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Title

Book review of Geological storage of CO2: Modeling applications for large-scale simulation, by Jan M. Nordbotten and Michael A. Celia

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Publication Date

2013-02-15

DOI

DOI:10.1111/gfl.12011

Peer reviewed

Book Review

Geological Storage of CO_2: Modeling Applications for Large-Scale Simulations

Geofluids (2012) *Nordbotten J.M., Celia M.A., Wiley & Sons, Hoboken, New Jersey, USA 241 pp. ISBN 978-0-470-88946-6*

One of the big film box-office successes of 1985 was the comedy 'Back to the Future', in which a 17-year-old boy is sent back in time from 1985 to 1955, with the help of a mad scientist named Dr. Emmett 'Doc' Brown. By helping his future father stand up against a bully and meet his future mother, he ensures (in addition to his own existence) that his family's miserable present-day life changes into a brighter future.

As this article is not a movie review, one may ask what 'Back to the Future' has to do with Nordbotten and Celia's book about modeling approaches for CO_2 storage in the subsurface. The answer is simple: Just as young Marty McFly builds a time machine using an amped-up DeLorean, the authors rely on simplifying analytical approaches dating decades or centuries back, dusting them off with some ingenious mathematics, and developing them into powerful simulation tools. These tools track the multiphase processes occurring when CO_2 captured from industrial sources is injected into appropriate formations deep underground. The comparison stops here, though: Nordbotten and Celia are no mad scientists like 'Doc' Brown; this is a well-written book, one that is useful for a wide audience interested in porous media flow processes and large-scale simulation applications relevant to carbon storage.

The basic idea conveyed by Nordbotten and Celia is intriguing and in fact wider than the CO_2 storage application at the center of this book. The buzz word is heterogeneous multiscale method (HMM), a new modeling philosophy borrowed from the mathematics community, which allows fine-scale models to inform coarse-scale simulation, even if the coarse-scale equations cannot be explicitly derived. The idea is to reduce a fine-scale model to a less complex 'coarse' representation, via a compression operator, so that the modeler is able to simulate very large lateral domains while retaining sufficient resolution. The coarse-scale solution is then converted back into a fine-scale solution using a reconstruction operator. The authors apply the concept of HMM to develop a consistent set of simplifying assumptions for CO_2-brine systems, and they explain why these are suitable based on the analysis of the spatial and temporal scale of the problem at hand.

The compression and reconstruction operations proposed in this book are all based on the well-established assumption of vertical equilibrium behavior in aquifers, which goes back to Jules Dupuit's 1863 paper on single-phase groundwater flow. For the multiphase problem of less dense CO_2 migrating in a brine aquifer, vertical equilibrium can be reconstructed, for example, as two density-segregated fluids forming a sharp interface, or, with a bit more complexity, using a capillary-fringe model that honors the balance between gravitational and capillary forces. Nordbotten and Celia make a convincing case that the analytical and numerical solutions built upon compression and reconstruction allow for efficient modeling of carbon-storage problems at scales spanning many kilometers horizontally, while retaining essential information about complex phenomena at much smaller scales.

The book is divided into six main chapters, each with a list of recommendations for further reading. Chapter 1, 'The Carbon Problem', discusses the possible role of carbon sequestration in the portfolio of emission–reduction strategies and describes the basic geologic features that make a suitable CO_2 storage site. Chapters 2 and 3, on single- and two-phase flow, respectively, introduce the classical theory of fluid flow in the subsurface and review basic solution strategies for the governing equations, together with common simplifications. While both chapters briefly consider the concept of compression and reconstruction via vertical averaging, Chapter 4 provides a much more involved mathematical framework for HMM, based on considerations of large length and timescales.

