

Geophysics and Geosequestration

Geosequestration involves the deep geological storage of carbon dioxide from major industrial sources, providing a potential solution for reducing the rate of increase of atmospheric concentrations of carbon dioxide and mitigating climate change. This volume provides an overview of the major geophysical techniques and analysis methods for monitoring the movement and predictability of carbon dioxide plumes underground. Comprising chapters from eminent researchers, the book is illustrated with practical examples and case studies of active projects and government initiatives, and discusses their successes and remaining challenges. A key case study from Norway demonstrates how governments and other stakeholders could estimate storage capacity and design storage projects that meet the requirements of regulatory authorities. Presenting reasons for embracing geosequestration, technical best practice for carbon management, and outlooks for the future, this volume provides a key reference for academic researchers, industry practitioners, and graduate students looking to gain insight into subsurface carbon management.

Thomas L. Davis is Professor Emeritus at the Colorado School of Mines and founder of the Reservoir Characterisation Project (RCP), which received the Distinguished Achievement Award from the Society of Exploration Geophysics (SEG) in 2014. He is an active member of the SEG as an organizer for conferences, workshops, and education programs, and has served as SEG's Second Vice President, Technical Program Chairman, and Distinguished Lecturer. He has received the C. J. Mackenzie Award from the Engineering College of the University of Saskatchewan, the Milton B. Dobrin Award from the University of Houston, and the Deans Excellence and Melvin F. Coolbaugh Memorial Awards from the Colorado School of Mines.

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Malcolm Wilson has worked within government, academia, and the petroleum research industry, and currently serves on the advisory council for the Reservoir Characterization Project (Colorado School of Mines) and on the International Advisory Board for the New Energy Coalition in the Netherlands. He was instrumental in the creation of the IEA Greenhouse Gas Weyburn CO₂ Monitoring and Storage Project – an extensive research program for monitoring the storage of CO₂ in an oilfield. He was also part of the Intergovernmental Panel on Climate Change (IPCC) special report on capture, transport, and storage of CO₂, and of the IPCC team that received the Nobel Peace Prize in 2007. Dr. Wilson is an adjunct professor at the Faculty of Engineering and Applied Science at the University of Regina, and has received the Alumni of Distinction Award from the University of Saskatchewan.

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New World Orange BioFuels



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Preface

Two famous scientists in the late nineteenth century laid the groundwork for this book. Svante Arrhenius developed the concept of the greenhouse effect based on the chemistry of the atmosphere and initiated our understanding of the results of changing atmospheric chemistry. Emil Johann Weichert, the first geophysics professor, was examining the use of “artificial earthquakes” to look into the subsurface. Over the last dozen decades, the science of geophysics has moved forward substantially, primarily as a result of demand from the resource industry, and the current state of the art is examined in this book. The issue of the greenhouse effect, now termed global warming, has taken a different path. Concern about global warming came to public attention with the publication in 1987 of *Our Common Future* by the Brundtland Commission and the Toronto Conference of 1988 that tried to develop a pathway for emissions reductions. In subsequent years, the importance of global warming and the need to reduce its impact on economies and ecosystems, including human ecosystems, was recognized by the award of part of the 2007 Nobel Peace Prize to the scientists working on the United Nations reports on climate change, the Intergovernmental Panel on Climate Change [IPCC].

Since the late 1980s much effort has gone into the development of ways to reduce the emissions of greenhouse gases, particularly carbon dioxide (CO₂), into the atmosphere. One of the ways identified is to inject CO₂ either into the deep subsurface as a solvent for enhanced oil recovery (Sagoc Field in Texas has been receiving CO₂ for more than 40 years) or into deep saline aquifers (the first of these projects is offshore Norway, the Sleipner project, started in 1996). This book contains case studies of both types of geosequestration of CO₂. Indeed, the International Energy Agency (IEA) estimates that by 2050, some 13% of reductions of greenhouse gas emissions will need to be realized through geosequestration or the cost of emissions reductions will increase significantly.

