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Geologic Carbon Sequestration Resource of References

Prepared for:

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Introduction

For more than fifteen years, research contributors to the field of Geologic Carbon Storage (GCS), public and private, have produced a body of research so significant that it can be sometimes challenging to navigate. The main purpose of this document is to provide a useful list of relevant, categorized, annotated references, which can be used as a guiding roadmap through the ample research conducted under the various topics of GCS.

Each reference is accompanied by a brief (a few sentences) summary. In addition, all references were assigned two categories: (1) GCS application value, and (2) process phase. The different application values (high, high-moderate, moderate) respond to our qualitative assessment of impact of that particular reference on GCS research. With some exemptions, field application studies are assigned a higher value than laboratory studies and conceptual studies. Also, in the case of older references, the number of citations reported in the "web of science" was used to assess application value. Given the volume of available references, low application value references were not included.

The process phase category indicates the phase or phases, along a project development and execution process, in which the reference is applicable. Following Chevron's guidelines, the identified process phases used in this project are: (1) identification of opportunities, (2) selection of alternatives, (3) development of selected alternatives, (4) execution, and (5) operation. The process phase category is indicated by a symbol, explained in the following section.

References were organized according to a classification scheme, which we developed as part of the project. The general GCS classifications are: (1) system characterization, (2) dynamic modeling of GCS, (3) Monitoring, Verification and Accounting (MVA), and (4) risk assessment.

Process Phase Symbols

The broad phases in which Chevron divides its project development and execution process are:

(1) Identification of opportunities,

(2) Selection of alternatives,

(3) Development of selected alternatives,

(4) Execution, and

(5) Operation

We created symbols to easily assign a process phase to each reference.

Example A: reference applicable during phase 2 (selection of alternatives)

Example B: reference applicable during phases 1 and 3 (identification of opportunities and development of selected alternatives)

Table of Contents

1. System characterization

1.1 Integrity of the confining system

1.1.1 Geochemical characterization

Assayag, N., Matter, J., Ader, M., Goldberg, D. and Agrinier, P., (2009). Water-rock interactions during a CO_2 injection field-test: Implications on host rock dissolution and alteration effects. Chemical Geology, **265**, 227-235.

Field application at the Lamont-Doherty Earth Observatory test site in which two push-pull test experiments were performed to investigate the nature and rates of in-situ CO_2-fluid-rock reactions during an aqueous phase CO_2 injection test. High value.

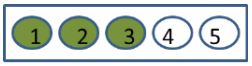
Busch, A., Alles, S., Gensterblum, Y., Prinz, D., Dewhurst, D.N., Raven, M.D., Stanjek, H., Krooss, B.M., (2008). Carbon dioxide storage potential of shales. International Journal of Greenhouse Gas Control 2, 297–308.

Laboratory experiment to assess the sealing integrity and the CO_2 storage potential of the Moderong shale, Australia, and different clay minerals through the study of diffusive transport and gas sorption on samples of these materials. Moderate value.

Chadwick, R. A., P. Zweigel, and others, (2004). Geological reservoir characterization of a CO_2 storage site: The Utsira Sand, Sleipner, northern North Sea. Energy 29(9–10): 1371-1381.

The paper provides generic conclusions on reservoir characterization based on the Sleipner operation where CO_2 is being injected into the Utsira Sand. High value.

Ellis, B. R., G. S. Bromhal, and others, (2011). Changes in caprock integrity due to vertical migration of CO_2-enriched brine. Energy Procedia 4(0): 5327-5334.



This article reviews a laboratory flow-through experiment performed to investigate fracture evolution of a fractured carbonate caprock during simulated leakage of CO_2-acidified brine. High-moderate value.

Gaus, I. (2010). "Role and impact of CO_2–rock interactions during CO_2 storage in sedimentary rocks." International Journal of Greenhouse Gas Control 4(1): 73-89.

This article discusses methodologies for assessing CO_2–rock interactions in 6 potential areas (or phases) of concern: (1) interactions during the injection phase and in the near well environment, (2) long-term reservoir and cap rock interactions, (3) CO_2–rock interactions along leakage pathways (well, cap rock and fault), (4) CO_2–rock interactions causing potable aquifer contamination as a consequence of leakage, (5) water–rock interactions caused by aquifer contamination through the CO_2 induced displacement of brines, and (6) engineered CO_2–rock interactions. The driving processes of CO_2–rock interactions are discussed as well as their potential impact in terms of changing physical parameters. Moderate value.

Gaus, I., M. Azaroual, and others, (2005). Reactive transport modelling of the impact of CO_2 injection on the clayey cap rock at Sleipner (North Sea). Chemical Geology 217(3–4): 319-337.

Reactive transport modelling study to assess the impact of major geochemical reactions between CO_2, the cap rock formation water, and the cap rock mineralogy on the porosity of the cap rock at Sleipner (37 °C, 101.3×10^5 Pa). A slight decrease of the porosity was predicted which might improve the sealing capacity of the cap rock, but this porosity change was found to be restricted to the lower meters, even in the most reactive case. High value.

Gaus, I., Audigane, P., André, L., Lions, J., Jacquemet, N., Durst, P., Czernichowski-Lauriol, I., Azaroual, M., (2008). Geochemical and solute transport modelling for CO_2 storage, what to expect from it? International Journal of Greenhouse Gas Control, Volume 2, Issue 4, Pages 605-625.

This paper provides an overview of geochemical and solute transport modelling for CO_2 storage, and highlights data requirements, challenges, and gaps up to 2008. High value.

Johnson, J. W. (2011). Geochemical assessment of isolation performance during 10 years of CO_2 EOR at Weyburn. Energy Procedia 4(0): 3658-3665.

Weyburn Geochemical Theme's final review of results. The paper reviews accomplishments of the principal objectives of the theme: to predict intra-reservoir CO_2 migration paths, dynamic CO_2 mass partitioning among distinct trapping mechanisms, and reservoir/seal permeability evolution through reactive transport modeling; to assess the impact of CO_2-brine-rock reactions on fracture flow and isolation performance through experimental studies that directly support the monitoring and modeling work; and to exploit a novel stochastic inversion technique that enables explicit integration of these diverse monitoring data and forward models to improve reservoir characterization and long-term forecasts of isolation performance. High value.

Johnson, J. W., J. J. Nitao, and others, (2005). Chapter 8 - Reactive Transport Modeling of Cap-Rock Integrity During Natural and Engineered CO_2 Storage. Carbon Dioxide Capture for Storage in Deep Geologic Formations. Amsterdam, Elsevier Science: 787-813.

Update of similar article published in 2003. It concludes that ultimate counterbalancing of geochemical and geomechanical effects is feasible, which suggests that shale cap rocks may in fact evolve into effective seals in both natural and engineered storage sites. Moderate value.

Johnson, J.W., Nitao, and others, (2003). Reactive transport modeling of geohazards associated with offshore CO_2 injection for EOR and geologic sequestration: Offshore Technology Conference, Houston, TX, May 5-8, 2003, 9 p.

This paper presents a conceptual model of the geochemical counterbalancing of geomechanical effects as a function of diffusion distance and reaction progresses. The conceptual model provides a theoretical framework for assessing geohazard potential. Moderate value.

