

Springer Geophysics

The Springer Geophysics series seeks to publish a broad portfolio of scientific books, aiming at researchers, students, and everyone interested in geophysics. The series includes peer-reviewed monographs, edited volumes, textbooks, and conference proceedings. It covers the entire research area including, but not limited to, geodesy, planetology, geodynamics, geomagnetism, paleomagnetism, seismology, and tectonophysics.

More information about this series at <http://www.springer.com/series/10173>

V. I. Ferronsky

Nuclear Geophysics

Applications in Hydrology, Hydrogeology,
Engineering Geology, Agriculture
and Environmental Science



Springer

V. I. Ferronsky
Water Problems Institute of the Russian
Academy of Sciences
Moscow
Russia

Every effort has been made to contact the copyright holders of the figures and tables which have been reproduced from other sources. Anyone who has not been properly credited is requested to contact the publishers, so that due acknowledgment may be made in subsequent editions.

Springer Geophysics
ISBN 978-3-319-12450-6 ISBN 978-3-319-12451-3 (eBook)
DOI 10.1007/978-3-319-12451-3

Library of Congress Control Number: 2014959274

Springer Cham Heidelberg New York Dordrecht London
© Springer International Publishing Switzerland 2015

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

Progress in geoen지니어ing, hydrology and environmental sciences as a whole closely depends on the development of new methods of investigation, which are based on the latest achievements in adjacent branches of science such as physics, chemistry, electronics, geophysics and so on. This book provides the fundamentals and field applications of nuclear techniques in engineering geology, hydrogeology, civil engineering, agriculture and environmental study. The book is intended for scientists and researchers, teachers, students and postgraduates engaged in field studies for solving scientific and practical problems in applied geology and hydrology for civil, road, power, airfield, harbour engineering, drainage and irrigation.

Nuclear geophysics is a branch of applied geophysics, where the nuclear methods for study of physical-chemical and geoen지니어ing properties of rocks and soils at their geological exploration are considered. Despite their relatively short history, nuclear methods have achieved worldwide popularity in science and technology. Because of their exceptionally advantageous features, they have found many practical applications whose range is continuously expanding.

The development of nuclear methods for solving geoen지니어ing and hydrological problems depends first of all on the development of reliable and objective methods for estimating the physical parameters of grounds and rocks and of studying the dynamics and geochemistry of underground waters under natural conditions. It is not long since methods based only on the study of samples taken from excavations were used both in estimating physical properties (density, moisture content and porosity) of rocks in regional studies and in surveys for suitable building areas.

The development of field methods for determining the physical properties of grounds began with the use of gamma-rays and neutrons, which are now regarded as uniquely reliable tools for estimating the density and the moisture content of grounds under natural conditions. Italian physicist Bruno Pontecorvo was the founder of nuclear geophysics. In 1941 he was the first to propose neutron well logging for geological exploration of oil and gas fields. Since that time nuclear techniques have started to develop for the geological exploration of mineral resources, engineering geology and hydrogeology.

In 1950, Bernhard and Berdan of Rutgers University (USA) were the first to use gamma-ray absorption as a method of determining the density of grounds. The

back-scattering of gamma-rays and of neutrons in 1950 was used by Belcher at Cornell University in the USA to investigate the density and the moisture content of grounds respectively. These methods were subsequently developed by many researchers in Germany, UK, France, former USSR, Poland and other countries.

The first gamma-ray density and neutron moisture gauges were used to estimate the suitability of various areas for civil engineering projects in the former USSR, e.g., at construction of the Volga and Nurek hydroelectric power stations for monitoring of density at the ground dam pouring out. They were also applied in geoenvironmental surveys in Western Siberia, in hydromelioration studies of irrigation schemes in Central Asia, in Southern Ukraine and many other areas in different countries.

The manufacture of neutron moisture and gamma-ray density gauges for the investigation of grounds and rocks was started in the USA, UK, France and the former USSR by firms such as Nuclear Chicago, Nuclear Enterprises, Russian Enterprise 'Isotope' and others. In 1966 the working group of the Coordinating Council of the International Hydrological Decade decided to recommend gamma-ray and neutron methods for determining the density and moisture content of soils and grounds as satisfactory and reliable for extensive practical use.

