# 2013 Summary of MatMoRA-II: Results and Impact

Project period: Jan 2012- Dec 2013

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*Recruitment positions:* Tore Bjørnarå (PhD, NGI/UiB; 2012-2014), Odd Andersen (PhD, SINTEF/UiB; 2012-2015), Bawfeh Kingsley Kometa (post.doc., UiB/Uni; 2013-2015)

## Executive Summary

The primary goal of the project is *to develop methods for modeling and simulating the pertinent flow dynamics of CO2 in appropriate storage sites.* The project has achieved substantial progress towards this goal, focusing on the five subareas: (i) thermal and mechanical effects, (ii) CO2 dissolution, (iii) caprock topography, (iv) optimized injection strategies, and (v) coupled flow-geomechanical models. The key results involve fully developed modeling capabilities at both the large and small scales in the caprock and dissolution subareas, as well as preliminary work in thermal and mechanical modeling and optimization. The project has examined important issues related to the role of heterogeneity and physical complexity to enhance or hinder the ability of convection-driven dissolution and structural features of the caprock to trap and secure CO2 over the long term. Additionally, continuous improvements to existing open-source software are part of ongoing work that will eventually lead to new, sophisticated optimization methods for engineering safe and cost-effective CO2 storage projects.

The key deliverables from the project thus far have been *publications in high-level peer-reviewed journals*. Additionally, new research codes have been developed and shared among the project partners. In particular, in collaboration with the spin-off project "Numerical CO2 laboratory", we have developed *a CO2-module* in the open-source software MRST [1], which offers a comprehensive set of tools for modeling structural/stratigraphic, residual and solubility trapping. The module supports industry-standard input formats and offers a wide range of methods, ranging from simple structural analysis (spill-point and percolation type models), via vertical equilibrium methods, to fully implicit methods in 3D. In addition, the module offers a number of tutorial examples as well as simple access to public data sets used for benchmarking, including the Johansen field, Layer 9 from Sleipner, as well as regional data sets from the recent North Sea Storage Atlas.

So far, the MatMoRA II project has provided extensive knowledge and novel research results motivated by the injection of CO2 in saline aquifers. Much of the basic research that is conducted also have other applications, particularly for enhanced oil and gas recovery using CO2, but also for unconventional reservoirs, where understanding thermal and mechanical effects on different scales become increasingly important.

[1] This software has a large user group worldwide. MRST 2013a, released in April 2013, has so far more than 1000 unique downloads from 64 different countries.

MatMoRA II has, in terms of results achieved p.t., been on target towards full project completion by end of 2015. No work package is behind schedule in terms of key milestones (see Table 1), and in several work packages, we are obtaining more results than anticipated due to collaboration with other projects at the partner institutions.

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<tr><td colspan="4">Fluid-rock interact.</td><td colspan="4">Effic. coupled model</td><td colspan="4">Verify coupled model</td><td colspan="2"></td></tr>
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**Table 1: Tentative list of milestones from the MatMoRA-II project description.**

MatMoRA-II has been planned to produce results along four project axes: Research, education, collaboration and public acceptance. In the following, status for in the project according to these is given, with a focus on the research results obtained.

## Research - work package status and remaining work

A summary of the status of each work package and corresponding deliverables, in addition to remaining work according to the MatMoRA-II project description is given below.

### WP1 Thermal and mechanical effects of CO2 injection

*Partners: UoB (responsible), NGI, Uni, SINTEF*

*Goal: to quantify thermal and mechanical effects to avoid caprock fracturing and hydrate formation in the vicinity of the injection well.*

Preliminary results have been achieved in model development using reduced models that employ simplifications of thermal processes to reduce computational effort while maintaining accuracy [1]. A further detailed study has made the significant step to model CO2 density more reliably near the critical point, where large variations are known to occur and affect the predictive capabilities of simulations. The results have been achieved through modification of classical equations-of-state for CO2 to better reflect the real impact of temperature and pressure [1]. The project has also released a new geomechanics benchmark to the international modeling community to compare various modeling approaches for a common set of problems [2].

Previous research in MatMoRA has focused on upscaled models based on an assumption of vertical equilibrium as a means to accurately and efficiently simulate the long-term behavior of injected CO2. In the project, we have extended the vertical-equilibrium formulations to also model *vertical* density changes; see e.g. [3].

