

SECOND EDITION

Reservoir Formation Damage

FUNDAMENTALS,
MODELING, ASSESSMENT,
AND MITIGATION



Faruk Civan



RESERVOIR FORMATION DAMAGE

**FUNDAMENTALS,
MODELING,
ASSESSMENT, AND
MITIGATION**

Second Edition

Faruk Civan



ELSEVIER

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 is an imprint of Elsevier
30 Corporate Drive, Suite 400, Burlington, MA 01803, USA
Linacre House, Jordan Hill, Oxford OX2 8DP, UK

Copyright © 2007, Elsevier Inc. All rights reserved.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of the publisher.

Permissions may be sought directly from Elsevier's Science & Technology Rights Department in Oxford, UK: phone: (+44) 1865 843830, fax: (+44) 1865 853333, E-mail: permissions@elsevier.com. You may also complete your request on-line via the Elsevier homepage (<http://elsevier.com>), by selecting "Support & Contact" then "Copyright and Permission" and then "Obtaining Permissions."

- ☞ Recognizing the importance of preserving what has been written, Elsevier prints its books on acid-free paper whenever possible.

Library of Congress Cataloging-in-Publication Data

Civan, Faruk.

Reservoir formation damage / Faruk Civan.—2nd ed.
p. cm.

Includes bibliographical references and index.

ISBN-13: 978-0-7506-7738-7 (acid-free paper)

ISBN-10: 0-7506-7738-4 (acid-free paper) 1. Hydrocarbon reservoirs.

2. Petroleum—Geology. I. Title.

TN870.57.C58 2007

622'.338—dc22

2006036419

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

ISBN 13: 978-0-7506-7738-7

ISBN 10: 0-7506-7738-4

For information on all Gulf Professional Publishing
publications visit our Web site at www.books.elsevier.com

Printed in the United States of America

07 08 09 10 9 8 7 6 5 4 3 2 1

**Working together to grow
libraries in developing countries**

www.elsevier.com | www.bookaid.org | www.sabre.org

ELSEVIER

BOOK AID
International

Sabre Foundation

PREFACE

Formation damage is an undesirable operational and economic problem that can occur during the various phases of oil and gas recovery from subsurface reservoirs including production, drilling, hydraulic fracturing, and workover operations. Formation damage assessment, control, and remediation are among the most important issues to be resolved for efficient exploitation of hydrocarbon reservoirs. Such damage is caused by various adverse processes including chemical, physical, biological, and thermal interactions of formation and fluids, and deformation of formation under stress and fluid shear. Formation damage indicators include permeability impairment, skin damage, and decrease of well performance. The properly designed experimental and analytical techniques presented in this book can help understanding, diagnosis, evaluation, prevention, and controlling of formation damage in oil and gas reservoirs.

This book provides an understanding of the fundamentals of the relevant processes causing formation damage and reducing the flow efficiency in the near-wellbore formation during the various phases of oil and gas production; an update review of the various approaches used in the modeling and simulation of formation damage for model-assisted analysis and interpretation of laboratory core tests, and for prediction and control of formation damage; and the techniques used for assessment, diagnosis, minimization, and control of formation damage in petroleum reservoirs. It focuses on the theory, modeling, and simulation of the rock, fluid, and particle interactions, fluid and particle invasion, filter cake, in situ mobilization, migration, and deposition of fines, organic and inorganic precipitation and scale formation, alteration of porosity, permeability, and

texture in laboratory cores and reservoir formations, and the effects of single- and multiphase fluid systems.

Formation damage is evolving to be more science than art. Formation damage is an interesting interdisciplinary subject that attracts many researchers. Cost-effective mitigation of formation damage is still as much art as science. This book is a recapitulation of the present state-of-the-art knowledge in the area of formation damage. It is intended to be a convenient source of information, widely spread over different sources. I have tried to cover the relevant material with sufficient detail, without overwhelming the readers. This book can be used by those who are engaged in the various aspects of formation damage problems associated with the production of hydrocarbons from subsurface reservoirs. It may serve as a useful reference and provides the knowledge of the theoretical and practical aspects of formation damage for various purposes, including model-assisted interpretation of experimental test data, prediction and simulation of various formation damage scenarios, evaluation of alternative strategies for formation damage minimization, and scientific guidance for conducting laboratory and field tests.