The successes in the development and application of neutron and gamma-ray methods in engineering geology and hydrogeology have not, however, led to the solution of a very important problem of cardinal improvement of the field methods of investigation in these applied sciences. When engineering geology surveys for suitable constructional areas are being carried out, it is essential to have data on the properties of the ground at depths down to 15–20 m.

So far, this can only be done by the nuclear well logging technique. This method is being widely used in industrial and prospecting geophysics. Many publications have appeared on this subject, including monographs by E.M. Filippov (1962), V.I. Ferronsky et al. (1968; 1969), C.G. Clayton (1983), IAEA (1968, 1971; 1981, 1983, 1999) and K. Froehlich (2010).

However, nuclear well logging, which was being used in prospecting geology and especially in prospecting for oil and gas fields, has not turned out to be suitable for engineering geological studies. The accuracy of the method was insufficient to determine the physical characteristics of grounds, owing to the interference by the very existence of the well casing.

The optimal solution of the problem of the nuclear logging method in engineering geology for studies of loose deposits down to a depth of 20–25 m was put forward by V.I. Ferronsky (1969). The idea of his approach was as follows. To avoid the influence of interference due to construction of the well, the penetration logging method (including gamma, gamma-gamma and neutron-neutron logging) is used. In this case the logging probe, which is mounted on the tip of the drill rod, is forced into unconsolidated deposits by an axial load, which is applied by a vehicle-mounted hydraulic-mechanical system. The method is most readily applicable in solving engineering geological problems and for hydrogeological investigations of aquifers in both saturated and unsaturated zones.

Practical applications of advanced original nuclear logging techniques and methods are presented in the book. These techniques are the penetration logging methodology and facilities, where the logging sonde is sunk into the friable deposits under investigation by a vehicle-mounted hydraulic device. The logging sonde is penetrated to depths about 40 m in loose formations at rates of up to 2 m/min on land and near shore marine areas. Besides having obvious operational advantages such as fast penetration, this method also avoids some of the well construction problems. The sonde is in direct contact with the medium and thus gives increased accuracy and reliability for interpretation.

Radioactive and stable isotopes, which are the constituents of water molecules, or migrate with them, have been used widely in recent years in a number of countries to investigate the motion of water on a regional scale. These isotopes include above all tritium (half-life of decay $T_{1/2} = 12.32$ year), carbon-14 ($T_{1/2} = 5730$ year), deuterium and oxygen-18. Natural tritium as a constituent of water molecules, chemical properties of which are practically indistinguishable from hydrogen, is particularly widely employed in investigations. Tritium and carbon-14 are used to solve many hydrogeological problems related to water movement in saturated and unsaturated zones.

Hydrogeological processes occurring over longer periods of time are being investigated with the aid of natural radioactive carbon-14. Because its half-life of decay is equal to 5730 year, it can be used to cover very long periods of time during the motion of water in nature, including the glacial period.

Some information related to other natural radioactive isotopes in groundwaters like ^7Be , ^{10}Be , ^{22}Na , ^{26}Al , ^{32}Si , ^{32}P , ^{33}P , ^{36}Cl , ^{37}Ar , ^{39}Ar and radioactive isotopes of the uranium-thorium series is presented in the book. But investigation of the regularities on the distribution of these isotopes in natural waters is limited by technical difficulties of sampling, concentration and measurement of the corresponding samples.

The use of stable isotopes of deuterium and oxygen-18 enables us to establish the interrelations between water-bearing horizons, the supply sources for groundwaters and the connections between open reservoirs and other sources of effluents and the origin of individual water-bearing horizons and also to investigate the conditions under which glaciers are formed and moved.

Systematic measurements of precipitation and of the abundance of natural isotopes in precipitation are essential for the success of regional hydrogeological and hydrological studies using naturally occurring isotopes. The first condition is satisfied by using the data supplied by the hydrometeorologic service supported by an appropriate national network of stations. To satisfy the second condition, the International Atomic Energy Agency (IAEA), since 1953, is collecting and publishing the data obtained from the WMO/IAEA Isotopes-in-Precipitation Network.

It must be stressed the role of the International Atomic Energy Agency in providing the Secretariat for the Working Group on Nuclear Techniques in Hydrology of the UNESCO International Hydrological Decade (1965–1974), regular scientific symposia and systematic research coordinated programs on this subject. All these

IAEA actions create an efficient basis for fruitful scientific cooperation of the specialists in nuclear techniques from different countries.

The use of artificial and natural radioactivity as a tracer in groundwater as well as mathematical modelling for interpretation of experimental data are also discussed.