*Deliverables p.t. Dec. 2013: software includes reduced thermal research code + 1 conference paper + 1 benchmark problem definition + 1 poster + 1 manuscript*

[1] Gasda, S.E., I. Aavatsmark, A. Stephansen, H.K. Dahle (2013) Upscaled modeling of $CO_2$ injection with coupled thermal processes. Energy Procedia, EGU Annual Meeting 2013.
[2] Gasda, S.E., M. Darcis, B. Flemisch, M. White and H. Class (2012) Geomechanical behavior of CO2 storage in saline aquifers (GeoCoSA): Benchmark problem description.
[3] O. Andersen, S. E. Gasda and H. M. Nilsen, Vertical Equilibrium Models with Variable Density for CO2, (2013) Poster NUPUS.

*Remaining work:*
A paper describing the inclusion of compressibility in the vertically averaged equations for CO2-injection and flow in porous media is to be submitted. Work also remains in terms of bringing theoretical developments into practical usage. Optimized equations of state promise more accurate and faster simulation. While the mathematical tools have largely been developed, actual assessment the coupling between thermal effects and mechanics remains to be undertaken. Benchmark study has been issued, and is ongoing in collaboration with partners.

**WP2: CO2 dissolution**

*Partners: Uni (responsible), UoB*

*Goal: to quantify the effect of heterogeneity on CO2 dissolution*

Significant progress has been made to examine convective-driven CO2 dissolution using both detailed modeling [4,6,7] as well as reduced models [5,7]. The detailed modeling examined the evolution of convection under different capillary pressure regimes and in the presence of heterogeneous distribution of impermeable flow barriers. In the latter case, capillarity was found to enhance convection, especially in permeable aquifers [5,8]. The barriers were found to reduce mixing to the same degree as the effective vertical permeability is reduced [6]. These valuable results can be used to constrain the parameter space when using reduced models to match to geophysical observations in large-scale domains, such as the Utsira [5]. It should be noted that much of the work in this work package has up to now been conducted in collaboration with the FME-SUCCESS[2].

*Deliverables p.t. Dec. 2013: 3 peer-reviewed papers + upscaled dissolution research code*

[4] Elenius, M.T., J. M. Nordbotten, and H. Kalisch (2012) Effects of a capillary transition zone on the stability of a diffusive boundary layer. *IMA Journal of Applied Mathematics*, online 2012.
[5] Mykkeltvedt, T. S., J. M. Nordbotten (2012), Estimating convective mixing rates from commercial-scale $CO_2$ injection, *Environmental Earth Sciences,* doi:10.1007/s12665-012-1674-3.
[6] Elenius, M.T. and S.E. Gasda (2013), Convective mixing in formations with horizontal barriers, *Advances in Water Resources,* under review.
[7] Elenius, M. T., J. M. Nordbotten, H. Kalisch, Convective mixing influenced by capillary transition zones, *Computational Geosciences*, under review.

*Remaining work:*
The work package is complete in terms of the research scope of the project, but work remains in dissemination of knowledge and finalization of publications.

**WP3: Caprock topography**

*Partners: UoB (responsible), Uni, SINTEF*

[2] M.T. Elenius' post.doc position was funded by FME-SUCCESS.

*Goal: to quantify the effect of caprock topography and parameterize the effect of sub-scale roughness on CO2 plume migration.*

Building on experience from the spin-off project IGEMS[3], several key results have established better understanding of the role of heterogeneity of the topsurface topography in long-term storage security, focusing on trapping efficiency and the extent of the mobile CO2 footprint. This new knowledge has been achieved largely through development of better and more efficient upscaled models that capture the important geological details of a structurally heterogeneous system with a more effective approach than classical grid refinement. The upscaled models were developed through a combination of mathematical theory [8,9] and detailed simulations [8,10] to determine the correct upscaled equations. Further study on representative geological structures [11] gave insight into the set of parameters required for accurate upscaling. An extensive set of tools is also developed for investigating stratigraphic and structural trapping. The toolkit uses geometrical and percolation-type analysis of the top-surface structure to identify cascades of structural traps, spill-point paths, accumulation regions, etc. In addition, the toolkit offers simulation capabilities (VE and 3D) for a wide range of models, from incompressible to compressible flow with dissolution, models with sharp interfaces or capillary fringe, as well as hysteresis effects. The toolkit was used to investigate basic trapping mechanisms using the public data sets made available as part of the recent storage atlas for the North Sea. The toolkit is implemented as a module of the open-source software MRST and a new version will be released at the end of this year.

