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Petrophysics

Theory and Practice of Measuring Reservoir Rock and Fluid Transport Properties

Djebbar Tiab and
Erle C. Donaldson

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AMSTERDAM • BOSTON • HEIDELBERG
LONDON • NEW YORK • OXFORD • PARIS
SAN DIEGO • SAN FRANCISCO • SINGAPORE
SYDNEY • TOKYO

Gulf Professional Publishing is an imprint of Elsevier

Gulf Professional Publishing

Gulf Professional Publishing is an imprint of Elsevier
200 Wheeler Road, Burlington, MA 01803, USA
Linacre House, Jordan Hill, Oxford OX2 8DP, UK

Library of Congress Cataloging-in-Publication Data
Tiab, Djebbar.
Petrophysics : theory and practice of measuring reservoir rock and fluid transport properties / Djebbar Tiab and Erle C. Donaldson.– 2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 0-7506-7711-2 (alk. paper)
1. Petroleum–Geology. 2. Petrology. I. Donaldson, Erle C. II. Title.
TN870.56.T53 2004
553.2′8–dc22
2003023604

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

ISBN: 0-7506-7711-2

For information on all Gulf Professional Publishing publications visit our website at www.gulfpp.com

04 05 06 07 08 10 11 9 8 7 6 5 4 3 2 1

Printed in the United States of America

Kapista gold Medal of Honor for "his outstanding contributors to the field of engineering." He received the prestigious 1995 SPE Distinguished Achievement Award for Petroleum Engineering Faculty. The citation read, "He is recognized for his role in student development and his excellence in classroom instruction. He pioneered the pressure derivative technique of well testing and has contributed considerable understanding to petrophysics and reservoir engineering through his research and writing." He is also the recipient of the 2003 SPE Formation Evaluation Award "For distinguished contributions to petroleum engineering in the area of formation evaluation."

Erle C. Donaldson began his career as a pilot plant project manager for Signal Oil and Gas Research in Houston, Texas. Later he joined the U.S. Bureau of Mines Petroleum Research Center in Bartlesville, Oklahoma, as a project manager of subsurface disposal and industrial wastes and reservoir characterization; when the laboratory was transferred to the U.S. Department of Energy, Dr. Donaldson continued as chief of petroleum reservoir characterization. When the laboratory shifted to private industry for operations, he joined the faculty of the School of Petroleum and Geological Engineering at the University of Oklahoma as associate professor. Since retiring from the university in 1990, he has consulted for various oil companies, universities, and U.S. agencies including: the Environmental Protection Agency, the U.S. Navy Ordinance Center, King Fahd Research Institute of Saudi Arabia, and companies in the U.S., Brazil, Venezuela, Bolivia, and Thailand.

Dr. Donaldson has earned four degrees: a Ph.D. in chemical engineering from the University of Tulsa, an M.S. in organic chemistry from the University of South Carolina, a B.Sc. in chemical engineering from the University of Houston, and a B.Sc. in chemistry from The Citadel. He has served as chairman of committees and sessions for the Society of Petroleum Engineers and the American Chemical Society, as well as other national and international conferences. He is a member of the SPE Twenty-Five Year Club, and is currently the managing editor of the *Journal of Petroleum Science and Engineering*.

ACKNOWLEDGMENT

The authors are especially indebted to Academician George V. Chilingar, Professor of Civil and Petroleum Engineering at the University of Southern California, Los Angeles, who acted as the technical, scientific, and consulting editor.

We can never thank him enough for his prompt and systematic editing of this book. He is forever our friend.

PREFACE TO THE FIRST EDITION

This book presents the developed concepts, theories, and laboratory procedures as related to the porous rock properties and their interactions with fluids (gases, hydrocarbon liquids, and aqueous solutions). The properties of porous subsurface rocks and the fluids they contain govern the rates of fluid flow and the amounts of residual fluids that remain in the rocks after all economical means of hydrocarbon production have been exhausted. It is estimated that the residual hydrocarbons locked in place after primary and secondary production, on a worldwide scale, is about 40% of the original volume in place. This is a huge hydrocarbon resource target for refined reservoir characterization (using the theories and procedures of petrophysics) to enhance the secondary recovery or implement tertiary (EOR) recovery. The use of modern methods for reservoir characterization with a combination of petrophysics and mathematical modeling is bringing new life into many old reservoirs that are near the point of abandonment. This book brings together the theories and procedures from the scattered sources in the literature.

In order to establish the basis for the study of rock properties and rock-fluid interactions, the first two chapters are devoted to a review of mineralogy, petrology, and geology. Next, the two rock properties that are perhaps the most important for petroleum engineering, i.e., porosity and permeability, are presented in detail in Chapter 3. Finally, the problem of porosity-permeability correlation has been solved. The subjects of Chapter 4 are the electrical resistivity and water saturation of rocks which are the basis for well logging techniques. The next chapter takes up the theories and applications of capillary pressure and wettability to various phenomena associated with fluid-saturated rocks, such as residual saturations due to fluid trapping, variations of relative permeabilities, effects on production, and the measurements and use of capillary pressure for determination of pore size distributions and wettability. Chapter 6 is devoted exclusively to the applications of Darcy's Law to linear, radial, laminar, and turbulent flows, and multiple variations of permeability and porosity in rocks.

Chapter 7 presents an introduction to the important topic of rock mechanics by considering rock deformation, compressibility, and the effects of stress on porosity and permeability. The book ends with a discussion of rock-fluid interactions associated with various types of formation damage. Finally, a set of 19 laboratory procedures for determination of the rock and fluid properties, and rock-fluid interactions—which are presented in the eight chapters of the book—are included in an Appendix.