Kharaka, Y. K., and Cole, D. R., (2011), Geochemistry of Geologic Sequestration of Carbon Dioxide, *in* Harmon, R.S., and Parker, A., eds., Frontiers in Geochemistry: Contribution of Geochemistry to the Study of the Earth: Blackwell Publishing Ltd., p. 136-174

Book chapter revising trapping mechanisms, geochemistry of natural CO_2 analogues, and geochemistry studies conducted at several carbon storage demonstration sites. High value.

Kharaka, Y.K., D.R. Cole, J.J. Thordsen, E. Kakouros, H.S. Nance, (2006). Gas–water–rock interactions in sedimentary basins: CO_2 sequestration in the Frio Formation, Texas, USA., Journal of Geochemical Exploration 89 (2006) 183–186, doi:10.1016/j.gexplo.2005.11.077

Geochemical analysis performed at the Frio pilot project, where 1,600 ton of CO_2 were injected into a 24-m sandstone section of the Frio Formation at 1,500 m depth. Down-hole and surface samples of formation water and gas were obtained and analyzed from both the injection and observation wells using a variety of sampling tools and methodologies. High value.

Kharaka, Y.K., Thordsen, J.J., Hovorka, S.D., Nance, H.S., Cole, D.R., Phelps, T.J., Knauss, and K.G., (2009), Potential environmental issues of CO_2 storage in deep saline aquifers: Geochemical results from the Frio-I Brine Pilot test, Texas, USA. Applied Geochemistry, v. 24, no. 6, p. 1106-1112

Analysis of geochemical parameters and perfluorocarbon tracer gases (PFTs) to monitor migration of injected CO_2 into an overlying layer at the Frio site. Results obtained from four shallow monitoring groundwater wells show no brine or CO_2 leakage through the Anahuac Formation, the regional cap rock. High value.

Landrot, G., Ajo-Franklin, J., and others, (2012), Measurement of accessible reactive surface area in a sandstone, with application to CO_2 mineralization, Chemical Geology 318–319 (2012) 113–125

This article presents a new characterization approach which enables the measurement of the surface area of each reactive mineral located within the connected pore network of a sandstone from a carbon sequestration pilot site in Cranfield, Mississippi. Moderate value.

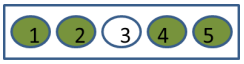
Lu, J., Larson, T.E., and Smyth, R.C., (2014), Gas diffusion in the Anahuac shale-- a core gas study submitted to Chemical Geology.

Detailed geochemical analysis of core collected from a relatively high porosity interval of the Anahuac shale, a regional confining layer overlying the prolific, oil-bearing Frio Fm. Comparison of stable carbon isotopes of methane extracted from pore spaces in the shale and from the underlying reservoir indicate slow gas transport. High Value

Lu, J., Mickler, P., Nicot, J. P., and others, (2014), Geochemical impact of oxygen on siliciclastic carbon storage reservoirs. International Journal of Greenhouse Gas Control 21 (2014) 214–231

This paper presents results from autoclave experiments designed to investigate the potential impact of O_2 as an impurity on geochemical reactions. The authors conclude that comparisons between experimental data show limited impact of O_2 on the Miocene and lower Tuscaloosa sandstones, which does not contain redox sensitive species. The most significant impact of O_2 observed is associated with oxidation of pyrite and ferrous iron in the Cardium experiment. High-moderate value.

Lu, J.; Kharaka, Y. K.; Thordsen, J. J.; Horita, J.; Karamalidis, A.; Griffith, C.; Hakala, J. A.; Ambats, G.; Cole, D. R.; Phelps, T. J.; Manning, M. A.; Cook, P. J.; Hovorka, S. D., (2012), CO_2−rock−brine interactions in Lower Tuscaloosa Formation at Cranfield CO_2 sequestration site, Mississippi, U.S.A. Chem. Geol. 2012, 291 (0), 269−277.



This paper shows results from an integrated geochemical program conducted at the Cranfield site, Mississippi, U.S.A. The program included extensive field geochemical monitoring, a detailed petrographic study, and an autoclave experiment under in situ reservoir conditions. Results show that mineral reactions in the Lower Tuscaloosa reservoir were minor during CO_2 injection. High value.

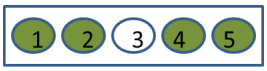
Mito, S., Z. Xue, and others, (2008). Case study of geochemical reactions at the Nagaoka CO_2 injection site, Japan. International Journal of Greenhouse Gas Control 2(3): 309-318.

This article shows results of an integrated field and experimental study on the geochemical reactions in a sandstone reservoir at Nagaoka, Japan, the first Japanese pilot project of CO_2 geological storage. High value.

Okamoto, I., Li, X., Ohsumi, T., (2005). Effect of supercritical CO_2 as the organic solvent on cap rock sealing performance for underground storage. Energy 30, 2344–2351.

Laboratory experiment to determine the sealing capacity of the cap rock at the Nagaoka injection test site. The results show that the pore radius distributions slightly shifted to a larger size after treatment, while the porosity and permeability changed less than 1%. Moderate value.

Ott, H., J. Snippe, and others, (2013). Salt precipitation due to Sc-gas injection: Single versus multi-porosity rocks. Energy Procedia.



Laboratory experiment designed to investigate the consequences of formation dry-out due to the injection of under-saturated supercritical acid gas/CO_2 into a Middle Eastern dolomite formation for enhanced oil recovery (EOR) and acid gas (AG)/CO_2 disposal purposes. Moderate value.

Ott, H., K. de Kloe, and others, (2011). Injection of supercritical CO_2 in brine saturated sandstone: Pattern formation during salt precipitation. Energy Procedia 4(0): 4425-4432.

Laboratory experiment conducted to report on the consequences of formation dry-out due to the injection of dry or under-saturated supercritical CO_2 into geological formations. The study concludes that a substantial impairment of the absolute permeability was found but, despite high local salt accumulation, the effective CO_2 permeability increased during the experiments, which is likely a result of the observed cross sectional precipitation pattern. High-moderate value.

Ott, H., K. de Kloe, and others, (2012). Core-Flood Experiment for Transport of Reactive Fluids in Rocks, Rev. Sci. Instrum. 83, 084501

Laboratory experiment designed to investigate physical and chemical processes caused by the flow of reactive and volatile fluids such as supercritical CO_2 and/or H_2S in geological formations. High-moderate value.

Pruess, K. and N. Müller (2009). Formation dry-out from CO_2 injection into saline aquifers: 1. Effects of solids precipitation and their mitigation. Water Resour. Res. 45(3): W03402.

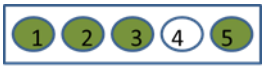
Numerical simulation study to evaluate the main physical mechanisms affecting the dry-out and salt precipitation process: (1) displacement of brine away from the injection well by injected CO_2, (2) dissolution (evaporation) of brine into the flowing CO_2 stream, (3) upflow of CO_2 due to gravity effects (buoyancy), (4) backflow of brine toward the injection point due to capillary pressure gradients that oppose the pressure gradient in the CO_2-rich ("gas") phase, and (5) molecular diffusion of dissolved salt. High-moderate value.

Raistrick, M., I. Hutcheon, and others, (2009). Carbon dioxide-water-silicate mineral reactions enhance CO_2 storage; evidence from produced fluid measurements and geochemical modeling at the IEA Weyburn-Midale Project. Energy Procedia 1(1): 3149-3155.