Exhaustive effort has been made to gather, analyze, and systematically present the state-of-the-art knowledge accumulated over the years in the area of formation damage in petroleum reservoirs. This book is intended to provide a quick and coordinated overview of the fundamentals, and the experimental and theoretical approaches presented in selected publications. However, it should not be viewed as a complete encyclopedic documentation of the reported studies. It discusses processes causing formation damage and reducing the productivity of wells in petroleum reservoirs and systematically presents various approaches used in the diagnoses, measurement, evaluation, and simulation of formation damage. The techniques for assessment, minimization, control, and remediation of the reservoir formation damage are described.

This book is intended for the petroleum, chemical, and environmental engineers, geologists, geochemists, and physicists involved in formation damage control, and for the undergraduate senior and graduate petroleum engineering students. The material presented in this book originates from my industry short courses and curriculum courses at the Mewbourne School of Petroleum and Geological Engineering at the University of Oklahoma. This book can be used in industry training courses and undergraduate senior and graduate level petroleum engineering courses. It is recommended for formation damage courses and as a companion for drilling, production, and stimulation courses. Readers will

- learn the mechanisms and theoretical background of the common formation damage processes
- be familiar with the testing, modeling, and simulation techniques available for formation damage assessment
- be able to develop strategies for better management of the adverse processes to minimize and avoid formation damage in petroleum reservoirs.

I am indebted to the researchers who have contributed to the understanding and handling of the various issues and aspects of formation damage and mitigation. Their efforts have led to the accumulation of a substantial amount of knowledge and expertise on formation damage and helped develop techniques and optimal strategies for effective detection, evaluation, and mitigation of formation damage in subsurface reservoirs. Their works have been published in various literatures. I am pleased to have had the opportunity to analyze, integrate, transfer, and present the state-of-the-art knowledge of formation damage in a consistent manner in one source for the readers of this book, based on more than 870 references. I believe that most effective learning is through teaching. I have enjoyed such exercise as it provided tremendous opportunities to others to benefit from my teaching.

Many of the figures, tables, and other relevant materials used in the preparation of this book were extracted from the literature published by various researchers, companies, and organizations. These include the following: Academic Press; AAPG – American Association of Petroleum Geologists; ACS – American Chemical Society; AGU – American Geophysical Union; AIChE – American Institute of Chemical Engineers; American Institute of Physics; API – American Petroleum Institute; ASME – American Society of Mechanical Engineers; A.A. Balkema Publisher; Baroid Drilling Fluids, Inc.; Canadian Institute of Mining, Metallurgy and Petroleum; *Chemical Processing* magazine; Chemicky Prumysl; Computational Mechanics, Inc.; Elsevier Science, The Geological Society Publishing House, IEEE – Institute of Electrical and Electronics Engineers, Inc.; ICheme-Institute of Chemical Engineers; International Institute for Geothermal Research, Italy; Illinois State Geological Survey; John Wiley & Sons Limited; Marcel Dekker, Inc.; M-I L.L.C.; OSA – The Optical Society of America; Petroleum Society of CIM; Plenum Press; Routledge/Taylor & Francis Group LLC.; Sarkeys Energy Center at the University of Oklahoma; SPE – Society of Petroleum Engineers; Springer-Verlag; SPWLA – Society of

Professional Well Log Analysts; Springer Science and Business Media, The American Oil & Gas Reporter; Transportation Research Board; National Academies, Washington, D.C.; *Turkish Journal of Oil and Gas*; and the U.S. Department of Energy. In addition, G. Atkinson, B. Bennett, T. Dewers, A. Hayatdavoudi, I. B. Ivanov, P. R. Johnson, P. A. Kralchevsky, R. Philip, T. S. Ramakrishnan, M. M. Reddy, M. Sahimi, G. W. Schneider, H. Tamura, K. J. Weber, and D. F. Zwager allowed the use of materials from their publications. B. Seyler of the Illinois State Geological Survey provided the photographs included in the book. The permission for use of these materials in this book is gratefully acknowledged.