In this book we systematically review and generalise the results obtained by the author and his colleagues from many countries during the field and laboratory studies concerned with the development and application of radioactive sources and tracer techniques in geoenvironment and hydrology.

Particular attention is paid to the range of validity of these methods and to the solution of practical problems. The basic physics of radioisotopes and emitted radiation, as well as the interaction of radiation with matter, methods of radiation detection, radiation hazard problems and many others are briefly discussed in the book.

The author is grateful to his colleagues V.A. Polyakov, V.S. Goncharov, V.T. Dubinchuk, T.A. Gryaznov, L.V. Selivanov, B.P. Krovopuskov, D.M. Lantsman, A.I. Avsyuk, Yu.B. Seletsky, V.M. Maslennikov, A.K. Priymachuk and V.I. Demchenko for many years of fruitful co-operation in the field, with laboratory investigations and providing design and preparation of the penetration logging equipment. The author especially wishes to thank B. Malashenkov for his assistance in preparation of the manuscript for the book.

References

- Clayton CG (1983) Nuclear geophysics. Pergamon Press, Oxford
- Ferronsky VI, Danilin AI, Dubinchuk VT et al (1968) Radioactive investigative methods in engineering geology and hydrogeology. Atomizdat, Moscow
- Ferronsky VI (1969) Penetration logging methods for engineering geological investigation. Nedra, Moscow
- Filippov EM (1962) Applied nuclear geophysics. USSR Academy of Sciences Publ House, Moscow
- Froehlich K (ed) (2010) Environmental radionuclides: tracers and timers of terrestrial processes. Elsevier, Amsterdam
- International Atomic Energy Agency (1968) Guidebook on nuclear techniques in hydrology. IAEA, Vienna
- International Atomic Energy Agency (1971) Nuclear well logging in hydrology. Technical report series No 126, IAEA, Vienna
- International Atomic Energy Agency (1981) Stable isotope hydrology. In: Gat JR, Gonfiantini R (eds). Technical reports series No 210, IAEA, Vienna
- International Atomic Energy Agency (1983) Guidebook on nuclear techniques in hydrology. IAEA, Vienna
- International Atomic Energy Agency (1999) Nuclear geophysics and its applications. IAEA, Vienna

Acknowledgements

Chapters 1, 2, 3, 4, 5, 6, 7, 8, 12, and 13 are based on the publications below and figures and tables in these chapters were reproduced with the kind permission of the copyright holder from these publications.

- V.I. Ferronsky, A.I. Danilin, V.T. Dubinchuk et al (1968) Radioisotope Investigative Methods in Engineering Geology and Hydrogeology. Atomizdat, Moscow (in Russian)
- V.I. Ferronsky, A.I. Danilin, V.T. Dubinchuk et al (1969) Radioisotope Investigative Methods in Engineering Geology and Hydrogeology. US AEC, Springfield (Translation of Russian edition)
- V.I. Ferronsky (1969) Penetration logging methods for engineering geological investigation. Nedra, Moscow (in Russian)
- V.I. Ferronsky, A.I. Danilin, V.T. Dubinchuk et al (1977) Radioisotope Investigative Methods in Engineering Geology and Hydrogeology (Second Edition). Atomizdat, Moscow (in Russian)
- V.I. Ferronsky (1969) Penetration Logging Methods in Engineering Geology. Nedra, Moscow (in Russian)
- V.I. Ferronsky and Gryaznov TA (1979) Penetration Logging. Nedra, Moscow (in Russian)
- International Atomic Energy Agency (1971) Nuclear Well Logging in Hydrology. Technical report series No 126, IAEA, Vienna
- V.I. Ferronsky, V.A. Polyakov (1983) Isotopy of the Hydrosphere. Nauka, Moskva (in Russian)

The figures and tables of Chap. 9, 10, and 11 were reproduced from the book: V.I. Ferronsky and V.A. Polyakov, Isotopes of the Earth's Hydrosphere, 2012, Springer, Dordrecht

Contents

1 Introduction: Fundamentals of Nuclear Physics.....	1
1.1 Natural Stable and Radioactive Isotopes	1
1.2 Nuclear Reactions and Sources of Radioactivity	11
1.3 Laws of Radioactive Decay and Attenuation of Radiation	13
1.4 Measurement Techniques and Health Hazards	15
References	15