This paper provides a review of positive results from the Weyburn-Midale geochemical research program. Geochemical reaction path simulations of the water-mineral- CO_2 system reproduce the changes in measured data observed over the first few years, confirming proposed reaction

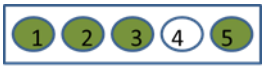
pathways and rates. Extension of these history matched reaction path simulations over 100s of years shows that alteration of K-feldspar and other silicate minerals present in the Weyburn reservoir will lead to further storage of injected CO_2 in the aqueous phase and as carbonate minerals. High value.

Raistrick, M., Mayer, B., and others, (2006). Using Chemical and Isotopic Data to Quantify Ionic Trapping of Injected Carbon Dioxide in Oil Field Brine. Environmental Science and Technology, 40 (21) 6744–6479



This paper focuses on demonstrating a technique for quantifying ionic trapping of injected CO_2 as HCO_3^- using geochemical data collected prior to and during 40 months of CO_2 injection into a hydrocarbon reservoir at the International Energy Agency (IEA) Weyburn CO_2 Monitoring and Storage Project, Saskatchewan, Canada. High-moderate value.

Trémosa, J., Castillo, C., and others, (2014), Long-term assessment of geochemical reactivity of CO_2 storage in highly saline aquifers: Application to Ketzin, In Salah, and Snøhvit storage sites. International Journal of Greenhouse Gas Control 20 (2014) 2–26

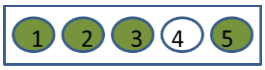


This paper presents conceptual models created for three CO_2 storage case-studies in saline sandstone aquifers (Ketzin, InSalah and Snøhvit). The models were based on field observations on mineral reactivity. Additionally, a methodology is proposed to evaluate the long-term geochemical reactivity of these saline aquifers as a result of CO_2 injection. High value.

Xu, T., Kharaka, Y. K., and others, (2010), Reactive transport modeling to study changes in water chemistry induced by CO_2 injection at the Frio-I Brine Pilot. Chemical Geology, Elsevier, 271 (2010) 153–164.

Reactive transport modeling was performed and history matched with field observations from the Frio-1 pilot project. A simple kinetic model of Fe release from the solid to aqueous phase was developed, which can reproduce the observed increases inaqueous Fe concentration. High value.

Xu, T., Li, J., (2013) Reactive transport modeling to address the issue of CO_2 geological sequestration, Procedia Earth and Planetary Science 7 (2013) 912-915.



Reactive transport modeling study of hydrogeochemical processes to assess short-term changes in groundwater chemistry, and long-term fate of injected CO_2. High-moderate value.

1.1.2 Geomechanical characterization

Chiaramonte, L., Zoback, M. D., Friedmann, J., Stamp, V., (2008). "Seal integrity and feasibility of CO_2 sequestration in the Teapot Dome EOR pilot: geomechanical site characterization." Environmental Geology, Volume 54, Issue 8, pp.1667-1675, doi: 10.1007/s00254-007-0948-7

This paper presents a report of a preliminary investigation of seal integrity at Teapot Dome oil field, Wyoming, USA, with the objective of predicting the potential risk of CO_2 leakage along reservoir-bounding faults. High-moderate value.

Gemmer, L., O. Hansen, and others, (2012). Geomechanical response to CO_2 injection at Krechba, In Salah, Algeria. First Break 30(2): 79-84.

This article discusses the geomechanical modelling of the rock mechanical response to CO_2 injection at the Krechba gas field in Algeria arguing that key factors to understanding are the sensitivity of the model to the initial stress field and the rock-mechanical properties of the fault/fracture zones. High value.

Hawkes, C. D., P. J. McLellan, and others, (2004). Geomechanical Factors Affecting Geological Storage of CO_2 in Depleted Oil And Gas Reservoirs: Risks And Mechanisms. Gulf Rocks 2004, the 6th North America Rock Mechanics Symposium (NARMS), June 5 - 9, 2004 , Houston, Texas, American Rock Mechanics Association.

This paper provides a review of the geomechanical factors affecting the hydraulic integrity of the bounding seals for a depleted oil or gas reservoir slated for use as a CO_2 injection zone. Equations are given which are helpful for identifying the key parameters that govern these geomechanical factors, and further enable first-order estimates of the risks that they pose to bounding seal integrity. The results of this review are compiled into a table that summarizes key geomechanics-related risks, the mechanisms associated with these risks, and approaches to assess and mitigate them. High value.

Morris, J. P., Hao, Y., Foxall, W., McNab, W., (2010), A study of injection-induced mechanical deformation at the In Salah CO2 storage project, International Journal of Greenhouse Gas Control, Elsevier, doi:10.1016/j.ijggc.2010.10.004

This paper is a simulation study of the hydromechanical response in the vicinity of the KB-502 CO_2 injection well at the Krenchba gas field at In-Salah (Algeria). The authors simulated the mm-scale uplift of the overburden associated with the injection and compared the results with observed ground surface deformation measured by InSAR. High-moderate value.

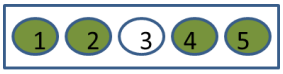
Rinaldi, A., and Rutqvist, J., (2013) Modeling of deep fracture zone opening and transient ground surface uplift at vKB-502 CO_2 injection well, In Salah, Algeria, International Journal of Greenhouse Gas Control 12 (2013) 155–167.

This paper presents a study of the transient evolution of uplift at the Krechba gas field at In Salah (Algeria) by comparing injection rate to the field Interferometric Synthetic Aperture Radar (InSAR) data using the displacement in the satellite line-of-sight. This is the first industrial scale on-shore CO_2 storage demonstration project, and is also known for satellite-based ground-deformation monitoring data of remarkable quality. High value.

Ringrose, P. S., D. M. Roberts, et al. (2011). Characterisation of the Krechba CO_2 storage site: Critical elements controlling injection performance. Energy Procedia **4**(0): 4672-4679.

This article evaluates geologic features controlling CO_2 injection performance. The main findings are that structural geological and rock mechanical aspects are most critical in the early injection phase, while characterisation of the pore space, combined with the dynamically created fracture permeability, becomes more important when considering the medium to long-term effects (10–1000 years) including geochemical, fluid dynamical and geomechanical aspects. When considering the quantity and type of data that are needed to sufficiently characterise this CO_2 storage site, high quality 3D seismic proves to be highly valuable (despite its relatively high cost). For the pore space characterisation, core samples from both the reservoir and the caprock are vital in order to calibrate and properly interpret static and dynamic well data. Finally, monitoring datasets, including well-head gas and tracer data, time-lapse seismic data, and satellite (InSAR) monitoring data need to be interpreted and only bring true value when utilised with detailed geological descriptions and models of the subsurface. High value.

Ringrose, P., A. S. Mathieson, and others, (2013). The In Salah CO_2 storage project: lessons learned and knowledge transfer. Energy Procedia.



In this study, the authors summarize the key elements of the project life-cycle and identify 3 key lessons learned from this demonstration project and how they can be applied to other major GCS projects: (1) The need for detailed geological and geomechanical characterization of the reservoir and overburden, (2) The importance of regular risk assessments based on the integration of multiple different datasets, and (3) The importance of flexibility in the design and operation of the capture, compression, and injection system. *High value.*

Rutqvist, J. and C. F. Tsang (2002). A study of caprock hydromechanical changes associated with CO_2-injection into a brine formation. Environmental Geology 42(2-3): 296-305.

