

Contents

1	Introduction	1
2	Time Scales and Ages	3
2.1	Absolute Time Scales	3
2.2	Relative Time Scales	4
2.3	Physical and Chemical Time Scales	5
3	Selection, Collection, Packing, Storage, Transport, and Description of the Samples	7
3.1	Selection and Collection of the Samples	7
3.2	Packing, Storage, and Transport of the Samples	8
3.3	Sample Description	8
4	Treatment and Interpretation of the Raw Data	9
4.1	Suitability of a Sample for Dating and Reliability of the Dates	9
4.1.1	Soft-Rock Dating	9
4.1.2	Hard-Rock Dating	10
4.1.3	Isotope Geochemistry	13
4.2	Mathematical Evaluation of Physical and Chemical Age Data	14
4.2.1	Rules for Simple Calculations with the Dating Results; Statistical Tests	15
4.2.2	Comparison of Age Values	17
4.2.3	Numerical and Graphical Evaluation of Age Values	18
4.3	Publication of the Age Values	21
5	Physical Dating Methods	23
5.1	Principles	23
5.2	Sample Treatment and Measurement Techniques	28
5.2.1	Sample Treatment	29
5.2.1.1	Hard-Rock Samples	29
5.2.1.2	Soft-Rock Samples	32
5.2.2	Radioactivity Measurements: Decay Counting Methods	32

5.2.2.1	Gas-Filled Proportional and Geiger-Müller Counters	34
5.2.2.2	Scintillation Counters	36
5.2.2.3	Semiconductor Detectors	37
5.2.3	Measurement of Stable and Long-Lived Isotopes:	
	Atom Counting Methods	38
5.2.3.1	Mass Spectrometry (MS)	38
5.2.3.2	Accelerator Mass Spectrometry (AMS)	40
5.2.3.3	Resonance-Ionization Spectrometry (RIS)	42
5.2.4	Other Analytical Techniques	43
5.2.4.1	Isotope Dilution Analysis (ID)	43
5.2.4.2	Neutron Activation Analysis (NAA)	45
5.2.4.3	Flame Photometry, Atomic Absorption Spectrometry (AA) and Inductive Coupled Plasma Analysis (ICP)	46
5.2.4.4	Ion-Microprobe (IMP) and Laser Microprobe Mass Analysis (LAMMA)	47
5.2.4.5	X-Ray Fluorescence Analysis (XRF)	48
6	Radiometric Dating Methods	51
6.1	Parent/Daughter Isotope Ratios as a Geochronometer	51
6.1.1	Potassium/Argon ($^{40}\text{K}/^{40}\text{Ar}$) Method ***	52
6.1.1.1	Conventional Potassium/Argon ($^{40}\text{K}/^{40}\text{Ar}$) Method *** . .	55
6.1.1.2	Argon/Argon ($^{39}\text{Ar}/^{40}\text{Ar}$) Method **	66
6.1.2	Potassium/Calcium ($^{40}\text{K}/^{40}\text{Ca}$) Method *	74
6.1.3	Rubidium/Strontium ($^{87}\text{Rb}/^{87}\text{Sr}$) Method ***	78
6.1.4	Lanthanum/Cerium ($^{138}\text{La}/^{138}\text{Ce}$) Method	94
6.1.5	Lanthanum/Barium ($^{138}\text{La}/^{138}\text{Ba}$) Method	95
6.1.6	Samarium/Neodymium ($^{147}\text{Sm}/^{143}\text{Nd}$) Method **	97
6.1.7	Lutetium/Hafnium ($^{176}\text{Lu}/^{176}\text{Hf}$) Method *	107
6.1.8	Rhenium/Osmium ($^{187}\text{Re}/^{187}\text{Os}$) Method *	111
6.1.9	Uranium/Thorium/Lead Methods *** ($^{238}\text{U}/^{206}\text{Pb}$, $^{235}\text{U}/^{207}\text{Pb}$, and $^{232}\text{Th}/^{208}\text{Pb}$ Methods)	114
6.1.10	Common Lead Method *	127
6.1.11	Lead/Lead ($^{207}\text{Pb}/^{206}\text{Pb}$) Method *	139
6.1.12	Chemical Lead Method	145
6.1.13	Lead/Alpha Method (Larsen Method)	146
6.1.14	Krypton/Krypton ($\text{Kr}_{\text{sf}}/\text{Kr}_{\text{n}}$) Method *	149
6.1.15	Xenon Methods *	152
6.1.15.1	Uranium/Xenon ($\text{U}/\text{Xe}_{\text{sf}}$) Method	152
6.1.15.2	Xenon/Xenon ($\text{Xe}_{\text{sf}}/\text{Xe}_{\text{n}}$) Method *	154

In Chapters 6 - 8 the following classification of dating methods has been used:

*** standard methods; ** routine methods; * individual case study methods;
without asterix: methods in development or obsolete.

