources essential to sustaining human life require that the Moon be considered as both a stepping stone toward Mars and the outer planets and a low-cost supply depot for exploration and settlement. Its planetary characteristics and lack of atmosphere justify the continued use of the Moon as a natural laboratory for comparative planetology and for solar and stellar astronomy.

In the context of these possibilities, as well as in even more general terms, *Lunar Sourcebook* provides an extremely important and heretofore unavailable first reference for those who may consider a return to the Moon for whatever purpose. The information compiled within and the guide to other data provided distills and, in one sense, immortalizes the dedication, imagination, and extraordinary hard work of hundreds of managers, scientists, engineers, and their supporters. Now others can begin to move forward to plan, in President Bush’s words, a “. . . return to the Moon, this time to stay . . .”

One can only vaguely imagine the ultimate legacy of the data from Apollo, the automated probes, and Earth-based observation through which *Lunar Sourcebook* guides its reader. The more easily conceived possibilities include permanent and self-sustaining settlements on the Moon,

serving solar and stellar observatories and far-ranging lunar surface expeditions; lunar engineering and training sites supporting the development of Mars exploration and settlement; huge solar collector arrays on the Moon producing the energy needed to support lunar activities as well as for potential export to Earth and to stations in space; underground mines in stratified mineral deposits within the mare that provide raw materials to space equipment manufacturing facilities on the Moon or in lunar orbit; and great farms that produce the food required by increasing numbers of men and women living in space, on the Moon, and on Mars.

Perhaps most critically, one can imagine large mobile processing plants, periodically stepping their way across the lunar maria, mining, extracting, and processing solar-wind gases from the regolith, to provide the life-sustaining consumables ( $H_2$ ,  $O_2$ ,  $H_2O$ ,  $CO_2$ ,  $NO_x$ , and  $^4He$ ) required by a spacefaring species. From solar-wind materials implanted in the lunar regolith, we may also extract the environmentally benign fusion fuel  $^3He$ , which can be used on Earth to sustain civilization as well as protect the biosphere.

On behalf of those privileged few who helped gather the samples, collect field information, and deploy the experiments that provided the data upon which much of this book draws, I wish to thank the editors and their contributor team for stepping once more into the breach. They have added great new value to the lunar exploration community's efforts. Unless what has been learned as a consequence of our activities becomes accessible, we, like the tree falling in the forest, have made no sound for those not present to hear. *Lunar Sourcebook* not only brings many individual sounds together into the beginnings of a symphony, but it serves waiting and appreciative new generations of composers and audiences.

*Harrison H. Schmitt, Apollo 17 astronaut  
Albuquerque, New Mexico  
September 20, 1990*

## EDITORS' PREFACE AND ACKNOWLEDGMENTS

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*Lunar Sourcebook* is intended for the post-Apollo generation of scientists, engineers, teachers, and students. It has two purposes. First, it summarizes what we know about the Moon as a result of U.S. and U.S.S.R. lunar missions and the continuing analysis of lunar samples and data here on Earth. Second, it provides a convenient, accessible sourcebook for planning the future study of the Moon and the eventual use of the Moon by spacefaring humans.

This book began in 1984, and we were at the active manuscript-editing stage on July 20, 1989, when President George Bush marked the 20th anniversary of the Apollo 11 landing by initiating what is now called the Space Exploration Initiative (or sometimes the Moon-Mars initiative), a program for the return of humans to the Moon, followed by human exploration of the planet Mars. We hope that *Lunar Sourcebook* will be a timely response to the renewed scientific and exploration interest in our nearest planetary neighbor, the only other world so far explored in person by human beings. We also hope that the book will help in our return to the Moon, and in the intelligent use of the Moon when we establish a permanent presence there.

The task of putting everything we know about the whole Moon into a single book is far more difficult now than it was before the Apollo program. Before Apollo, only a few people were needed to summarize the available information about the Moon, and they could (and did) produce books from their own knowledge. The Apollo and Luna programs, with their intensive close-up studies and the return of samples to Earth, have produced an explosion in lunar knowledge. The available scientific information about the Moon is now scattered throughout many books and thousands of articles in journals from a wide range of scientific disciplines: astronomy, geosciences, nuclear chemistry, space physics, materials science, life sciences, and engineering, to name just a few.

In this post-Apollo age, assembling *Lunar Sourcebook* would have been impossible without help from many different people. We owe the most to our scientist-authors for sifting the immense amount of knowledge in each field, organizing it, and then patiently enduring multiple syntheses, continuing editorial changes, extensive rewriting, and doubts that their work would ever see daylight on a printed page.