This paper reports on a numerical study of hydromechanical changes during a deep underground injection of supercritical CO_2 in a hypothetical brine aquifer/caprock system. Results show that most hydromechanical changes are induced in the lower part of the caprock near its contact with the injection zone, whereas the sealing mechanism of the upper part may remain intact, despite an injection pressure close to the lithostratic stress value. Moderate value.

Rutqvist, J., J. T. Birkholzer, and others, (2008). "Coupled reservoir–geomechanical analysis of the potential for tensile and shear failure associated with CO_2 injection in multilayered reservoir–systems." International Journal of Rock Mechanics and Mining Sciences 45(2): 132-143.

This is a failure analysis modeling study that evaluates factors affecting the potential for breaching a geological CO2-storage system. The paper also evaluates methods for estimating the maximum CO2-injection pressure that could be sustained without causing such a breach. To these ands, coupled reservoir–geomechanical simulations were conducted to study the potential for tensile and shear failure—e.g., tensile fracturing and shear slip along pre-existing fractures—associated with underground CO2-injection in a multilayered geological system. High-moderate value.

Streit, J. E., A. F. Siggins, et al. (2005). Predicting, monitoring and controlling geomechanical effects of CO_2 injection. Greenhouse Gas Control Technologies 7. Oxford, Elsevier Science Ltd**:** 643-651.

This is a book chapter presenting a discussion on the effects of pore-fluid pressure change on effective stresses in porous reservoir rock. High value.

1.2 CO_2 distribution and areal extent

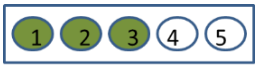
Bandilla, K. W., Kraemer, S. R., Birkholzer, J., (2012), Using semi-analytic solutions to approximate the area of potential impact for carbon dioxide injection, International Journal of Greenhouse Gas Control 8 (2012) 196–204, doi:10.1016/j.ijggc.2012.02.009

This study examines using the threshold critical pressure increase and the extent of the carbon dioxide (CO_2) plume to delineate the area of potential impact (AoPI) for geologic CO_2 storage projects, which the authors define as the combined area covering both the CO_2 plume and the region where the pressure is greater than the threshold critical pressure increase. Moderate value.

Birkholzer, J., Nicot, J. P., and others, (2011), Brine flow up a well caused by pressure perturbation from geologic carbon sequestration: Static and dynamic evaluations, International Journal of Greenhouse Gas Control 5 (2011) 850–861, doi:10.1016/j.ijggc.2011.01.003

This paper analyzes brine leakage potential in temperature and salinity-stratified systems through static mass-balance calculations as well as through dynamic well flow simulations. The authors evaluate the minimum reservoir pressure that would generate continuous migration of brine up a leaking wellbore into a freshwater aquifer. High-moderate value.

Bryant, S. L., S. Lakshminarasimhan, and others, (2008). Buoyancy-Dominated Multiphase Flow and Its Effect on Geological Sequestration of CO_2. SPE Journal 13(4): 447-454.



In this paper the authors study the mechanisms governing buoyancy dominated displacement in a series of fine-grid numerical simulations. The study builds upon the previously proposed "inject low and let rise" injection strategy to prevent CO_2 from moving predominantly along the bedding plane rather than vertically. High-moderate value.

Cavanagh, A. and P. Ringrose (2011). Simulation of CO_2 distribution at the In Salah storage site using high-resolution field-scale models. Energy Procedia 4(0): 3730-3737.

This paper presents a simulation results study that highlights the role high-resolution heterogeneous field-scale models can play in developing a comprehensive storage monitoring program.

Cavanagh, Andrew. 2011. Calibration and prediction of the Sleipner CO_2 plume from 2006 to 2012. American Geophysical Union, Fall Meeting 2011, abstract #H42C-04. http://adsabs.harvard.edu/abs/2011AGUFM.H42C.04C

This article presents a benchmark study aimed at improving flow simulation tools, modeling methods and understanding of CO_2 flow dynamics. Unlike other benchmark studies, this one is constrained by monitoring data, and considers detailed geological and reservoir engineering aspects. High value.

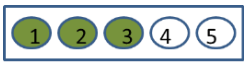
Chang, K. W., Hesse, M. A., Nicot, J. P., (2013) Reduction of lateral pressure propagation due to dissipation into ambient mudrocks during geological carbon dioxide storage, Water Resources Research, Vol. 49, 2573–2588, doi:10.1002/wrcr.20197.

This paper presents a dimensional analysis and numerical simulation study, which shows that the lateral extent of the pressure front follows a power law that depends on a single dissipation parameter. The authors conclude that pressure dissipation into ambient mudrocks retards lateral pressure propagation significantly and therefore increases the storage capacity. High-moderate value.

Deflandre, J. P., and others, (2013), Assessing Field Pressure and Plume Migration in CO_2 Storages: Application of Case-specific Workflows at in Salah and Sleipner, Energy Procedia

CO2ReMoVe sponsored project which applied site specific workflows at In Salah and Sleipner to respectively predict the reservoir pressure field and the CO_2 plume migration. High-moderate value.

Juanes, R., E. J. Spiteri, and others, (2006). Impact of relative permeability hysteresis on geological CO_2 storage. Water Resources Research 42(12).



In this paper, the authors evaluate the relevance of relative permeability hysteresis when modeling geological CO_2 sequestration processes. The study concludes that modeling of relative permeability hysteresis is required to assess accurately the amount of CO_2 that is immobilized by capillary trapping and therefore is not available to leak. Moderate value.

Lu, J., P. J. Cook, S. A. Hosseini, C. Yang, K. D. Romanak, T. Zhang, B. M. Freifeld, R. C. Smyth, H. Zeng, (2012), Complex fluid flow revealed by monitoring CO_2 injection in a fluvial formation, Journal of Geophysical Research, 117, B03208, doi:10.1029/2011JB008939

Applied field demonstration study. Several field observations at the Cranfield site showed significant heterogeneity of fluid flow and for the first time clearly demonstrated that fluid flow evolved with time and at different injection rates. It was found that the wells were connected through numerous, separate flow pathways. High value.

Nicot, J. P., Oldenburg, C., Houseworth, J. E., Choi, J. W., (2013), Analysis of potential leakage pathways at the Cranfield, MS, U.S.A., CO2 sequestration site, International Journal of Greenhouse Gas Control 18 (2013) 388–400, http://dx.doi.org/10.1016/j.ijggc.2012.10.011

This study combines geological insights, stochastic numerical modeling of the pressure field, analysis of fourteen cement bond logs, and the application of a wellbore flow model, to conclude that the limited pressure increase and mostly intact wellbores result in a low CO_2- and brine-leakage risk. High value.

Thatcher, K., S. Mathias, and others, (2011). "Simulating CO_2 storage in fluvial-channel structures of the Triassic Bunter Sandstone, Southern North Sea." Geophysical Research Abstracts 13(EGU2011-8686)

This article presents a simulation study performed to assess the effect of channel structures on pressure wave propagation and injectivity. The numerical modelling was performed using ECLIPSE 100 and simulated CO_2 injection into a saline aquifer with stochastically generated channel structures. High-moderate value.

1.3 Flow Processes

Apps, J. A., Zheng, L., Zhang, Y., Xu, T., Birkholzer, J. T., (2009), Evaluation of Potential Changes in Groundwater Quality in Response to CO_2 Leakage from Deep Geologic Storage, Transp Porous Med (2010) 82:215–246, DOI 10.1007/s11242-009-9509-8.

This article presents a systematic evaluation of the possible water quality changes in response to CO_2 intrusion into aquifers currently used as sources of potable water in the United States. High-moderate value.