The enthusiasm for sequestration in the subsurface is tempered by fear of the unknown. What happens if the CO₂ leaks into my basement, underground parking, or other such confined spaces? This is the same question that plagued the nuclear industry and the storage of spent nuclear fuel in man-made caverns. As an example, Shell was unable to move ahead with a proposed storage project in Barendrecht, Netherlands, some years ago. Fear of the CO₂ (which is known to have asphyxiated people in old coal mines, for example) and concerns about housing prices prevented this venture. In areas where the oil and gas industry is important and people understand enhanced oil recovery (EOR), the issues are far less pronounced. Hence Shell was able to go ahead with the Quest project in Alberta and there were only insignificant problems with EOR in Weyburn, Saskatchewan.

The key to public acceptance is the ability to demonstrate the safe sequestration of the CO₂ in the subsurface. In addition, the regulator must be able to confirm the volumes of CO₂ sequestered to be able to calculate national emissions. Voluntary standards are in the process of being developed in recognition of this need for confirmation. We can measure the CO₂ being injected into the subsurface with a great deal of accuracy, but we need to confirm that the CO₂ stays where it is intended. This important fact underlies the significance of this volume: using geophysics, particularly seismic surveying, as the only way to “watch” the CO₂ in the subsurface and ensure its stable sequestration in its intended injection location. From the perspective of the resource sector, geophysics has proven irreplaceable as a technique for improving the efficiency with which CO₂ is used to extract oil resources. Regardless of environmental issues, CO₂ has a cost and is, therefore, an expensive solvent to put in the ground. Understanding where the CO₂ is going is important to minimizing CO₂ utilization and effectively recovering the oil. This is vitally important for

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sustaining high-quality jobs in what are often under-developed parts of the world.

The focus of this volume is, therefore, to evaluate the state of the art in seismic work to determine the location and movement of CO₂ in the subsurface. This is a truly exciting venture, not just from the perspective that Weichert would have recognized – the use of seismic surveys to ensure effective and safe exploitation of fossil fuel resources – but also to meet a growing and important need to ensure to the regulator and the public that this is being done safely. In this latter regard, the technology is meeting the goal of the Brundtland Commission to reduce emissions to the atmosphere. Chapter 3 by Daley and Harbert examines in more detail why we need to monitor what is happening in the subsurface.

This volume discusses the technology as it exists today (for example, the excellent review by Lumley in Chapter 2) and then puts the basics of seismic and other geophysical techniques work into the real world with a series of important case studies including Sleipner and Snohvit, among others, as pure sequestration projects (Landrø, one of the editors and contributors, has played a significant role in this work) and also a number of EOR projects where the CO₂ can be monitored in oil fields (Davis, as editor and

contributor, has a long history with pushing the limits of geophysics in EOR projects). The authors of the various chapters have all developed distinguished reputations in the field of geophysics, and are worthy successors to the likes of Weichert, with a particular focus on the use of CO₂ in the fossil fuel industry or sequestration in the deep subsurface. Chapter 16 by Lawton *et al.* also examines our ability to track small volumes of CO₂ at shallow subsurface levels should the CO₂ escape from its storage location (this is also mentioned in Chapter 13 by Eiken on the Sleipner storage project), thereby demonstrating our ability to take action should the remote probability of leakage actually occur. Chapter 19 by Bauer *et al.* shows the sequestration of CO₂ under an area with significant surface activity, demonstrating not only an ability to survey under less than optimal conditions, but also the acceptance by the public in a situation where care is taken to understand the processes deep beneath the public's feet.

This volume will be a major contribution to students and practitioners of geophysics and to those concerned with the issue of global warming and taking concrete action to reduce emissions to the atmosphere in a safe and sustainable manner. We thank you for reading the book.

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To our authors from around the world we say thanks. Your willingness to present your work and then to follow through as you have is quite remarkable

and very much appreciated. There is little reward to offer other than “job well done.”

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Abbreviations

B	magnetic field	ERT	electrical resistance tomography
CSEM	controlled source electromagnetics	H	magnetic field ($B = \mu H$)
CO ₂	carbon dioxide	HED	horizontal electric dipole
DC	direct current	TDS	total dissolved solids
E	electric field	VMD	vertical magnetic dipole
EM	electromagnetic		