# Contents

1 Introduction ................................................................. 1

Part I Stable Isotopes

2 Isotope Geochemistry of Natural Waters .......................... 11
   2.1 Some Properties of Waters and Solutions ...................... 11
      2.1.1 The Notion of Activity and the Activity Coefficient .... 13
      2.1.2 The Relationship between Solvent and Solute Activity ..... 14
   2.2 Water Vapor Pressure over the Water and Solution .......... 15
   2.3 Physicochemical Foundations of Isotope Separation .......... 17
   2.4 Hydrogen and Oxygen Isotope Separation at Phase Transition
      of Water .................................................................. 26
   2.5 Relationship Between the Isotope Reaction Change Constant
      and the Fractionation Factor ....................................... 30
   2.6 Hydrogen and Oxygen Isotope Fractionation at Interaction
      Between Water and Gases and Rocks ............................ 33
   2.7 Isotope Geothermometry ............................................ 35

3 Isotopic Composition of Ocean Water ............................... 49
   3.1 Distribution of Hydrogen and Oxygen Isotopes
      and Water Dynamics ................................................ 49
   3.2 Effect of Evaporation and Vertical Water Exchange ........... 54
   3.3 Dynamics of the Ocean Water .................................... 57
   3.4 Isotopic Composition of Ocean Water in the Past .............. 62

4 Isotopic Composition of Atmospheric Moisture .................. 67
   4.1 Hydrogen and Oxygen Isotope Fractionation
      in the Hydrological Cycle .......................................... 67
   4.2 Isotopic Balance in the Global Hydrologic Cycle at Evaporation
      and Condensation of Water ........................................ 79
   4.3 Isotopic Composition of Atmospheric Water in the Past ....... 86
5 Isotopic Composition of Surface Continental Waters .......................... 95
  5.1 Isotopic Balance of the Continental Waters .......................... 95
  5.2 Isotopic Composition of the River and Lake Water ................. 101
  5.3 Isotopic Composition of Water in Evaporating Basins .......... 107

6 Isotopic Composition of Water in the Unsaturated and Saturated Zones ........................................ 115
  6.1 Relationship Between Surface and Ground Water ................. 116
  6.2 Groundwater Recharge at Present Time .......................... 118
  6.3 Groundwater Recharge in the Past ................................ 118
  6.4 Identification of Area of Groundwater Recharge ................. 119
  6.5 Relationship Between Aquifers ................................... 123
  6.6 Mixing Proportions of Groundwater of Different Genesis ..... 125
  6.7 Groundwater Residence Time in an Aquifer ..................... 126
  6.8 Relationship of Waters in Conjugate Hydrologic Basins ... 127

7 Isotopic Composition of Formation Waters ................................. 129
  7.1 Relationship Between Hydrogen and Oxygen Isotopes in Formation Waters ........................................ 129
  7.2 Isotopic Composition of Formation Water in Sedimentary Basins ... 134

8 Hydrogen and Oxygen Isotopic Composition of Sedimentary Rocks of Marine Genesis and Implications for Paleothermometry ... 155
  8.1 Isotopic Composition of Sediments and Pore Water ............. 155
  8.2 Paleothermometry Based on the Isotopic Composition of Cherts ... 161
  8.3 Paleothermometry Based on the Isotopic Composition of Carbonate Rocks ........................................ 169
  8.4 Isotopic Composition of Evaporates ................................ 175

9 Hydrogen and Oxygen Isotopic Composition of Groundwater in Volcanic Regions ........................................ 179
  9.1 Use of Isotopes in Studying the Origin of Thermal Water .......... 179
  9.2 Isotopic Geothermometers ..................................... 192

10 Hydrogen and Oxygen Isotopic Composition of Minerals of Magmatic and Metamorphic Rocks and Fluid Inclusions .......... 195
  10.1 Role of Water in Hydrothermal Alteration of the Rocks and Minerals ........................................ 195
  10.2 Meteoric Water in the Processes of Hydrothermal Formation of Minerals ........................................ 201

11 Other Stable Isotopes in the Hydrosphere ................................. 205
  11.1 Stable Isotopes of Carbon ..................................... 205
  11.2 Stable Isotopes of Sulfur ..................................... 209
## Part II  Cosmogenic Radioisotopes

### 12 Origin and Production of Cosmogenic Radioisotopes

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.1 Composition of Cosmic Radiation in the Earth’s Atmosphere</td>
<td>215</td>
</tr>
<tr>
<td>12.2 Composition and Steady-state Abundances of Cosmogenic Radioisotopes in the Outer Shells of the Earth</td>
<td>218</td>
</tr>
<tr>
<td>12.3 Distribution of Cosmogenic Radioisotopes in the Exchange Reservoir</td>
<td>223</td>
</tr>
</tbody>
</table>