In Chapters 5 and 6, with large-scale equations at hand, the authors develop analytical and numerical solution methods that can solve for large-scale injection, migration, and leakage of both CO_2 and brine, while also accommodating interphase mass exchange and subsequent transport of dissolved CO_2. Each chapter ends with practical applications to real-world CO_2 storage projects. Most interesting is the Alberta Basin application in Chapter 6 that involves modeling probabilistic risk assessment of hypothetical yet realistic storage operations in a multilayer subsurface domain of 50 km × 50 km lateral extent. Because of past and ongoing oil and gas operations, the region is perforated by about 1 250 wells, which could potentially act as vertical pathways for fluids. Nordbotten and Celia simulate 50 years of CO_2 injection into this domain to assess the potential risks arising from the migration and possible leakage of CO_2. These simulations—utilizing a semianalytical approximation with vertical equilibrium representation of aquifers, coupled to simplified fine-scale models for vertical well leakage—are so efficient that thousands of stochastic realizations can be easily performed on standard PCs. This is truly impressive and brings out many relevant aspects of system behavior and system sensitivity.

The book is very concise and progresses on a steep slope from basic concepts of porous-medium flow in its first half to fairly involved mathematics in its second half. The material is very well explained, however, and even if some readers may not be able to follow all the mathematical derivations, they will take home a solid knowledge of the basic concepts of fluid flow relevant to CO_2 storage, as well as understand the main modeling philosophies for large-scale simulations.

The discussions in the book clearly show that the two authors have different but complementary backgrounds: Jan Nordbotten is a gifted young mathematics professor at the University of Bergen in Bergen, Norway, who has a strong interest in applying multiscale methods to environmental modeling problems, such as CO_2 storage or geothermal energy. Michael Celia, a civil engineering professor at Princeton University, is a world-renowned expert on groundwater hydrology and contaminant transport, multiphase flow, and CO_2 sequestration. Nordbotten and Celia, who have been fruitfully collaborating on carbon sequestration topics since the early 2000s, have a very close working relationship that shows in the book. Readers who know them can easily imagine the good times they had while 'hiding out' in Lausanne, Utrecht, and Barcelona to concentrate on their book writing.

Skeptical readers may wonder whether the multiscale modeling approach based on vertical equilibrium assumptions is superior to other methods for simulating large-scale CO_2-brine systems. After all, there are many groups worldwide that follow alternative modeling philosophies, often attempting to represent the complex three-dimensional processes with as much detail as possible. What about the new era of ever-faster modern supercomputers? What about advances in numerical solution techniques using adaptive gridding techniques? What about methods with full dimensionality, but simplified physics, such as invasion percolation approaches? A related question is whether the vertical equilibrium assumption is still reasonable in more involved modeling problems, for example, when spatial heterogeneity leads to localized CO_2 migration pathways, or when geochemical reactions, or geomechanical damage affect the system behavior? The authors do not shy away from this discussion, but they also point to the fact that there is no general answer. The suitability of vertical equilibrium compression and reconstruction is, of course, problem-specific; the book presents a systematic framework for evaluating the vertical equilibrium assumption (or for that matter any other assumption related to compaction and reconstruction) via analysis of the relevant temporal and spatial scales. In my opinion, this is one of the most powerful messages to take from this book: That application of any model to a specific complex problem will benefit from such systematic analysis of space and timescales, leading to better model formulation and more informed simulations.

It is worth pointing out that the methodologies developed and applied in this book reside at the forefront of current research in the area of large-scale carbon-storage problems. Both Nordbotten and Celia, and various collaborators, are actively working on improved approaches that would push vertical equilibrium modeling further into new application territories—for example, developing adequate compression and reconstruction methods for strongly heterogeneous storage aquifers. Given their scientific caliber, the authors will almost certainly surprise us with new HMM applications that go well beyond what is currently described in the book. I am certainly looking forward to this.

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This work was supported by the Assistant Secretary for Fossil Energy, Office of Sequestration, Hydrogen, and Clean Coal Fuels, through the National Energy Technology Laboratory, U.S. Department of Energy, under Contract No. DE-AC02-05CH11231.