Part I Use of Nuclear Techniques for Determination of Soil Properties

2 Methods Based on the Absorption of Gamma-Ray Beams by Matter ...	19
2.1 Main Principles	19
2.2 Transmission of Narrow and Broad Gamma-Ray Beams Through Matter	22
2.3 Mass Absorption Coefficients of Rocks	25
2.4 Sensitivity of the Method	32
2.5 Deviations from the Mean Density	37
2.6 Determination of Soil Density by Gamma-Ray Absorption	39
2.7 Studies of Moisture Content Dynamics in Soil	45
2.8 Determination of the Amount of Water Stored in Snow Cover	49
2.9 Studies of Evaporation Processes	51
References	51
3 The Gamma-Ray Back-Scattering Method	53
3.1 Principles and Range of Application	53
3.2 Optimal Parameters of Measuring Probe	56
3.3 Design of Gamma-Ray Density Gauges and the Range of Their Application	62
3.3.1 Surface-Type Gamma-Ray Density Gauges	63
3.3.2 Gamma-Ray Density Gauges Used in Wells	63
3.3.3 Gamma-Ray Density Gauges for Direct Insertion into the Ground	65
3.4 Technological Aspects of Measurement and Calibration	66
References	67

4 Neutron Back-Scattering Method..... 69

4.1 Principles and Range of Application 69

4.2 Optimal Parameters of Measuring Probe 74

 4.2.1 Sensitivity of the Method 74

 4.2.2 Maximum Working Depth 76

 4.2.3 Effects of Parameters of the Medium 79

4.3 Design of Neutron Moisture Gauges 83

4.4 Possible Errors in the Moisture Content Measured by the
 Neutron Method 86

4.5 Calibration of Neutron Moisture Gauges 87

References 87

Part II Penetration Logging Techniques

5 Penetration Logging Methods and Equipment..... 91

5.1 Essence of Penetration Logging Techniques and Conditions
 of Application 92

5.2 Experimental Penetration Logging Rig SUGP-10 97

5.3 The Penetration Logging Rig and Equipment SPK 98

5.4 The Submerged Penetration Logging Rig PSPK-69 Mounted
 on the Exploration Catamaran Type Ship “Geologist-1” 101

References 104

6 Theoretical Basis of Penetration Logging Tests 105

6.1 Solutions Based on the Theory of Ultimate Equilibrium 106

6.2 Imbedding of Spherical Probe into an Infinite Elastic Medium 117

6.3 Imbedding of Spherical Probe into Elastic-Creeping Media 125

6.4 Two-Dimensional Axis-Symmetric Problem of Relaxation Stress ... 137

6.5 Conditions for Measuring Ground Parameters by Static
 Penetration 145

References 146

**7 Experimental Studies and Interpretation of Penetration
Logging Data** 149

7.1 Density, Moisture, Porosity, Groundwater Level 149

7.2 Influence of Sounding Parameters on Ground Resistance
 and Friction 159

7.3 Modulus of Ground Compressibility 172

7.4 Ground Shear and Rheology Parameters 174

7.5 Normal Pressure 179

7.6 Lithology Stratification 180

7.7 Application of Statistical and Probability Methods 190

References 191

8 Application of Penetration Logging Techniques for Geoen지니어ing Exploration 193

8.1 Geological and Geographical Conditions for Application of Penetration Logging 193

8.2 Practical Applications 195

8.3 Engineering Geological and Hydrogeological Mapping 197

8.3.1 Study for Irrigation Land Projects 197

8.3.2 Study for Drainage Land Projects 202

8.3.3 Geoen지니어ing Studies in a Region of Glacial Sediments ... 203

8.3.4 Prospecting for Building Construction 209

8.3.5 Study of a Landslide Slope 213

8.3.6 Study of Bottom Marine Sediments at Novorossiysk Port ... 217

8.3.7 Study of Novorossiysk Oil Jetty Structures 219

8.4 Combined Application of Penetration Logging and Traditional Geophysical Methods 221

References 223

Part III Natural Isotopes in Environmental Studies

9 Stable Isotopes in Study of the Global Hydrological Cycle..... 227

9.1 Separation of Hydrogen and Oxygen Isotopes at Phase Transition of Water 227

9.2 Isotopic Composition of Ocean Water 230