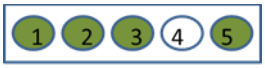
Boreham, C., Underschultz, J., and others, (2011), Monitoring of CO_2 storage in a depleted natural gas reservoir: Gas geochemistry from the CO2CRC Otway Project, Australia, International Journal of Greenhouse Gas Control 5 (2011) 1039–1054, doi:10.1016/j.ijggc.2011.03.011

This is a field demonstration study where fluid samples were collected from an observation well via U-tube at the CO2CRC Otway project to identify CO_2 breakthrough, which was confirmed to occur between 100 and 121 days after CO_2 injection began. High-moderate value.

Bryant, S. and L. W. Lake (2005). Chapter 18 - Effect of Impurities on Subsurface CO_2 Storage Processes. Carbon Dioxide Capture for Storage in Deep Geologic Formations. Amsterdam, Elsevier Science: 983-996.

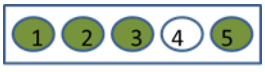
This is a book chapter examining the potential effect of highly reactive impurities (SO_x; NO_x) on two important aspects of large scale geological storage of CO_2: well injectivity and enhanced oil recovery processes. High value.

Jun, Y. C., Giammar, D., Werth, C. J., (2012), Impacts of Geochemical Reactions on Geologic Carbon Sequestration, Environmental Science and Technology, dx.doi.org/10.1021/es3027133



This study examines the rates and mechanisms of key geochemical reactions and their impacts on geological carbon storage performance, the multiphase reactive transport of CO_2, and the management of environmental risks. High-moderate value.

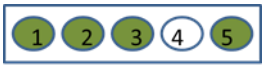
Keating, E. H., Newell, D., Viswanathan, H., and others, (2012), CO_2/Brine Transport into Shallow Aquifers along Fault Zones, Environmental Science and Technology , dx.doi.org/10.1021/es301495x



In this paper the authors focus on the upward intrusion of displaced brine or brackish-water into a shallow aquifer as a result of CO_2 injection. Using multiphase transport simulations they show

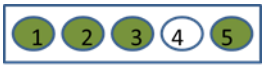
the subset of conditions under which significant CO_2 can be transported through deep brine aquifers into shallow layers. High-moderate value.

Lemieux, J. M., Review: The potential impact of underground geological storage of carbon dioxide in deep saline aquifers on shallow groundwater resources, (2011), Hydrogeology Journal (2011) 19: 757–778, DOI 10.1007/s10040-011-0715-4



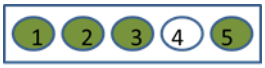
This study discusses two potential impacts from vertical CO_2 leakage: the near-field impact due to the upward vertical migration of free-phase CO_2 to surficial aquifers, and the far-field impact caused by large-scale displacement of formation waters by the injected CO_2. High value.

Little, M., Jackson, R., (2010), Potential Impacts of Leakage from Deep CO_2 Geosequestration on Overlying Freshwater Aquifers, Environmental Science and Technology, doi 10.1021/es102235w



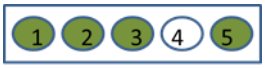
Laboratory experiment where incubations of CO_2 infiltration under oxidizing conditions were performed to understand: (1) how CO_2 leakage affects freshwater quality, (2) develop selection criteria for deep sequestration sites based on inorganic metal contamination caused by CO_2 leaks to shallow aquifers, and (3) identify geochemical signatures for early detection criteria. High-moderate value.

Lu, J., Partin, J. W., Hovorka, S. D., (2010), Potential risks to freshwater resources as a result of leakage from CO_2 geological storage: a batch-reaction experiment, Environ Earth Sci (2010) 60:335–348, DOI 10.1007/s12665-009-0382-0



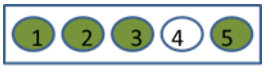
A laboratory-batch experiment was conducted to explore the range of CO_2 impact on groundwater quality of a spectrum of representative aquifers, in the Gulf Coast region, USA.

Mickler, P. J., Yang, C, Scanlon, B., (2013), Potential Impacts of CO_2 Leakage on Groundwater Chemistry from Laboratory Batch Experiments and Field Push−pull Tests, Environmental Science and Technology, dx.doi.org/10.1021/es401455j



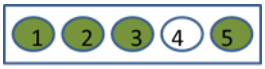
This study examines the effects of an increase in pCO_2 (partial pressure of CO_2) on groundwater chemistry in a siliclastic-dominated aquifer by comparing a laboratory batch experiment and a field single-well push−pull test on the same aquifer sediment and groundwater. High-moderate value.

Romanak, K. D, Smyth, R. C., and others, (2012), Sensitivity of groundwater systems to CO_2: Application of a site-specific analysis of carbonate monitoring parameters at the SACROC CO_2-enhanced oil field , International Journal of Greenhouse Gas Control 6 (2012) 142–152, doi:10.1016/j.ijggc.2011.10.011



This paper presents a field study and geochemical modeling of a shallow aquifer, situated above a long-running (>35 years), large-scale (~250 km2) CO_2-enhanced oil recovery site (SACROC oil field), to determine potential impact to shallow groundwater of long term CO_2 injection. High value.

Shevalier, M., and others, (2013), Brine geochemistry changes induced by CO_2 injection observed over a 10 year period in the Weyburn oil field, International Journal of Greenhouse Gas Control 16S (2013) S160–S176, http://dx.doi.org/10.1016/j.ijggc.2013.02.017



This is a field demonstration application of geochemical monitoring. Results of two geochemical surveys are discussed. A baseline geochemical survey and regular geochemical monitoring survey which occurred in two parts: Part 1 from 2000 to 2004 and Part 2 from 2008 to 2010 resulting in 17 sampling events where wellhead fluid and gas samples were collected. High value.

Siirila, E., Navarre-Sitchler, A. K., and others, (2010), A quantitative methodology to assess the risks to human health from CO_2 leakage into groundwater, Advances in Water resources, doi:10.1016/j.advwatres.2010.11.005

This article presents a quantitative methodology to assess the risks to human health from CO_2 leakage by examining multiple pathways of exposure through a probabilistic risk assessment given that leakage has occurred. Moderate value.

Yang, C., Dai, Z., Romanak, K., Hovorka, S. D., Treviño, R.,(2014), Inverse Modeling of Water-Rock-CO_2 Batch Experiments: Potential Impacts on Groundwater Resources at Carbon Sequestration Sites, Environmental Science and Technology, DOI: 10.1021/es4041368

This study developed a multicomponent geochemical model to interpret responses of water chemistry to introduction of CO2 into six water-rock batches with sedimentary samples collected from representative potable aquifers in the Gulf Coast area. The model simulated CO_2 dissolution in groundwater, aqueous complexation, mineral reactions (dissolution/precipitation) and surface complexation on clay mineral surfaces. An inverse method was used to estimate mineral surface area, the key parameter for describing kinetic mineral reactions. High-moderate value.

1.4 Petroleum geochemistry: interactions with reservoir hydrocarbons and impact on oil recovery and flow

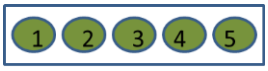
Bryant, S. and L. W. Lake (2005). Chapter 18 - Effect of Impurities on Subsurface CO_2 Storage Processes. Carbon Dioxide Capture for Storage in Deep Geologic Formations. Amsterdam, Elsevier Science: 983-996.