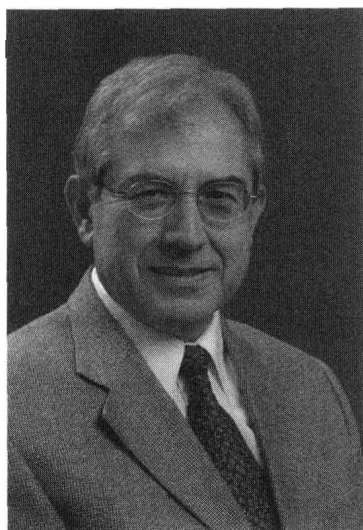
I am also grateful to Elsevier – Gulf Professional Publishing Company, Andrea Sherman and Julie Ochs, Integra Software Services Pvt. Ltd., India, and Kalpalathika Rajan for their support in the preparation and realization of the second edition of this book. Special thanks are due to Susan Houck for her care in typing the manuscript of the first edition of this book. I have typed all the additional materials included in the second edition.

This book provides a broad background and knowledge on the practical and theoretical aspects of the various problems dealing with the processes and operations causing formation damage in subsurface geological porous formations. I wish that this book will be a convenient, informative, and useful companion for those involved in the reservoir formation damage issues at various capacities, from practitioners to academicians.

Faruk Civan, Ph.D.
Norman, Oklahoma, U.S.A.

While every effort was made to identify copyright holders and obtain permission for the re-use of all material with a third-party copyright that appears in this book, it is possible that there are items herein that are not correctly acknowledged, or for which we were unable to trace the copyright holder, or unable to obtain permission for re-use. If you are aware of any such case, please notify the publishers and the omission or error will be rectified in future printings of this book.

ABOUT THE AUTHOR



Faruk Civan is an Alumni Professor of the Mewbourne School of Petroleum and Geological Engineering at the University of Oklahoma in Norman. Previously, he worked in the Chemical Engineering department at the Technical University of Istanbul, Turkey.

Dr. Civan received an Advanced Engineering Degree from the Technical University of Istanbul, Turkey; an MS degree from the University of Texas at Austin, Texas; and a PhD degree from the University of Oklahoma, Norman, Oklahoma. All of his degrees are in chemical engineering.

Dr. Civan specializes in petrophysics and reservoir characterization; formation and well damage modeling, diagnosis, assessment, and mitigation; reservoir and well analyses, modeling, and simulation; natural gas engineering, measurement, processing, hydrates, transportation, and storage; carbon dioxide sequestration; coal-bed methane production; improved reservoir recovery techniques; corrosion protection in oil and gas wells; filtration and separation techniques; and air, water, and ground pollution modeling and control.

He has published more than 200 technical articles in journals, edited books, handbook, and encyclopedia, and conference proceedings, and presented 85 invited seminars and/or lectures at various technical meetings, companies, and universities. He teaches industry short courses on

a number of topics worldwide. Additionally, he has written numerous reports on his funded research projects. Dr. Civan's publications have been cited frequently in various publications, as reported by the Science Author Citation Index.

Dr. Civan has received 20 honours and awards, including five distinguished lectureship awards and the 2003 SPE Distinguished Achievement Award for Petroleum Engineering Faculty.

He is a member of the Society of Petroleum Engineers, the American Society of Mechanical Engineers, and the American Institute of Chemical Engineers. Dr. Civan serves as a member of the editorial boards of the *Journal of Petroleum Science and Engineering*, *Turkish Oil and Gas Journal*, *Journal of Porous Media*, and *Journal of Energy Resources Technology*. He has served on numerous petroleum and chemical engineering, and other related conferences and meetings in various capacities, including as committee chairman and member, session organizer, chair or co-chair, instructor, and as member of the editorial board of the *Society of Petroleum Engineers Reservoir Engineering Journal* and the special authors series of the *Journal of Petroleum Technology*.