9.3 Isotopic Composition of Atmospheric Moisture 237

9.4 Isotopic Composition of Continental Surface Waters 261

9.5 Isotopic Composition of Water in Evaporating Basins 274

9.6 Isotopic Composition of Water in Unsaturated and Saturated Zones 281

9.7 Isotopic Composition of Formation Waters 282

9.8 Isotopic Composition of Groundwater in Volcanic Regions 300

9.8.1 Isotopes in Studying the Origin of Thermal Waters 300

9.8.2 Isotopic Geothermometers 313

References 315

10 Cosmogenic Radioisotopes for Study of the Genesis and Dynamics of Water 323

10.1 Origin and Distribution of Cosmogenic Radioisotopes 323

10.2 Sources of Tritium Discharge into Natural Waters 334

10.3 Global Circulation of Tritium Water 343

10.3.1 Tritium in Atmospheric Hydrogen and Methane 343

10.3.2 Tritium in Atmospheric Water Vapour 346

10.3.3 Tritium in Precipitation 348

10.3.4 Formation of Tritium Concentrations in the Atmosphere ... 351

10.4	Tritium in Ocean Waters	358
10.5	Tritium in Continental Surface Waters	363
10.5.1	Tritium Content in River Water	363
10.5.2	Tritium in Lakes and Reservoirs	370
10.6	Tritium in Groundwaters	373
10.7	Dating by Tritium	375
10.7.1	Piston Flow Model	376
10.7.2	Dispersive Model	376
10.7.3	Complete Mixing Model	378
10.7.4	Symmetrical Binominal Age Distribution Model	379
10.7.5	Model of Mixing Waters of Different Ages	380
10.7.6	Complicated Model	382
10.8	Radiocarbon in Natural Waters	383
10.8.1	Origin and Distribution of Radiocarbon in Nature	383
10.8.2	Natural Variations of Radiocarbon in the Atmosphere and Biosphere	389
10.8.3	Natural Radiocarbon in Oceans	394
10.8.4	Technogenic Radiocarbon in the Atmosphere and Oceans	398
10.8.5	Forecast of Carbon Dioxide Increase in the Atmosphere .	407
10.8.6	Principles of Radiocarbon Dating	410
10.8.7	Radiocarbon Dating of Groundwater	413
10.9	The Other Cosmogenic Isotopes in Natural Waters	416
	References	418
11	Radiogenic Isotopes in Dating of Natural Waters and Sediments	427
11.1	Production and Distribution of Radiogenic Isotopes	427
11.2	Separation of Radiogenic Isotopes	431
11.2.1	Separation of Uranium Isotopes	433
11.2.2	Separation of Thorium Isotopes	434
11.2.3	Separation of Radium Isotopes	434
11.3	Distribution of Radiogenic Isotopes in Natural Waters	435
11.3.1	Uranium Isotopes in Natural Waters	436
11.3.2	Thorium Isotopes in Natural Waters	442
11.4	Dating of Surface and Groundwaters	449
11.4.1	Dating of Closed Reservoirs	449
11.4.2	Dating of Groundwater	453
11.5	Dating of Sediments	456
11.5.1	Uranium-Uranium Method	456
11.5.2	Uranium-Ionium Method	458
11.6	Radiogenic Isotopes as Indicators of Hydrologic Processes	461
	References	466

Part IV Other Applications

12 Radioactive Contamination of Natural Waters	473
12.1 Sources of Radioactive Contamination of Water	473
12.1.1 Nature and Properties of Radioactive Effluents	475
12.1.2 Future Developments in Nuclear Technology and Disposal of Effluents	478
12.2 Migration of Radioactive-Effluent Components Through Soil and Ground	479
12.2.1 Migration Activity	479
12.2.2 Natural Mineral Sorbents	483
12.2.3 Natural Organic Sorbents	486
12.3 Estimation of Absorbing Properties of Soil and Ground and Migration Activity of Radioactive Micro-Components	488
12.3.1 Determining the Absorption Capacity	488
12.3.2 Absorption Capacity of Soil and Ground for Components of Contaminants	490
12.3.3 Absorption of Radioactive Components Under Dynamic Conditions	495
References	498
13 Induced-Activity Method for Analysis of Rocks and Groundwaters	501
13.1 Principles and Range of Application	501
13.2 Activation Reactions in Principle Rock-Forming Elements and Water	502
13.3 Theory of the Method	506
13.4 Laboratory Activation Analysis for Aluminium and Silicon	509
13.5 Conclusions	515
References	516
Index	517