This is a book chapter examining the potential effect of highly reactive impurities (SO_x; NO_x) on two important aspects of large scale geological storage of CO_2: well injectivity and enhanced oil recovery processes. High value.

Klusman, R. W. (2003). "Evaluation of leakage potential from a carbon dioxide EOR/sequestration project." Energy Conversion and Management 44(12): 1921-1940.

This research presents a protocol for baseline surface geochemical measurements to evaluate the potential risk of upward movement of buoyant gases displaced by CO_2. The objective is to detect a subtle signal from depth in the presence of a large amount of near surface noise. High-moderate value.

Lake, L. W., (1989). "Enhanced Oil Recovery". Prentice Hall.



Must-have book covering fundamental aspects of Enhanced Oil Recovery. Enhanced oil recovery definitions • Basic equations for fluid flow in permeable media • Petrophysics and petrochemistry • Phase behavior and fluid properties • Displacement efficiency • Volumetric sweep • Solvent methods • Polymer methods • Micellar-polymer flooding • Other chemical methods • Thermal methods. High value.

Nicot, J.-P., J.-W. Choi, and others, (2008). Impact of Mixed Gas Stream on CO_2 Plume Characteristics during and after Carbon Storage Operations in Saline Aquifers, Bureau of Economic Geology, John A. and Katherine G. Jackson School of Geosciences.

Chevron contract report not publicly available. High-moderate value.

Nobakht, M., S. Moghadam, and others, (2008). "Mutual interactions between crude oil and CO_2 under different pressures." Fluid Phase Equilibria 265(1–2): 94-103. http://dx.doi.org/10.1016/j.fluid.2007.12.009

This is a laboratory experiment that studies the mutual interactions between a crude oil and CO_2 under different pressures and their effects on the crude oil–CO_2 interfacial tension (IFT) and CO_2 EOR. Moderate value.

Wilkinson, J. R., A. Leahy-Dios, and others, (2010). Use of CO_2 Containing Impurities for Miscible Enhanced Oil Recovery. International Oil and Gas Conference and Exhibition in China, 8-10 June 2010, Beijing, China, Society of Petroleum Engineers

This paper discusses the impact of miscibility, density and viscosity on the efficiency of the CO_2 miscible EOR process. It also presents investigations aimed at extending current light oil recovery projects into reservoirs with either residual oil zones (ROZ), viscous oils or biodegraded crudes. Moderate value.

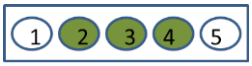
Wang, J., Ryan, D., Anthony, E., Wigston, A., (2012), The effect of impurities in oxyfuel flue gas on CO_2 storage capacity, International Journal of Greenhouse Gas Control 11 (2012) 158–162, http://dx.doi.org/10.1016/j.ijggc.2012.08.002

This study proposes a formula for measuring the impact of impurities such as N_2, O_2, Ar, SO_x, etc., on CO_2 storage capacity, and based on the formula important insights are obtained. It has been shown that the impurities in oxyfuel flue gas reduce the structural trapping capacity for CO_2 by reducing the density of CO_2, and the reduction of the trapping capacity is greater than the volume fraction of the impurities.

2. Dynamic modeling of GCS

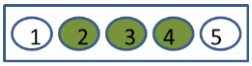
2.1 Fluid flow

Brooks, R.H., Corey, A.T., (1964). Hydraulic Properties of Porous Media, Hydrogeology Papers, p. 27. Colorado State University, Fort Collins, Colorado.



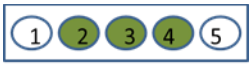
This article presents a theory that develops not only the relationships among saturation, pressure difference, and the permeabities of air and liquid but also the similitude between any two flow systems in porous media occupied by two immiscible fluid phases with static nonwetting phase. Both descriptions are expressed in terms of the hydraulic properties of porous media. High value.

Burdine, N.T., (1952). Relative permeability calculations from pore-size distribution data. Trans. Am. Inst. Min. Met all. Pet. Eng. Inc. (AIME) **198**, 71–78



This paper discusses procedures for measuring tortuosity factors. Values of relative permeability calculated by the formulas are compared with experimental results. High-moderate value.

Busch, A., Alles, S., Gensterblum, Y., Prinz, D., Dewhurst, D.N., Raven, M.D., Stanjek, H., Krooss, B.M., (2008). Carbon dioxide storage potential of shales. Int. J. Greenh. Gas Control **2**, 297–308



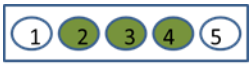
Experimental study performed to obtain information on the sealing integrity and the CO_2 storage potential of shale (Muderong Shale, Australia) and different clay minerals. All measurements were performed under reservoir conditions relevant for CO_2 storage (T = 45–50 ° C; p < 20 MPa). Results provide a positive view on the sealing integrity of intact cap rock formations. High value.

Chalbaud, C., Lombard, J.-M.,Martin, F., Robin, M., Bertin, H., Egermann, P., (2007). Two Phase Flow Properties of Brine-CO_2 Systems in a Carbonate Core: Influence ofWettability on *Pc* and *kr* , SPE 111420, Reservoir Characterization and Simulation Conference SPE/EAGE Abu Dhabi, UAE, October 28–31.

This paper presents CO_2 and N2 injection experiments in a carbonate core sample. Two different wettability conditions were investigated: water-wet and intermediate-wet. Thermodynamic conditions (pressure, temperature and water salinity) are representative of storage conditions and were the same for the entire core flooding experiments. Multirate experiments were

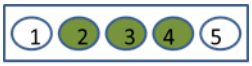
conducted with in-situ saturation monitoring and enhanced interpretation workflow (heterogeneous approach) of the production curves in order to obtain relevant and complete sets of kr and Pc data. The second part is devoted to visualization experiments. CO_2 injections were performed in glass micromodels, under the same conditions, in order to track the fluids distribution as a function of the thermodynamic and the wettability conditions. Moderate value.

Chiquet, P., Broseta, D., Thibeau, S., (2007). Wettability alteration of caprock minerals by carbon dioxide. Geofluids **7**, 112–122



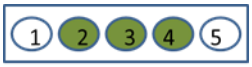
This paper provides experimental evidence showing that the water-wettability of mica and quartz is altered in the presence of CO_2 under pressures typical of geological storage conditions. The alteration is more pronounced in the case of mica. Both minerals are representative of shaly caprocks and are strongly water-wet in the presence of hydrocarbons. For hydrocarbon reservoirs that were initially close to capillary leakage, the maximum allowable CO_2 storage pressure is only a fraction of the initial reservoir pressure. High-moderate value.

Christie, M.A., (2011). Flow in porous media-scale up of multiphase flow. Curr. Opin. Colloid. Interface Sci. **6**, 236–241



This review will highlight recent developments in methods for scale-up of multi-phase flow in porous media. Scale-up is a necessary step when going from multi-million cell geostatistical models to reservoir simulation models. Multi-phase scale-up methods available include steady state methods as well as dynamic methods, along with recent developments which may remove the need for scale-up as an activity separate from simulation. High-moderate value.

Chun, B.S., Wilkinson, G.T., (1995). Interfacial tension in high-pressure carbon dioxide mixtures. Ind. Eng. Chem. Res. **34**, 4371–4377

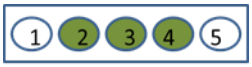


This paper investigates phenomena that are of particular relevance to phase separation and mass transfer in light hydrocarbon fractionation plants and in propane deasphalting in lubricating oil refining. Moderate value.