In addition to detailed experimental procedures, the authors have included examples for each experiment. Although this book was primarily organized and prepared for use as a textbook and laboratory manual, it also will serve as a reference book for petroleum engineers and geologists, and can be used in petrophysical testing laboratories. It is the first comprehensive book published on the subject since 1960 (J. W. Amyx, D. M. Bass, Jr., and R. L. Whiting, *Petroleum Reservoir Engineering*, McGraw-Hill, New York, NY). The book also can serve as the basis for the advancement of theories and applications of petrophysics as the technology of petroleum engineering continues to improve and evolve. This unique book belongs on the bookshelf of every petroleum engineer and petroleum geologist.

Djebbar Tiab
Erle C. Donaldson
George V. Chilingar

Preface to the Second Edition

This second edition of *Petrophysics* has been designed to amplify the first volume (from 8 to 10 chapters) and comply with suggestions from colleagues and numerous readers who were generous in taking time to convey their advice.

Readers will find that the first chapter, an introduction to mineralogy, has been considerably amplified to assist in better recognition of the multitude of minerals and rocks. There was no noticeable change to Chapter 2 (Introduction to Petroleum Geology), Chapter 7 (Applications of Darcy's Law), or Chapter 10 (Fluid-Rock Interactions).

Chapter 3 (Porosity and Permeability) underwent major changes. The following topics were added: concept of flow units, directional permeability, correlations between horizontal and vertical permeability, averaging techniques, Dykstra-Parsons coefficient of permeability variation, effective permeability from cores and well test data, and several more examples. Chapter 4 (Formation Resistivity and Water Saturation) was amplified, mainly to include the characterization and identification of flow units in shaly formations, and more examples. Chapter 5 of the first edition was divided into two new chapters: Chapter 5 (Capillary Pressure) and Chapter 6 (Wettability), because of the large amount of work that has been conducted on wettability since the publication of the first edition. Capillary pressure and wettability are, however, bound together because much of the basis for various tests and theories of wettability and its impact on oil recovery is based on capillary pressure behavior as a function of fluid saturation. It seems natural, therefore, that a thorough understanding of capillary pressure is necessary for the study of wettability.

Chapter 8 (Naturally Fractured Reservoirs) is a new chapter. Practically all readers who contacted us suggested that we include a more detailed discussion of the petrophysical aspects of naturally fractured rocks. The main topics covered in this chapter are: geological and engineering classifications of natural fractures, indicators of natural fractures, determination of fracture porosity and permeability, fracture intensity index, porosity partitioning coefficient, and effect of fracture shape on permeability. A new concept of hydraulic radius of fracture is introduced in this chapter. Methods for determining the fracture storage capacity and inter-porosity from well test data are briefly discussed.

Several important topics were added to Chapter 9 (Effect of Stress on Reservoir Rock Properties): the effect of change in the stress field due to depletion and repressurization, stress and critical borehole pressure in vertical and horizontal wells, critical pore pressure, and estimation of unconfined compressive rock strength from porosity data.

The Appendix, covering petrophysics laboratory experiments, is essentially the same because the basic methods for the experimental study of petrophysics have not changed very much. A recently developed general method for calculation of relative permeability, however, was included in Experiment 12. The procedure is applicable to both constant rate and constant pressure unsteady state displacement.

Djebbar Tiab
Erle C. Donaldson

UNITS

Units of Area

acre = 43,540 ft^2 = 4046.9 m^2
ft^2 = 0.0929 m^2
hectare = 10,000 m^2

Constants

Darcy = 0.9869 mm^2
Gas constant = 82.05 (atm × cm^3)/(g mol × K)
= 10.732 (psi × ft^3)/(lb mol × °R)
= 0.729 (atm × ft^3)/(lb mol × °R)
Mol. wt. of air = 28.97

Units of Length

Angstrom = 1×10^{-8} cm
cm = 0.3937 in.
ft = 30.481 cm
in. = 2.540 cm
km = 0.6214 mile
m = 39.370 in. = 3.2808 ft

Units of Pressure

atm = 760 mm Hg (0°C) = 29.921 in. Hg = 14.696 psi
atm = 33.899 ft water at 4°C
bar = 14.5033 psi = 0.987 atm = 0.1 MPa
dyne/cm^2 = 6.895 kPa (kilopascal)
ft water = 0.4912 psi
kg(force)/cm^2 = 14.223 psi
psi = 2.036 in. Hg (0°C) = 6.895 kPa

Units of Temperature

Degrees Fahrenheit (°F) = 1.8°C + 32
Degrees Rankine (°R) = 459.7 +°F
Degrees Kelvin (K) = 273.16 +°C

Units of Volume

acre-ft = 43,560 ft^3 = 7,758.4 bbl = 1.2335×10^3 m^3
bbl = 42 US gal = 5.6145 ft^3 = 0.1590 m^3
cu ft (ft^3) = 7.4805 gal = 0.1781 bbl = 0.028317 m^3
cu in. (in^3) = 16.387 cm^3
cu m (m^3) = 6.2898 bbl
gal = 231 in^3 = 3785.43 cm^3
molarity = mass of solute equal to the molecular weight per 1,000 grams of solvent
normality = equivalent weight of solute per 1,000 grams of solvent (mass of solute equal to the molecular weight divided by the valence per 1,000 g of solvent)

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