6.2	Dating with Cosmogenic Radionuclides	158
6.2.1	Radiocarbon (^{14}C) Method ***	162
6.2.2	Tritium (^{3}H) Methods	180
6.2.2.1	Classical Tritium (^{3}H) Method *	180
6.2.2.2	Tritium/Helium-3 ($^{3}\text{H}/^{3}\text{He}$) and Helium-3 (^{3}He) Methods **	182
6.2.3	Beryllium-10 (^{10}Be) Method **	185
6.2.4	Sodium-22 (^{22}Na) Method	190
6.2.5	Aluminium-26 (^{26}Al) Method *	191
6.2.6	Silicon-32 (^{32}Si) Method *	194
6.2.7	Chlorine-36 (^{36}Cl) Method **	196
6.2.8	Argon-39 (^{39}Ar) Method **	201
6.2.9	Calcium-41 (^{41}Ca) Method	203
6.2.10	Manganese-53 (^{53}Mn) Method **	205
6.2.11	Krypton-81 (^{81}Kr) Method *	206
6.2.12	Iodine-129 (^{129}I) Method *	208
6.2.13	Aluminium-26/Beryllium-10 ($^{26}\text{Al}/^{10}\text{Be}$) Method *	210
6.2.14	Beryllium-10/Chlorine-36 ($^{10}\text{Be}/^{36}\text{Cl}$) Method	211
6.3	Dating Based on Radioactive Disequilibrium of the Uranium, Thorium, and Protactinium Decay Series: The Uranium/Thorium/Protactinium Methods ***	212
6.3.1	$^{230}\text{Th}/^{234}\text{U}$ Method ***	222
6.3.2	$^{231}\text{Pa}/^{235}\text{U}$ Method *	229
6.3.3	$^{231}\text{Pa}/^{230}\text{Th}$ Method **	230
6.3.4	$^{234}\text{U}/^{238}\text{U}$ Method **	231
6.3.5	^{230}Th -excess Method **	234
6.3.6	^{231}Pa -excess Method *	236
6.3.7	^{230}Th -excess/ ^{232}Th or $^{230}\text{Th}/^{238}\text{U}$ Method **	237
6.3.8	^{231}Pa -excess/ ^{230}Th -excess Method **	239
6.3.9	^{234}Th -excess Method	240
6.3.10	^{228}Th -excess/ ^{232}Th Method	241
6.3.11	Dating Methods Based on Supported ^{226}Ra and Unsupported ^{226}Ra	243
6.3.12	^{224}Ra and ^{228}Ra Methods	244
6.3.13	^{210}Pb Method ***	245
6.3.14	Uranium/Helium (U/He) Method **	248
6.3.15	Radium/Radon Method	252
6.4	Age Determination Using Radiation Damage	253
6.4.1	Thermoluminescence (TL) Method ***	256
6.4.2	Optical Dating (OSL) Method *	271
6.4.3	Electron Spin Resonance (ESR or EPR) Method **	272
6.4.4	Exo-Electron Method (TSEE Method) *	282
6.4.5	Thermally Stimulated Current (TSC) Method	283
6.4.6	Differential Thermoanalysis (DTA)	284
6.4.7	Fission Track Method (FT Method) ***	286

6.4.8	Alpha-Recoil Track Method	298
6.4.9	Age Determination Using Pleochroic Haloes	299
6.5	Dating Meteorites and Lunar Rocks	300
6.5.1	Introduction	300
6.5.2	Sample Preparation and Measurement	303
6.5.3	Formation Interval	305
6.5.4	Solidification Ages	307
6.5.5	Gas Retention Ages	308
6.5.6	Cosmic Ray Exposure Ages	309
6.5.7	Terrestrial Ages of Meteorites	312
7	Chronostratigraphic Methods Using Global Time Markers	315
7.1	Paleomagnetic Dating Methods ***	315
7.2	Chronostratigraphic Time-Scale Using $\delta^{18}\text{O}$ Values ***	324
7.3	Chronostratigraphic Time-Scale Using $\delta^{34}\text{S}$ and $\delta^{13}\text{C}$ Values and $^{87}\text{Sr}/^{86}\text{Sr}$ Ratios **	332
7.4	Artificial Radionuclides as Time Markers ***	335
7.5	Geochemical Time Markers *	342
7.6	Chemical Pollution as Time Markers *	343
8	Chemical Dating Methods	345
8.1	Amino-Acid Racemization Method (AAR) ***	346
8.2	Amino-Acid Degradation Method	355
8.3	Dating of Bones Using the Nitrogen or Collagen Content *	356
8.4	Chemical Electron-Spin-Resonance (ESR) Dating	359
8.5	Molecular (Protein and DNA) Clocks	360
8.6	Obsidian Hydration Method ***	361
8.7	Dating of Man-Made Glass	367
8.8	Calcium Diffusion and Cation-Ratio Methods	367
8.9	Dating of Bones Using the Fluorine or Uranium Content *	369
9	Phanerozoic Time-Scale	373
9.1	Objectives and History of Geochronology	373
9.2	Geological Time-Scales	378
9.3	The Future	378
10	Literature	381
10.1	Journals that Frequently Publish Geochronological Papers	381
10.2	Geochronology Textbooks	382
10.3	References	383

Contents	XI
Acknowledgments	445
Appendix A: Geochronology Glossary	447
Appendix B: Radioactive and Stable Isotopes in Geochronology	470
Appendix C: List of Addresses	475
Subject Index	486
Foldout Table: Dating Methods, Ranges, and Materials (inside back cover)	