Corey, A.T., (1954). The interrelation between gas and oil relative permeabilities. Prod. Mon. **19**, 38–41

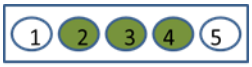
This paper presents results from several laboratory measurements by the capillary pressure technique. A relationship was observed between gas and oil relative permeabilities. The study also presents a rationalization of the relationship based on the Kozeny-Carman equation. High value.

Donaldson, E.C., Kendall, R.F., Pavelka, E.A., Crocker, M.E., (1980). Equipment and procedures for fluid flow and wettability tests of geological materials, Report, Department of Energy, Bartlesville Energy Technology Center Bartlesville, OK (USA) (1980)



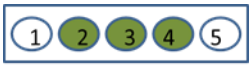
This paper describes the design features and operational procedures of 4 apparatus: (1) measurement of petroleum reservoir fluids at simulated subsurface conditions of temperature and pressure, (2) apparatus for saturation of geological cores with liquids, (3) design of a low internal volume pressure relief valve, and (4) apparatus and procedures for the quantitative determination of the relative wetting of oil and water on geologic materials. In addition, the article describes the computer programs used for the calculation of miscible phase dispersion of reservoir fluids and adsorption characteristics of reservoir chemicals. High-moderate value.

Dria, D.E., Pope, G.A., Sepehrnoori, K., (1993). Three-phase gas/oil/brine relative permeabilities measured under CO_2 flooding conditions. SPE Reserv. Eng. **20184**, 143–150



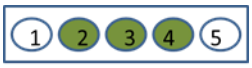
Experimental study where steady-state three-phase gas/oil/brine relative permeabilities were measured in a carbonate core under CO_2 flooding permeabilities were measured in a carbonate core under CO_2 flooding conditions. Results show that the relative permeability of each phase depends only on the saturation of that phase instead of on phase depends only on the saturation of that phase instead of on two saturations, as many previous studies have concluded. Results also show that significant differences exist between the three-phase gas/oil/brine relative permeabilities measured when the gas is CO_2 and those permeabilities measured when the gas is CO_2 and those measured when the gas was N_2. High-moderate value.

Egermann, P., Chalbaud, C., Duquerroix, J.P., Le Gallo, Y., (2006). An Integrated Approach to Parameterize Reservoir Models for CO2 Injection in Aquifers. SPE 102308, San Antonio, TX



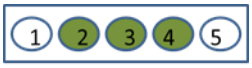
This paper presents an integrated workflow based on experiments and numerical simulations to determine in a comprehensive and robust manner the appropriate parameters at the core scale for a CO_2 injection in aquifer. CO_2 injection experiments were conducted under reservoir conditions. Experiment were carried out on companion plugs under several thermodynamic conditions and with different fluid systems (different brine salinities) in order to collect data (production curves and differential pressure evolution as a function of time) over a wide range of CO_2 storage conditions. Then, these experiments were modeled using a compositional simulator dedicated to CO_2 geological storage.

Grigg, R.B., Svec, R.K, (2003). Co-injected CO_2-Brine Interactions with Indiana Limestone, International Symposium of the Society of Core Analysts, SCA2003-19, Pau, France.



This paper reports findings of core flooding limestone with co-injected carbon dioxide (CO_2) and brine at reservoir pressure and temperature. Metal chlorides were added as tracer components to the injection brine and appeared in quantities well above natural levels in deposited carbonates. Core segment porosity and permeability are reported to indicate dissolution and deposition. Finally, the core was sectioned and analyzed by chemical and back-scattered electron imaging (BSEI) and chemical titration for compositional changes.

Hadley, G.F., Handy, L.L.: A Theoretical and Experimental Study of the Steady State Capillary End Effect. SPE 707, Los Angeles, California (1956)

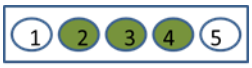


This paper presents the derivation of formulas for calculating the steady state saturation profile and pressure profile resulting from the end effect. A numerical integration was conducted to obtain the results. A discussion is given to show that in the measurement of relative permeability curves by the dynamic method, the end effect has a large influence on the preferentially nonwetting phase relative permeability curve if the pressure drop is measured in the wetting phase. If the pressure drop is measured in the nonwetting phase, the largest error appears in the wetting phase curve. If the pressures are measured in both phases, the errors tend to be self-correcting for each relative permeability curve. High-moderate value.

Hebach, A., Oberhof, A., Dahmen, N., Kögel, A., Ederer, H., Dinjus, E., (2002). Interfacial tension at elevated pressures measurements and correlations in the water + carbon dioxide system. J. Chem. Eng. Data **47**, 1540– 1546

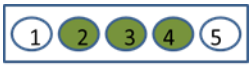
This article presents a novel apparatus, PeDro, for high-pressure measurement of the interfacial tension using the pendant drop method. This apparatus was constructed for accurate measurements in the two-component system of water and compressed carbon dioxide. The main influences on accurate and reproducible results have been investigated, and the results have led to an optimized experimental setup and a quasi-static measuring method. PeDro was calibrated against well-established data for water + air. The experimental error of measurement is smaller than 2%. In this two-phase system measurements were conducted in the ranges (278 to 335) K and (0.1 to 20) MPa. The interfacial tension showed a pronounced dependence on pressure and temperature. A regression function has been found which describes the experimental data in the range investigated with high precision. Moderate value.

Hosseini, S. A., and Kelkar, M., 2010, Analytical upgridding method to preserve dynamic flow behavior: SPE Reservoir Evaluation & Engineering, v. 13, no. 3, p. 473–484. doi: 10.2118/116113-PA.



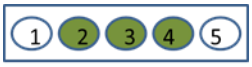
This study proposed a new upgridding method that preserves the pressure profile at an upscaled level. The new method is currently developed for single-phase flow; however, the authors used it for both single-phase and two-phase flows for 2D and 3D cases. The method differs fundamentally from other methods that try to preserve heterogeneities. Instead, they combine the gridblocks that have similar pressure profiles. The procedure is analytical but preserves the pressure profile in the reservoir. High-moderate value.

Juanes, R., Spiteri, E.J., Orr, F.M. Jr., Blunt, M.J., (2006). Impact of relative permeability hysteresis on geological CO2 storage. Water Resour. Res. **42**, 1–13



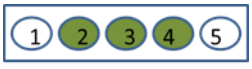
In this study, the authors evaluate the relevance of relative permeability hysteresis when modeling geological CO_2 sequestration processes. The authors concentrate on CO_2 injection in saline aquifers. In this setting the CO_2 is the nonwetting phase, and capillary trapping of the CO_2 is an essential mechanism after the injection phase during the lateral and upward migration of the CO_2 plume. They demonstrate the importance of accounting for CO_2 trapping in the relative permeability model for predicting the distribution and mobility of CO_2 in the formation. The authors conclude that modeling of relative permeability hysteresis is required to assess accurately the amount of CO_2 that is immobilized by capillary trapping. High-moderate value.

Maas, J., Zweers, A., Scherpenisse, W., Wit, K., (1999). Relative Permeability Measurements on Heterogeneous Samples: A Pragmatic Approach. SCA-9909, 11



The study explores the reliability of measured flow parameters like relative permeability and residual oil, when laboratory practices, including SCAL, require data to be obtained from homogeneous samples. The paper proposes a method to address this problem. High-moderate value.