*Deliverables p.t. Dec. 2013: 3 peer-reviewed papers, 1 conference paper, 2 manuscripts + research code shared between partners*


[8] Gray, W. G., P. A. Herrera, S. Gasda, H. K. Dahle (2012), Derivation of vertical equilibrium models for $CO_2$ migration from pore scale equations, *International Journal of Numerical Analysis and Modeling,* 9(3), 745-776, 2012.

[9] Gasda, S. E., H. M. Nilsen, H. K. Dahle and W. G. Gray (2012), Effective models for CO2 migration in geological systems with varying topography, *Water Resources Research*, W10546, doi: 10.1029/2012WR012264.

[10] Gasda, S. E., H. M. Nilsen and H. K. Dahle (2012), Upscaled models for CO2 migration in geological formations with structural heterogeneity, *in Proceedings of ECMOR XIII*, Biarritz, France, 9-13 September, 2012.

[11] Gasda, S.E., H.M. Nilsen, H.K. Dahle (2013), Impact of structural heterogeneity on upscaled models for large-scale CO2 migration and trapping in saline aquifers, *Advances in Water Resources*, doi:10.1016/j.advwatres.2013.05.003.


*Remaining work:*
WP3 is completed in terms of the model development and analysis. The project description calls for further validation of model concepts through application to field data, which is currently ongoing. In addition, work remains in dissemination of knowledge and finalization of publications. Currently, two papers on spill-point analysis and structural trapping capacity in saline aquifers, which also include code examples, are to be submitted.

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[3] H. M. Nilsen, A. R. Syversveen, K.-A. Lie, J. Tveranger, and J. M. Nordbotten. Impact of top-surface morphology on CO2 storage capacity. Int. J. Greenhouse Gas Control, Vol. 11, pp. 221-235, 2012. DOI: 10.1016/j.ijggc.2012.08.012,
A. R. Syversveen, H. M. Nilsen, K.-A. Lie, J. Tveranger, and P. Abrahamsen. A study on how top-surface morphology influences the CO2 storage capacity. In "Geostatistics Oslo 2012", Quantitative Geology and Geostatistics, Springer Verlag, Vol. 17, pp.481-492, 2012. DOI: 10.1007/978-94-007-4153-9_39.

**WP4: Optimized and engineered injection strategies**

*Partners: SINTEF (responsible), Uni, UoB*

*Goal: to develop models and computational methods suitable for optimizing CO2 storage.*

So far, the work in WP4 has mainly focused on developing and collecting the comprehensive set of optimization methods and simulation tools that are required in a single software framework:

- *Input of industry-standard data*. The open-source MRST software suite is capable of reading Eclipse-type input decks, and supports a large number of the keywords used to model fluids, wells completions, production schedules, etc. The software also includes routines for handling publicly available data sets, e.g., regional data from the North Sea storage atlas, the Sleipner GHGT, etc.
- *Proven concepts for production optimization and well placement* that can be extended to EOR and EGR. This includes, in particular, a fully implicit black-oil simulator for industry-standard reservoir models with sensitivities for optimization and possibilities for temperature effects. The simulator has been verified against a leading commercial simulator for 20 years of production data on a full field model.
- *Concepts and software components for hierarchical optimization.* To efficiently determine optimal injection strategies, we generally propose a two-stage optimization process in which fast simulation tools relying on simplified physics is used to extensively search the parameter space and suggest optimized strategies that subsequently can be translated, adjusted, and verified using more comprehensive ('full-physics') simulation tools. This concept has been successfully utilized to optimize both water- and gas-injection scenarios as part of the Second Norne Comparative Case Study[4].
- *Fast simulation capabilities.* This includes:
    - Case-specific upscaling and POD-type model reduction for fast simulation
    - Fully implicit VE models with different physical complexity and detailed inventory of various trapping mechanisms (see WP3).
    - Geometric and percolation-type analysis tools for (interactively) finding good starting points that maximize structural trapping (see WP3).

Using this software, one can for instance, quickly realize a two-step algorithm to search for optimal injection points that will maximize the trapping retardation effects of structural an stratigraphic traps on the North Sea CO2 atlas data[5]. In addition, the more advanced computational tools which sensitivities based on adjoint calculations can be used for optimization, both for the global storage problem and the more local operational problem. Parts of these ideas will be presented in [12,13], a paper describing the combined use of these methods is also in preparation.