The editorial and production staff at the Lunar and Planetary Institute (LPI) in Houston, Texas, worked hard and patiently—literally for years—to turn an overwhelming amount of manuscript pages and disorganized art work into an attractive and readable text. Renee Dotson, as technical editor at the LPI, suffered (with remarkable equanimity) through enough versions of this book to fill her bookshelves. The excellent illustration work by Donna Jalufka, Pam Thompson, Shirley Brune, and others at the LPI, with special notice of the herculean effort and dedication of Steve Hokanson, resulted in a set of polished figures that were often compiled from crude sketches and all too often forced through time-consuming revisions. We also thank our editors at Cambridge University Press in New York, Peter-John Leone and Nancy Seltzer, for their faith in the whole project and their patience with an unexpectedly long process.

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## UNITS AND ABBREVIATIONS\*

Unit	Abbreviation	Unit	Abbreviation
absolute permeability	K	Kelvin	K
activation energy	E	kilobar	kbar
angstrom	Å	kilocalorie	kcal
antenna gain	G	kiloelectron volt	keV
ampere	A	kilogram	kg
astronomical unit ( $1.496 \times 10^8$ km)	A.U.	kilohertz	kHz
atomic mass unit	amu	kilometer	km
billion years	b.y.	kilopascal	kPa
bulk density	$\rho$	kilowatts electric	kWe
centimeter	cm	kurtosis (statistical)	$K_G$
coefficient of lateral stress	$K_o$	loss tangent	$\tan \delta$
cohesion	c	magnetic field strength	A/m, $\gamma$
Cole-Cole frequency distribution		mean (statistical)	$\bar{x}$ , Mz
parameter	$\alpha$	median (statistical)	Md
compression index	$C_c$	megaelectron volt	MeV
conductance (1/ohm)	mho	meter	m
conductivity	$\sigma$	metric ton (tonne)	t
cone penetration resistance	q	microgram	$\mu$ g
degree Celsius	$^{\circ}$ C	micrometer	$\mu$ m
degree of polarization	P	milligal	mgal
density of water	$\rho_w$	milligram	mg
depth into regolith (cm)	z	millimeter	mm
equivalent surface area ratio	ESAR	million years	m.y.
electron volt	eV	millisecond	msec
factor of safety	F.S.	milliwatt	mW
ferromagnetic resonance intensity	Is	minutes	min
flow rate	Q	mole	mol
Fresnel reflection coefficient	$\rho$	mole percent	mol.%
friction angle	$\phi$ (degrees)	nanogram	ng
galactic cosmic ray	GCR	nanometer	nm
gamma ( $10^{-5}$ oersted)	$\gamma$	normal stress	$\sigma$
geometrical albedo	p	newton	N
gigaelectron volt	GeV	nucleon	u
gram	g	parts per billion by weight	ng/g
gross pull per wheel (N)	H	parts per million by weight	$\mu$ g/g
Hertz	Hz	parts per thousand	$\text{‰}$
horizontal stress	$\sigma_h$	Pascal	Pa
hour	hr	phase angle (optical)	g
initial relative density	$D_{Ri}$	phase integral (optical)	q
integrated mass depth	$d_m$	phi scale (grain size)	$\phi$
joule	J	poise	p

\* Note multiple uses of the symbols G, k, p, W,  $\alpha$ , and  $\sigma$ . Units and abbreviations that are explicitly defined where they are used in the text are not listed here.

UNITS AND ABBREVIATIONS *(continued)*

Unit	Abbreviation	Unit	Abbreviation
porosity (in situ)	n	specific gravity	G
P-wave velocity	$\alpha$	specific surface area	SSA
radar cross-section	$\sigma$	static allowable bearing capacity	q <sub>all</sub>
received echo power (radar)	P <sub>r</sub>	static ultimate bearing capacity	q <sub>ult</sub>
recompression index	C <sub>r</sub>	steradian	sr
relative density	D <sub>R</sub>	subradar point	i
relative dielectric permittivity	k	torricelli	torr
seismic attenuation	Q	wavelength	$\gamma$
second	sec	wheel load (N)	W
shear strength	$\tau$	vertical stress	$\sigma_v$
skewness (statistical)	SK, $\alpha_3$	void ratio	e
soil compaction resistance per wheel (N)	R <sub>c</sub>	volume percent	vol.%
solar cosmic ray	SCR	watt	W
sorting (statistical)	$\sigma$	weight percent	wt.%
		year	yr

## LUNAR DATABASES AND ARCHIVES

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Manned and unmanned missions to the Moon were responsible for an enormous volume of diverse data, ranging from measurements of the tenuous lunar magnetic field to sample analyses. Most of these data and reports are available to researchers, at the cost of transferring the information or images.