### 13 Tritium in Natural Waters

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.1 Properties of Tritium and Sources of Its Occurrence</td>
<td>227</td>
</tr>
<tr>
<td>13.2 Global Circulation of Tritium Water</td>
<td>235</td>
</tr>
<tr>
<td>13.2.1 Tritium in Atmospheric Hydrogen and Methane</td>
<td>236</td>
</tr>
<tr>
<td>13.2.2 Tritium in Atmospheric Water Vapor</td>
<td>239</td>
</tr>
<tr>
<td>13.2.3 Tritium in Precipitation</td>
<td>241</td>
</tr>
<tr>
<td>13.2.4 Global Distribution of Tritium</td>
<td>249</td>
</tr>
<tr>
<td>13.3 Regional Distribution of Tritium in Precipitation</td>
<td>253</td>
</tr>
<tr>
<td>13.3.1 The North American Continent</td>
<td>254</td>
</tr>
<tr>
<td>13.3.2 The European–Asiatic Continent</td>
<td>254</td>
</tr>
<tr>
<td>13.3.3 The African Continent</td>
<td>258</td>
</tr>
<tr>
<td>13.3.4 The South American Continent</td>
<td>261</td>
</tr>
<tr>
<td>13.3.5 Australia and New Zealand</td>
<td>262</td>
</tr>
<tr>
<td>13.3.6 Antarctic</td>
<td>263</td>
</tr>
<tr>
<td>13.3.7 Tritium in Precipitation over the Oceans</td>
<td>264</td>
</tr>
<tr>
<td>13.4 Formation of Tritium Concentrations in the Atmosphere</td>
<td>264</td>
</tr>
<tr>
<td>13.5 Tritium in Ocean Waters</td>
<td>270</td>
</tr>
<tr>
<td>13.6 Tritium in Continental Surface Waters</td>
<td>277</td>
</tr>
<tr>
<td>13.6.1 Tritium Content in River Water</td>
<td>277</td>
</tr>
<tr>
<td>13.6.2 Tritium in Lakes and Reservoirs</td>
<td>285</td>
</tr>
<tr>
<td>13.7 Tritium in Groundwaters</td>
<td>289</td>
</tr>
<tr>
<td>13.8 Dating by Tritium</td>
<td>292</td>
</tr>
<tr>
<td>13.8.1 Piston Flow Model</td>
<td>292</td>
</tr>
<tr>
<td>13.8.2 Dispersive Model</td>
<td>293</td>
</tr>
<tr>
<td>13.8.3 Complete Mixing Model</td>
<td>294</td>
</tr>
<tr>
<td>13.8.4 Symmetrical Binominal Age Distribution Model</td>
<td>296</td>
</tr>
<tr>
<td>13.8.5 Model of Mixing Waters of Different Ages</td>
<td>297</td>
</tr>
<tr>
<td>13.8.6 Complicated Model</td>
<td>298</td>
</tr>
</tbody>
</table>

### 14 Radiocarbon in Natural Waters

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.1 Origin and Distribution of Radiocarbon in the Nature</td>
<td>301</td>
</tr>
<tr>
<td>14.2 Natural Variations of Radiocarbon in the Atmosphere and Biosphere</td>
<td>306</td>
</tr>
<tr>
<td>14.3 Natural Radiocarbon in the Oceans</td>
<td>312</td>
</tr>
<tr>
<td>14.4 Technogenic Radiocarbon in the Atmosphere and Oceans</td>
<td>316</td>
</tr>
<tr>
<td>14.5 Forecast of Carbon Dioxide Increase in the Atmosphere</td>
<td>327</td>
</tr>
<tr>
<td>14.6 Principles of Radiocarbon Dating</td>
<td>331</td>
</tr>
</tbody>
</table>
14.7 Radiocarbon Dating of Groundwater ................................................................. 335
14.8 Formation of Chemical and Isotopic Composition of Groundwater’s Carbonate System ................................................................. 339
14.9 Corrections in Groundwater Dating by Radiocarbon ........................................ 343

15 The Other Cosmogenic Isotopes in Natural Waters .............................................. 361
15.1 Origin of Other Cosmogenic Radioisotopes in the Atmosphere ............................ 361
15.2 Distribution of Other Cosmogenic Isotopes in the Hydrosphere ............................ 363
15.3 Use of Radioisotopes as Tracers in the Hydrological Cycle ................................. 365

