

Springer Theses

Recognizing Outstanding Ph.D. Research

Aims and Scope

The series “Springer Theses” brings together a selection of the very best Ph.D. theses from around the world and across the physical sciences. Nominated and endorsed by two recognized specialists, each published volume has been selected for its scientific excellence and the high impact of its contents for the pertinent field of research. For greater accessibility to non-specialists, the published versions include an extended introduction, as well as a foreword by the student’s supervisor explaining the special relevance of the work for the field. As a whole, the series will provide a valuable resource both for newcomers to the research fields described, and for other scientists seeking detailed background information on special questions. Finally, it provides an accredited documentation of the valuable contributions made by today’s younger generation of scientists.

Theses are accepted into the series by invited nomination only and must fulfill all of the following criteria

- They must be written in good English.
- The topic should fall within the confines of Chemistry, Physics, Earth Sciences, Engineering and related interdisciplinary fields such as Materials, Nanoscience, Chemical Engineering, Complex Systems and Biophysics.
- The work reported in the thesis must represent a significant scientific advance.
- If the thesis includes previously published material, permission to reproduce this must be gained from the respective copyright holder.
- They must have been examined and passed during the 12 months prior to nomination.
- Each thesis should include a foreword by the supervisor outlining the significance of its content.
- The theses should have a clearly defined structure including an introduction accessible to scientists not expert in that particular field.

More information about this series at <http://www.springer.com/series/8790>

Shib Sankar Ganguli

Integrated Reservoir Studies for CO₂-Enhanced Oil Recovery and Sequestration

Application to an Indian Mature Oil Field

Doctoral Thesis accepted by
Academy of Scientific and Innovative Research

Author

Dr. Shib Sankar Ganguli
Academy of Scientific and Innovative
Research (AcSIR)/CSIR-National
Geophysical Research Institute
Hyderabad, Telangana State
India

Supervisor

Prof. V.P. Dimri
CSIR-National Geophysical Research
Institute
Hyderabad, Telangana State
India

ISSN 2190-5053

Springer Theses

ISBN 978-3-319-55842-4

DOI 10.1007/978-3-319-55843-1

ISSN 2190-5061 (electronic)

ISBN 978-3-319-55843-1 (eBook)

Library of Congress Control Number: 2017934318

© Springer International Publishing AG 2017

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. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer imprint is published by Springer Nature

The registered company is Springer International Publishing AG

The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Dedicated to my beloved parents

*Thank you for instilling in me the virtues of
perseverance and commitment and
encouraging me to strive for excellence.*

Supervisor's Foreword

It gives me immense pleasure to write the foreword of this excellent Ph.D. work. It is very widely accepted that CO₂ sequestration through enhanced oil recovery (EOR) can aid to climate change mitigation by reducing about 20% of CO₂ emission in the atmosphere. CO₂-EOR and sequestration is a cutting edge and imminent research in India, and there is an urgent need for the assessment of Indian hydrocarbon reservoirs for feasible CO₂-EOR and storage. This involves integrated reservoir studies such as reservoir flow modeling and simulation, rock physics, and seismic to recommend better cost-effective and technologically efficient CO₂-EOR and storage model, in particular for an Indian mature oil field.

Shib Sankar Ganguli was seriously involved in this joint Indo-Norwegian project funded by Norwegian Embassy in India and conducted his Ph.D. work in National Geophysical Research Institute, since 2011. One of the most challenging queries of this study was how to identify an Indian mature hydrocarbon field which would be feasible for CO₂-EOR followed by permanent storage, prior to its abandonment, with limited data provided by the operator. Moreover, as per the review by the operator, the studied field is not suitable for miscible CO₂ injection. In this view, I must admit that Shib has worked hard and come up with an outstanding scientific solution by developing a new injection scheme for miscible CO₂ displacement and better CO₂ EOR and storage model for Cambay Basin, India.

This work contributes significantly to the feasibility study of CO₂-EOR and sequestration in an Indian mature oil field for the first time in India with cross-disciplinary approach that combines the results from reservoir modeling and flow simulation, rock physics modeling, geomechanics, and time-lapse (4D) seismic monitoring study. The key findings of this work indicate that the field under study has great potential for EOR followed by CO₂ storage just after its economic abandonment. Just as certainly, I strongly believe this work is not only limited to

Indian mature oil fields, but also can be implemented anywhere in the world if justified properly with integrated approach. Moreover, this study provides a valuable resource and can be treated as a base work which can aid to better understanding of CO₂-EOR and storage in future. My heartiest congratulations go to Shib for this excellent piece of work.