CONTENTS

Preface, *xv*

About the author, *xix*

1 Overview of Formation Damage..... 1

Introduction, 1; Common Formation Damage Problems, Factors, and Mechanisms, 5; Team for Understanding and Mitigation of Formation Damage, 7; Objectives of the Book, 7

PART I Characterization of Reservoir Rock for Formation Damage – Mineralogy, Texture, Petrographics, Petrophysics, and Instrumental Techniques..... 11

2 Mineralogy and Mineral Sensitivity of Petroleum-Bearing Formations 13

Introduction, 14; Origin of Petroleum-Bearing Formations, 14; Constituents of Sedimentary Rocks, 15; Composition of Petroleum-Bearing Formations, 16; Mineral Sensitivity of Sedimentary Formations, 18; Mechanism of Clay Swelling, 28; Modeling Clay Swelling, 34; Cation Exchange Capacity, 56; Shale Swelling and Stability, 63

3 Petrographical Characteristics of Petroleum-Bearing Formations.....	78
Introduction, 78; Petrographical Characteristics, 79; Morphology of Dispersed Clays in Sandstones, 93; Rock Damage Tendency and Formation Damage Index Number, 95; Reservoir Characterization, 99	
4 Petrophysics – Flow Functions and Parameters	101
Introduction, 101; Wettability Alteration, 102; Dependence of End-Point Saturations to Porosity and Permeability, 108; Alteration of Flow Functions: Capillary Pressure and Relative Permeability, 111; Temperature Dependency of the Rock Wettability, 116; Effect of Temperature on Formation Damage, 119; Effect of Morphology of Dispersed Clays on Capillary Pressure and Relative Permeability in Sandstones, 121	
5 Porosity and Permeability Relationships of Geological Formations.....	125
Introduction, 125; Basic Models for Permeability of Rocks, 126; Special Effects, 137; Advanced Applications, 139	
6 Instrumental and Laboratory Techniques for Characterization of Reservoir Rock.....	154
Introduction, 154; Formation Evaluation (FE), 155; Instrumental Laboratory Techniques, 158	
PART II Characterization of the Porous Media Processes for Formation Damage – Accountability of Phases and Species, Rock–Fluid-Particle Interactions, and Rate Processes.....	175
7 Multiphase and Multispecies Transport in Porous Media.....	177
Introduction, 177; MultiPhase and Species Systems in Porous Media, 178; Alternative Expressions of Various Species and Flow for Systems in Porous Media, 179; MultiSpecies and MultiPhase Macroscopic Transport Equations, 184	

8	Particulate Processes in Porous Media	191
	Introduction, 191; Particulate Processes, 193; Properties Affecting Particles, 194; Forces Acting Upon Particles, 195; Rate Equations for Particulate Processes in Porous Matrix, 203; Particulate Phenomena in Multiphase Systems, 220; Temperature Effect on Particulate Processes, 227	
9	Crystal Growth and Scale Formation in Porous Media.....	235
	Introduction, 235; Types of Precipitation, 236; Solid–Liquid Equilibrium and Solubility Equation, 237; Crystallization Phenomena, 239; Particle Growth and Dissolution in Solution, 249; Scale Formation and Dissolution at the Pore Surface, 250; Crystal Surface Pitting and Displacement by Dissolution, 253	
PART III	Formation Damage by Particulate Processes-Fines Mobilization, Migration, and Deposition	257
10	Single-Phase Formation Damage by Fines Migration and Clay Swelling	259
	Introduction, 259; Algebraic Core Impairment Model, 260; Ordinary Differential Compartments-in-Series Core Impairment Model, 273; Simple Partial Differential Core Impairment Model, 277; Partial Differential Core Impairment Model Considering the Clayey Formation Swelling and both the Indigenous and the External Particles, 279; Plugging–Nonplugging Parallel Pathways Partial Differential Core Impairment Model, 285; Model-Assisted Analysis of Experimental Data, 292	
11	Multiphase Formation Damage by Fines Migration	317
	Introduction, 317; Formulation of a Multiphase Formation Damage Model, 318; Model-Assisted Analysis of Experimental Data, 331	
12	Cake Filtration: Mechanism, Parameters, and Modeling	341
	Introduction, 342; Incompressive Cake Filtration without Fines Intrusion, 345; Compressive Cake Filtration Including Fines Invasion, 374	