Part III Radiogenic Isotopes

16 Production and Distribution of Radiogenic Isotopes ....................................... 377
  16.1 Geochemistry of Radiogenic Elements ......................................................... 378
     16.1.1 Uranium ................................................................................................. 378
     16.1.2 Thorium ................................................................................................. 382
     16.1.3 Protactinium ......................................................................................... 383
     16.1.4 Actinium ................................................................................................ 384
     16.1.5 Radium .................................................................................................. 384
     16.1.6 Radon ..................................................................................................... 385
  16.2 Separation of Radiogenic Elements and Isotopes ............................................. 386
     16.2.1 Separation of Uranium Isotopes ............................................................. 388
     16.2.2 Separation of Thorium Isotopes ............................................................ 389
     16.2.3 Separation of Radium Isotopes ............................................................ 390
  16.3 Distribution of Radiogenic Elements in Natural Waters ................................. 391
     16.3.1 Uranium Isotopes in Natural Waters ..................................................... 392
     16.3.2 Thorium Isotopes in Natural Waters ..................................................... 398

17 Dating of Surface Water, Groundwater, and Sediments .................................... 407
  17.1 Dating of Closed Reservoirs ......................................................................... 407
  17.2 Dating of Groundwater .................................................................................. 411
  17.3 Dating of Sediments ...................................................................................... 413
     17.3.1 Uranium-Uranium Method ................................................................. 413
     17.3.2 Uranium-Ionium Method .................................................................... 415
  17.4 Isotopes of Radiogenic Elements as Indicators of Hydrologic Processes .......... 418

Part IV Applications

18 Applications to the Problems of Dynamics of Natural Waters ............................ 427
  18.1 Dynamics of Moisture in the Atmosphere ..................................................... 427
  18.2 Mixing of River and Sea Waters in Estuaries ............................................... 436
  18.3 Water Exchange in the River Basins, Lakes, and Reservoirs ......................... 446
  18.4 Water Dynamics in Unsaturated and Saturated Zone .................................... 452
  18.5 Recharge and Discharge of Groundwater ..................................................... 456
  18.6 Relationship of Aquifers .............................................................................. 462
  18.7 Separation of Recharged Water of Different Genesis in Mining ..................... 469
18.8 Determination of Radiocarbon Age of Groundwater ............ 470
18.9 Determination of Flow Velocity and Direction in Regional Scale . 478
18.10 Paleoclimatic and Paleohydrogeologic Studies .................. 480

19 Paleohydrology of the Aral-Caspian Basin ........................ 491
19.1 Formulation of the Problem ...................................... 491
19.2 General Description of Study in the Caspian Sea ............... 492
  19.2.1 Laboratory Data of Core Analysis ........................... 493
  19.2.2 Structure of Core Cross Section ............................ 495
  19.2.3 Carbonate Mineral Content of Sediments ................... 495
  19.2.4 Ion-Salt Composition of Water Extracts .................... 497
  19.2.5 Radiocarbon Age of Sediments ............................. 498
  19.2.6 Isotope Record in Carbonates .............................. 498
19.3 Interpretation of Paleoclimatic Events .......................... 504
  19.3.1 Rate of Sedimentation and Change in the Regime of the Northern and Southern Rivers .................. 504
  19.3.2 Variations in the Sea Level ................................. 506
19.4 Study of Water Regime in the Aral Sea ........................... 508
19.5 Interpretation of Bottom Sediments .............................. 512
  19.5.1 Kara-Bogaz-Gol Gulf ..................................... 512
  19.5.2 Lake Issyk-Kul .......................................... 515
  19.5.3 Aral Sea .............................................. 518
19.6 Results and Conclusions ....................................... 521

20 The Nature and Mechanism of the Earth Shell Separation and Origin of Hydrosphere ...................................... 525
20.1 Existing Approaches to the Problem Solution .................... 525
20.2 Separation of Hydrogen and Oxygen Isotopes in Natural Objects ............................................. 527
20.3 Evidence from Carbon and Sulfur Isotopes ....................... 539
20.4 Chemical Differentiation of Proto-Planetary Substance ........ 545
20.5 Recent Results of Study of the Earth Gravitational Field by the Satellites ........................................ 557
20.6 The Nature and Mechanism of the Earth Shell Separation .... 558
20.7 Physical Meaning of Archimedes’ and Coriolis’ Forces ........ 560
20.8 Self-Similarity Principle and Radial Component of Nonuniform Sphere ........................................ 561
20.9 Charges-like Motion of Nonuniformities and Tangential Component of the Force Function ................... 562
20.10 Differentiation of the Substances with Respect to Density and Condition for the Planet and the Satellite Separation ........ 563
20.11 The Third Kepler’s Law as a Kinematics Basis for the Solar System Bodies Creation Problem Solution .......... 571
20.12 Conclusion .................................................... 576

References .......................................................... 579

Index ............................................................. 621