Hyderabad, India
December 2016

Prof. V.P. Dimri

Parts of this thesis have been published in the following journal articles:

Ganguli, S. S., Vedanti, N., Akervoll, I., & Dimri, V. P. (2016a). Assessing the Feasibility of CO₂-Enhanced Oil Recovery and Storage in Mature Oil Field: A Case Study from Cambay Basin. *Jour. of Geol. Soc. of India*, 88(3), 273–280.

Ganguli, S. S., Vedanti, N., & Dimri, V. P. (2016b). 4D reservoir characterization using well log data for feasible CO₂-enhanced oil recovery at Ankleshwar, Cambay Basin-a rock physics diagnostic and modelling approach. *Jour. of Applied Geophy.*, 135, 111–121.

Acknowledgements

My journey to get a Ph.D. degree from Academy of Scientific and Innovative Research (AcSIR) at CSIR-National Geophysical Research Institute (NGRI) has been the most delightful, eloquent, and enriching experience for me. During this journey, I am obliged to the people, without whom significant contributions and support this dissertation would have not been possible.

First and foremost, I would like to acknowledge the kind support and encouragement of Prof. V.P. Dimri. I have been fortunate to have him as my Ph.D. mentor. He is an outstanding teacher, mentor, scientist, and most importantly a great human being with immense knowledge, insights, experience, patience, and time. He has not only shaped my thesis, but also shaped me from a naïve student to a researcher, and for that I am indebted to him. Thank you for caring not only about my research, but about my personal matters, my frustrating enquiries, nurturing my future, etc. I am truthfully obliged to him for believing on me, providing freedom all the time and energy on me more than past 4 years.

The next person whom I would like to thank is Dr. Nimisha Vedanti, my Ph.D. Co-supervisor. She has been a great source of support for my research, both in educational and financial aspects. She has been the project in-charge of research group dealing with Indo-Norwegian collaboration project on CO₂-EOR study at CSIR-NGRI, which is unique and exciting group to do research, and I am thankful to her for giving me the opportunity to work with this group. Whenever, my research work seemed like tough work, she has provided great encouragement to complete the assignments.

I would like to express my gratitude to Prof. Mrinal K. Sen, Dr. S.K. Ghosh, and Dr. Kalachand Sain, members of my Doctorial Advisory Committee (DAC) of AcSIR, CSIR-NGRI for their priceless guidance and support during my Ph.D. journey. I have been fortunate to have their technical comments/suggestions to improve my research.

I wish to thank Dr. R.K. Tiwari, Coordinator, AcSIR for providing constant support and motivation. It was really fruitful to have his motivational words for continuing career in research.

I am fortunate to avail two financial supports to complete my Ph.D., a part of which was borne by The Royal Norwegian Embassy at New Delhi, and CSIR-Senior Research Fellowship. My sincere thanks to ONGC Pvt. Ltd. for sharing data with me to complete the thesis.

In 2013, I did internship with SINTEF Petroleum Research at Trondheim, Norway, and it was awesome to interact with Dr. Idar Akervoll, Dr. Per E Bergmo, Dr. R. Holt, Dr. Lindeberg, Dr. Dag, and others. The advice I received from them was a turning point and I returned with great many ideas which helped me to shape this thesis.

To Dr. Om P. Pandey, thank you for spending your valuable time with me discussing my research problems and providing direction to solve those.

I extend my sincere gratitude to Dr. R.P. Srivastava for inspiring and making me realize for the first time that Ph.D. degree would be a better option for sustainable career. He was truly a great support during my early career at NGRI. My sincere thanks are also due to Dr. Kirti Srivastava, Dr. A.R. Bansal, Dr. A. Chamoli, and all other former and present research members of theoretical and computational research group for giving me such a great opportunity to discuss my work with them.

I would like to extend my special gratefulness to Dr. Prakash Kumar for showing me the importance of everlasting curiosity in science and providing technical suggestions whenever I discuss with him. Thanks to Dr. Biswajit Mandal and Dr. M. Ojha for giving me continuous encouragement and guidance, starting from the day one to the last day of my Ph.D.

My special thanks to my lovely friends Sunil, Upananda, Anoop, and Arjun for their love and support during this wonderful journey. Thanks to Uma, Ajay, Ahmed, Deepak, Parveen, Nagarjuna, and Swamy for every kind of support during my research at NGRI. My special regards to Mrs. Vani for taking care of all administrative works at AcSIR.

Last but not the least, I deeply indebted to my parents, sisters, and fiancée, Pallavi, for their extraordinary love, patience, and encouragement. Huge thanks to Pallavi for walking beside me through every difficult situations of my journey to Ph.D. I would have not finished this dissertation without her constant support. I dedicate this dissertation to my parents and my best compassionate Pallavi.