**Lunar and Planetary Institute (LPI).** The best place to begin your search for lunar data is the Lunar and Planetary Institute, 3303 NASA Road 1, Houston, Texas 77058-4399. The LPI was established by NASA as the Lunar Science Institute in 1969 and is managed by the Universities Space Research Association. The Center for Information and Research Services (CIRS) contains lunar and planetary photographs, maps, reports, and lunar sample information. CIRS also maintains a lunar and planetary bibliography and a literature collection to support the bibliography. The LPI Geophysical Data Facility has a selection of Moon datasets.

**National Space Science Data Center (NSSDC).** Documents, imagery, and geophysical data are available from the NSSDC. For U.S. investigators, the address is National Space Science Data Center, Code 601.4, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771. For researchers outside of the United States, the address is World Data Center A, Rockets and Satellites, Code 601, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771 USA. The database includes images, reports, and geophysical data from the Ranger, Surveyor, Lunar Orbiter,

Apollo, Luna, and Zond Programs. A comprehensive catalog was published by W. S. Cameron, E. J. Mantel, and E. R. Miller (1977) *Catalog of Lunar Mission Data*, NSSDC/WDC-A-RS Document #77-02, 204 pp.

**National Technical Information Service (NTIS).** For out-of-print reports, facsimile paper copies or microfiche can be ordered from NTIS, 5825 Port Royal Road, Springfield, Virginia 22152.

**NASA Johnson Space Center History Office.** Over 30,000 documents from the Apollo program have been saved as an archive for the purpose of historical studies by the History Office, NASA Johnson Space Center, Code BY4, 2101 NASA Road 1, Houston, Texas 77058-3696. The materials are arranged and described according to accepted archival practice and in a computer index. This office has also published excellent histories of the Apollo program [C. G. Brooks, J. Grimwood, and L. Swenson Jr. (1979) *Chariots for Apollo: A History of Manned Lunar Spacecraft* NASA SP-4205, 553 pp.; W. D. Compton (1989) *Where No Man Has Gone Before: A History of Apollo Lunar Exploration Missions*, NASA SP-4214, 415 pp.]

**NASA Johnson Space Center Lunar Sample Curatorial Facility.** To obtain lunar samples, a researcher must submit a request to the Lunar Sample Curator, Code SN2, NASA Johnson Space Center, Houston, Texas 77058-3696. This request will be reviewed by NASA's Lunar and Planetary Sample Team. Sample histories are also available from the Curator (see Appendix to Chapter 2).

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**Regional Planetary Image Facilities.** The system of Regional Planetary Image Facilities (RPIF) represents a coordinated effort to provide easy access to planetary data products by scientists, students, educators, and the general public. Although each facility has different specific strengths, the close cooperation among RPIF members permits accessing materials without unnecessary trips to more distant centers. The RPIFs are not designed to provide hard-copy products for permanent retention, but are established to provide assistance in both locating the necessary data products and in accessing them through the NSSDC. RPIF facilities are located:

Arizona State University  
Department of Geology  
Tempe, Arizona 85287

Brown University  
Box 1846  
Department of Geological Sciences  
Providence, Rhode Island 02912

Cornell University  
Center for Radiophysics and  
Space Research  
Ithaca, New York 14853

Jet Propulsion Laboratory  
Mail Stop 202-101  
4800 Oak Grove Drive  
Pasadena, California 91109

Lunar and Planetary Institute  
Center for Information and  
Research Services  
3303 NASA Road 1  
Houston, Texas 77058-4399

National Air and Space Museum  
Center for Earth and Planetary  
Studies  
Room 3101  
Washington, DC 20560

U.S. Geological Survey  
Branch of Astrogeologic Studies  
2255 N. Gemini Drive  
Flagstaff, Arizona 86001

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Phototheque Planetaire  
Université Paris-Sud  
Laboratoire de Geologie  
Dynamique Interne  
Orsay Cedex FRANCE

Abt. Planetare Erkundung  
DLR - Institut für Optoelektronik  
8031 Oberpfaffenhofen  
GERMANY

**\* Note added in proof: These addresses were current at the time of publication (1991). For an updated list of RPIFs, go to <http://www.lpi.usra.edu/library/RPIF/index.shtml>.**