PART IV Formation Damage by Inorganic and Organic Processes – Chemical Reactions, Saturation Phenomena, Deposition, and Dissolution..... 405

13 Inorganic Scaling and Geochemical Formation Damage..... 407

Introduction, 407; Geochemical Phenomena—Classification, Formulation, Modeling, and Simulation, 410; Reactions in Porous Media, 412; Geochemical Modeling, 421; Graphical Description of the Rock–Fluid Chemical Equilibrium, 426; Geochemical Model–Assisted Analysis of Fluid–Fluid and Rock–Fluid Compatibility, 431; Geochemical Simulation of Rock–Fluid Interactions in Brine-Saturated Sedimentary Basins, 456

14 Formation Damage by Organic Deposition..... 468

Introduction, 468; Characteristics of Asphaltenic Oils, 471; Mechanisms of the Heavy Organic Deposition, 477; Asphaltene and Wax Phase Behavior, 479; Prediction of Asphaltene Stability and Measurement (detection) of the Onset of Asphaltene Flocculation, 502; Algebraic Model for Formation Damage by Asphaltene Precipitation in Single Phase, 514; Plugging–Nonplugging Pathways Model for Asphaltene Deposition in Single Phase, 516; Two-Phase and Dual-Porosity Model for Simultaneous Asphaltene–Paraffin Deposition, 521; Single-Porosity and Two-Phase Model for Organic Deposition, 532

PART V Assessment of the Formation Damage Potential – Testing, Simulation, Analysis, and Interpretation 557

15 Laboratory Evaluation of Formation Damage..... 559

Introduction, 559; Fundamental Processes of Practical Importance for Formation Damage in Petroleum Reservoirs, 561; Selection of Reservoir-Compatible Fluids, 562; Experimental Setup for Formation Damage Testing, 564; Recommended Practice for Laboratory Formation Damage Tests, 577; Protocol for Standard Core Flood Tests, 588; Laboratory Procedures for Evaluation of Common Formation Damage Problems, 595; Evaluation of the Reservoir Formation Damage Potential by Laboratory Testing – a Case Study, 616

16 Formation Damage Simulator Development 645

Introduction, 645; Description of Fundamental Model Equations, 647; Numerical Solution of Formation Damage Models, 649; Ordinary Differential Equations, 651; Partial Differential Equations, 655

17 Model-Assisted Analysis and Interpretation of Laboratory and Field Tests 670

Introduction, 671; Measurement Error, 673; Model Validation, Refinement, and Parameter Estimation, 682; Formation Damage Potential of Stimulation and Production Techniques, 689; Reactive-Transport Simulation of Dolomitization, Anhydrite Cementation, and Porosity Evolution, 718; Impact of Scale Deposition in a Reservoir, 720; Simulation of fine particle mobilization, migration, and deposition in a core plug, 727

PART VI Formation Damage Models for Fields Applications-Drilling Mud Invasion, Injectivity of Wells, Sanding and Gravel-Pack Damage, and Inorganic and Organic Deposition..... 739

18 Drilling Mud Filtrate and Solids Invasion and Mudcake Formation 741

Introduction, 741; Depth of Mud Damage Correlation, 746; Single-Phase Mud Filtrate Invasion Model, 747; Two-Phase Wellbore Mud Invasion and Filter Cake Formation Model, 751; Near-Wellbore Filtrate Invasion, 755; Dynamically-Coupled Mudcake Build-up and Immiscible Multiphase Filtrate Invasion, 758; Drilling Mud Loss into Naturally Fractured Reservoirs, 762

19 Injectivity of the Waterflooding Wells..... 775

Introduction, 775; Injectivity of Wells, 777; Water Quality Ratio (WQR), 780; Single-Phase Filtration Processes, 787; Diagnostic-Type Curves for Water Injectivity Tests, 800; Injection Rate Decline Function, 802; Field Applications, 802

**20 Reservoir Sand Migration and Gravel-Pack Damage:
Stress-Induced Formation Damage, Sanding Tendency,
and Prediction 814**

Introduction, 814; Prediction of Sanding Conditions Using a Simple Model, 816; Prediction of Massive Sand Production Using a Differential Model, 817; Modeling Sand Retention in Gravel-Packs, 823; Reservoir Compaction and Subsidence, 824