Contents

1 Introduction	1
1.1 Background and Motivation	1
1.1.1 CO ₂ -Enhanced Oil Recovery and Sequestration-An Overview	1
1.1.2 Global Status of CO ₂ -Enhanced Oil Recovery and Sequestration	4
1.1.3 CO ₂ Sequestration in Mature Hydrocarbon Reservoirs	5
1.2 Research Objectives and Scope	6
1.3 Thesis Outline	7
References	8
2 Ankleshwar Oil Field: A Proposed CO₂ Injection Site	11
2.1 Introduction	11
2.2 Tectonics and Geologic Setting	12
2.3 Stratigraphy	14
2.4 Reservoir Structure	15
2.5 Production Scenario	17
2.6 Previous Work	19
2.7 Conclusions	19
References	20
3 Reservoir Modeling and Fluid Flow Simulations of Ankleshwar Oil Field, Cambay Basin	21
3.1 Introduction	21
3.2 3D Reservoir Model	21
3.2.1 Reservoir Characterization and Geomodel Building	22
3.2.2 Description of Geomodels	23
3.3 Reservoir Flow Equations	27

3.4	Numerical Solution	30
3.4.1	Discretization	30
3.4.2	Boundary Conditions	32
3.4.3	Solution of Black Oil Equations—The Newton-Raphson Method	32
3.5	Reservoir Flow Models	36
3.6	Fluid Flow Simulation Set Up	37
3.6.1	Reservoir Description and Fluid Properties	37
3.6.2	Equation-of-State (EOS) Characterization	38
3.6.3	Calculation of Minimum Miscibility Pressure (MMP)	40
3.6.4	Rock-Fluid Properties	40
3.6.5	Model Initialization and Validation	42
3.7	Simulation Results and Discussion	43
3.7.1	History Matching	43
3.7.2	CO ₂ -WAG Injection Study from Sector Model	43
3.7.3	Feasibility of CO ₂ -EOR from Conceptual Model	46
3.7.4	Calculation of Theoretical CO ₂ Sequestration Capacity of Ankleshwar Oil Field	53
3.8	Conclusions	56
	References	57
4	Acoustic Properties of Reservoir Fluids-CO₂ System	59
4.1	Introduction	59
4.2	Ankleshwar Fluid Properties	60
4.2.1	Brine Properties	60
4.2.2	Oil Properties	63
4.2.3	CO ₂ Properties	65
4.2.4	Oil + CO ₂ Mixtures	67
4.3	Conclusions	69
	References	70
5	Rock Physics Modeling of Ankleshwar Reservoir: A CO₂-EOR Perspective	71
5.1	Introduction	71
5.2	Well-Log Analysis of Ankleshwar Oil Field	72
5.3	Rock Physics Diagnostics—An Overview of Theory and Models	75
5.3.1	The Friable-Sand Model	75
5.3.2	The Contact-Cement Model	77
5.3.3	The Constant-Cement Model	78
5.4	Evaluating Rock Property Relationships Through Cross-Plot Analysis	79
5.5	Time-Lapse Well Log Analysis, Fluid Substitution: Gassmann’s Approach	87

5.6	Rock Physics Template (RPTs) Analysis	90
5.6.1	Static Rock Physics Template Analysis for Ankleshwar Oil Field	91
5.6.2	Dynamic Rock Physics Template Analysis for Ankleshwar Oil Field	93
5.7	Conclusions	96
	References	97
6	Implication of CO₂-EOR and Storage at Ankleshwar Oil Field—A Reservoir Geomechanics Viewpoint	99
6.1	Introduction	99
6.2	Building a Geomechanical Model: Ankleshwar Oil Field Example	100
6.2.1	Estimation of Mechanical Properties	101
6.2.2	Estimation of Vertical Stress, Minimum Horizontal Stress, Fracture Pressure and Pore Pressure for Ankleshwar Oil Field	103
6.3	Feasibility of Dynamic In Situ Stress System: Ankleshwar Oil Field Example	108
6.3.1	Estimation of Time-Lapse Vertical Stress, Minimum Horizontal Stress, Fracture Pressure and Pore Pressure for Ankleshwar Oil Field.	109
6.3.2	Reservoir Pressure Profile During Production at Ankleshwar Oil Field	109
6.4	Conclusions	112
	References	113
7	Time-Lapse Monitoring of CO₂ Response at Ankleshwar Oil Field: A Seismic Modeling Approach for Feasible CO₂-EOR and Storage	117
7.1	Introduction	117
7.2	Seismic Modeling of CO ₂ Response: Ankleshwar Oil Field Example	118
7.3	Feasibility of 4D Seismic Analysis at Ankleshwar Oil Field.	123
7.4	Conclusions	126
	References	129
8	Conclusions	131
8.1	Limitations of the Study	133
8.2	Future Research	133
8.3	Concluding Remarks.	134
	References	134