*Deliverables p.t. Dec. 2013: extensive software development released as open source*

[4] Results are described in "Flow diagnostics for use in reservoir management", O. Møyner, S. Krogstad, and K-A. Lie, 2013.

[5] In the first pass, tools from WP3 are used to determine all traps, their accumulation areas, and how individual traps (and accumulation areas) are connected by spill paths. We then calculate the total volume of traps that can be reached along spill paths emanating from an arbitrary point inside each accumulation area. A good injection point will then lie on the border between the two (or more) accumulation areas that together have the highest structural trapping potential. In the second pass, vertical equilibrium simulation is used to estimate dynamic effects depending on the injection rate.

[12] MRST software and documentation: http://www.sintef.no/MRST/
[13] CO2-lab software, http://www.sintef.no/co2lab/

*Remaining work:*
An abstract framework and software is in place for multi-stage optimization workflow. The project description calls for extensive application of the optimization toolbox on realistic field data. So far, application to classical petroleum-related problems shows promising results. The developed software is compatible with the $CO_2$ storage atlas, and application of the optimization toolbox to this data is ongoing.

**WP5: Fast evolution of fluid-rock couplings**

*Partners: NGI (responsible), SINTEF, UoB, Uni*

*Goal: to quantify the effect of pressure on reservoir/caprock integrity using simplified coupled flow-geomechanical models*

Within this subproject, we have established that the traditional approach to fluid-rock couplings, through extended reliance on finite element package, is only partially suited for modeling CO2 storage. Thus we are following a two-pronged approach, where the ongoing quantification of model coupling and development of reduced-order models within the COMSOL software package is complemented with additional research into the fundamental couplings in numerical simulation of poromechanical flows [14,15]. Furthermore, highly accurate solutions to the classical McWhorter-Sunada problem have been established in order to aid code validation studies.

*Deliverables p.t. Dec. 2013:*

[14] Bjørnarå, T.I. and S.A. Mathias (2013) A pseudospectral approach to the McWhorter and Sunada equation for two-phase flow in porous media with capillary pressure, *Computational Geoscience*, in press.
[15] Nordbotten, J. M., Cell-centered finite volume methods for deformable porous media, *International Journal for Numerical Methods in Engineering*, under review
[16] Nordbotten, J. M., Finite volume poromechanical simulation of fractured and fracturing porous media, *Water Resources Research*, under review.
[17] Nordbotten, J. M., Finite volume hydro-mechanical simulation in porous media, *Water Resources Research*, under review.

*Remaining work:*
Work remains in complete development and testing of coupling between vertically integrated models and deformation. The coupled discretizations is also planned to be extended to internally compactive flows (heat, capillary forces). In the context of CO2 storage, a suite of model reduction/de-coupling studies also remains. A coupled geomechanics and flow modelling of In Salah data by means of the reduced-order model that has been developed is planned. The main purpose of this activity is to evaluate the performance of the developed reduced-order model in terms of measured field data (and possibly also identify what and/or how we should improve further in the future). This activity will contribute to general injection applications, not only to CO2 injection, by increasing our understanding of reservoir geomechanics coupled with flow.

## Education

Several master students have been educated in MatMoRA-II spin-off master project. The PhD and post.doc candidates funded by the project are progressing according to schedule.

## Collaboration

The MatMoRA-II project has extensive international collaboration with a broad range of European and foreign universities. Amongst others, the personnel in the project team were central in the organizing committee and scientific committee for the 2. International conference on non-linearities and upscaling in porous media (NUPUS) 30 September – 2 October with more than 100 participants, where applications related to $CO_2$ storage were prominent. NUPUS is an international and interdisciplinary cooperation of Universities and research is carried out at the University of Bergen, TU Delft, TU Eindhoven, University of Stuttgart, Utrecht University and Wageningen University. This collaboration is of particular benefit for the PhD and post.doc candidates in the MatMoRA-II project.

## Public acceptance

The project team is active in its outreach to the public and has a continued presence on print, online, radio, TV and with public lectures. The MatMoRA-II and MRST websites are actively maintained.

- http://www.sintef.no/Projectweb/MatMoRA/
- http://www.sintef.no/Projectweb/MRST/