21 Near-Wellbore Formation Damage..... 829

Introduction, 829; Modeling Near-Wellbore Deposition and Its Effect on Well Performance, 831; Near-Wellbore Sulfur Deposition, 836; Near-Wellbore Calcite Deposition, 840; Near-Wellbore Asphaltene Deposition, 842

**PART VII Diagnosis and Mitigation of Formation
Damage—Measurement, Assessment,
Control, and Remediation..... 857**

**22 Field Diagnosis and Measurement
of Formation Damage 859**

Introduction, 859; Diagnosis and Evaluation of Formation Damage in the Field, 860; Pseudo-Damage vs. Formation Damage, 863; Measures of Formation Damage, 864; Model-Assisted Estimation of Skin Factor, 873; Model-Assisted Analysis of the Near-Wellbore Permeability Alteration Using Pressure Transient Data, 873; Productivity Decline Caused by Mud Invasion into Naturally Fractured Reservoirs, 878; Continuous Real Time Series Analysis for Detection and Monitoring Formation Damage Effects, 881; Formation Damage Expert System, 886

**23 Determination of Formation Damage and
Pseudo-Damage from Well Performance-Identification,
Characterization, and Evaluation 889**

Introduction, 890; Completion Damage and Flow Efficiency, 891; Formation Damage Assessment in the Field by Well surveillance, 902; Well-Testing Techniques, reservoir parameters, and interpretation methods, 904; Components of the Total Skin Factor, 915; Variable skin factor, 929

**24 Formation Damage Control
and Remediation – Conventional Techniques and
Remedial Treatments for Common Problems 937**

Introduction, 938; Selection of Treatment Fluids, 941; Clay Stabilization, 942; Clay and Silt Fines, 948; Effect of Drilling Fluids on Shale Stability, 949; Bacterial Damage, 953; Inorganic Scales, 954; Organic Deposits, 956; Mixed Organic/Inorganic Deposits, 959; Formation Damage Induced by Completion-Fluids and Crude-Oil Emulsions, 959; Wettability Alteration and Emulsion and Water Blocks, 960; Intense Heat Treatment, 960; Sand Control, 960; Well Stimulation, 968; Recapitalization of the Methods for Formation Damage Mitigation, 969; Sandstone and Carbonate Formation Acidizing, 969; Water Injectivity Management, 981; Controlling the Adverse Side Effects of Remedial Treatments, 982

**25 Reservoir Formation Damage Abatement – Guidelines,
Methodology, Preventive Maintenance, and
Remediation Treatments 985**

Introduction, 986; Comprehensive Methodology for Mitigation of Formation Damage, 989; Treatment Fluid Application Methods, 1010; Thermal and Hydraulic Coupling of Wellbore with Reservoir During Remedial Fluid Treatments Illustrated for Hydraulically Fractured Well Acidizing, 1011

References, 1028

Index, 1091

OVERVIEW OF FORMATION DAMAGE

Summary

A comprehensive review of the various types of formation damage problems encountered in petroleum reservoirs is presented. The factors and processes causing these problems are described in detail. The design of a team effort necessary for understanding and controlling of the formation damage problems in the field is explained. The motivation for the writing of this book and the specific objectives are stated. The approach taken in the presentation of the materials in this book is explained. A brief executive summary of the topics covered in the book is given. The roles played by different professionals, such as the petroleum and chemical engineers, chemists, physicist, geologists, and geochemists, are described.

1.1 INTRODUCTION

Formation damage is a generic terminology referring to the impairment of the permeability of petroleum-bearing formations by various adverse processes. Formation damage is an undesirable operational and economic problem that can occur during the various phases of oil and gas recovery from subsurface reservoirs including drilling, production, hydraulic fracturing, and workover operations (Civan, 2005). As expressed by Amaefule et al. (1988), "Formation damage is an expensive headache to the oil and gas industry." Bennion (1999) described formation damage as, "The impairment of the invisible, by the inevitable and uncontrollable, resulting in an indeterminate reduction of the unquantifiable!" Formation damage assessment, control, and remediation are among the most important