Manrique, E.J., Muci, V.E., Gurfinkel, M.E., (2007). EOR field experiences in carbonate reservoirs in the United States. SPE Reserv. Eval. Eng. **10**, 667–686 (2007) Marini, L.: Geological Sequestration of Carbon Dioxide—Thermodynamics, Kinetics, and Reaction Path Modeling, p. 453. Elsevier, Amsterdam, The Netherlands.



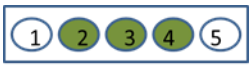
This paper presents an overview of EOR field experiences in carbonate reservoirs in the United States, an analysis of recent efforts and discusses briefly on new opportunities for novel chemical

methods. The main EOR experiences reviewed are CO2 injection, polymer flooding, steam injection and in-situ combustion. High value.

Mathias, S. A., Gluyas, J. G., Gonzalez Martinez de Miguel, G. J., and Hosseini, S. A., (2011). Role of partial miscibility on pressure buildup due to constant rate injection of CO_2 into closed and open brine aquifers: Water Resources Research, v. 47, W12525, doi:10.1029/2011WR011051, 11 p.

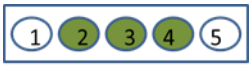
This work presents the extension of an existing analytical solution for pressure buildup due to CO_2 injection in brine aquifers by incorporating effects associated with partial miscibility. These include evaporation of water into CO_2, dissolution of CO_2 into brine and salt precipitation. The resulting equations are closed-form, including the locations of the associated leading and trailing shock fronts. The resulting equations remain simple to evaluate in spreadsheet software and represent an improvement on current methods for estimating pressure limited CO_2 storage capacity. Moderate value.

Mualem,Y., (1976). A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. **12**, 513–522



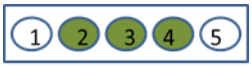
A simple analytic model is proposed which predicts the unsaturated hydraulic conductivity curves by using the moisture content-capillary head curve and the measured value of the hydraulic conductivity at saturation. It is similar to the Childs and Collis-George (1950) model but uses a modified assumption concerning the hydraulic conductivity of the pore sequence in order to take into account the effect of the larger pore section. A computational method is derived for the determination of the residual water content and for the extrapolation of the water content-capillary head curve as measured in a limited range. The proposed model is compared with the existing practical models. Moderate value.

Muller, N., Qi, R., Mackie, E., Pruess, K., Blunt, M.J., (2008). CO_2 injection impairment due to halite precipitation. Energy Procedia **1**, 3507–3514



This paper presents an injection impairment study performed for the CO2SINK Project, a European Union research project on testing geological carbon storage near Ketzin, Germany . Core flood experiments showed that halite precipitates due to brine evaporating in dry super-critical CO_2. The phenomenon was studied with two research codes, TOUGH2 and a streamline-based simulator. Both codes predict substantial salt deposition close to the injection point, with associated severe injection impairment. Simulations also suggest that simple reservoir engineering measures, such as a brief (hours) preflush with fresh water, can mitigate adverse effects. High-moderate value.

Muller, Nadja, (2010), "Supercritical CO_2-brine relative permeability experiments in reservoir rocks - literature review and recommendations." Springer Science+Business Media B.V., Transp Porous Med (2011) 87:367–383, DOI 10.1007/s11242-010-9689-2



Study to obtain a relative permeability data through steady state and unsteady state approaches. Moderate value.

Oak, M.J., Baker, L.E., Thomas, C.C., (1990). Three-phase relative permeability of Berea sandstone. J. Pet. Technol. **42**, 1054–1061

Experimental study to investigate prediction methods. Two- and three-phase relative permeabilities were measured on a water-wet fired Berea sandstone core with a fully automated steady-state method. Reservoir engineering calculations frequently require consideration of coexisting oil, water, and gas phases. Such three-phase flow occurs when oil is displaced by simultaneous gas/water flow as in CO_2, water-alternating-gasflooding, steamflooding, or other enhanced recovery processes. For this reason, reservoir simulators generally include three-phase relative permeability prediction methods. High-moderate value.

Perrin, J.-C., Krause, M., Benson, S.M., (2008): Relative Permeability Properties of the CO_2/Brine System in Saline Aquifers: An Experimental Study, Seventh Annual Conference on Carbon Capture & Sequestration, Pittsbrugh, p. 22

Experimental study where s total of 51 samples of core material from one well (Dh4) were collected and tested to find potential units for CO_2 injection. Analysis of the results shows that the permeability is generally less than 2 millidarcies and the capillary entry pressure is high. This poses a serious challenge with respect to achieving practical levels of injectivity and injection pressure. High-moderate value.

Perrin, J.-C., Krause, M., Kuo, C.-W., Miljkovic, L., Charoba, E., Benson, S.M., (2009). Core-scale experimental study of relative permeability properties of CO_2 and brine in reservoir rocks. Energy Procedia **1**, 3512–3522

Experimental studies where two new sets of steady state relative permeability measurements were made in two different rock samples, and over a range of injection flow rates. These studies show that multi-phase brine displacement efficiency is strongly affected by the heterogeneity of the core. Moreover, the authors observe that, at any given fractional flow, different flow rates result in different CO_2 saturations. Similarly, different flow rates lead to different relative permeability curves. Numerical simulations of two phase displacement are performed on one

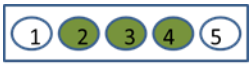
sample, and at one fractional flow of CO_2. Numerical simulations demonstrate that some of the features of the saturation distributions can be qualitatively replicated. However, improvements in the correlations between porosity, saturation and capillary pressure will be needed to replicate the saturation distributions measured in the experiments. High-moderate value.

Pruess, K., (2004). The TOUGH codes—a family of simulation tools for multiphase flow and transport processes in permeable media. Vadose Zone J. 3, 738–746 (2004)

This article discusses a suite of codes, developed primarily at Lawrence Berkeley National Laboratory (LBNL), with the capability to model multiphase flows with phase change. They provide a summary, history and goals in the development of the TOUGH codes, and present the governing equations for multiphase, multicomponent flow. Special emphasis is given to space discretization by means of integral finite differences (IFD). Issues of code implementation and architecture are addressed, as well as code applications, maintenance, and future developments. High value.

2.2 Property (PVT) model

André, L., Audigane, P., Azaroual, M., Menjoz, A., 2007, Numerical modeling of fluid-rock chemical interactions at the supercritical CO_2-liquid interface during CO_2 injection into a carbonate reservoir, the Dogger aquifer (Paris Basin, France), Energy Conversion and Management, Volume 48, Issue 6, Pages: 1782-1797.



Simulation study comparing the reactivity of CO2 saturated water with the reactivity of supercritical CO2. Results imply that supercritical CO_2 injection is weakly reactive, with a limited modification of well injectivity. Moderate value.

Bakker, R. J., (2003). Package FLUIDS 1. Computer programs for analysis of fluid inclusion data and for modelling bulk fluid properties. Chemical Geology 194 (2003) 3–23

This paper describes computer package FLUIDS, which contains five sets of computer programs written in C++ for the calculation of fluid properties. It includes a group of programs (Aqso) that allows purely empirical modeling of Henry's law for dilute gas-bearing aqueous solutions. The programs are available on the University of Leoben web site at http:/www.unileoben.ac.at/~buero62/minpet/ronald. High-moderate value.

Canjar, L. N., and Manning, F., (1967) Thermodynamic properties and reduced correlations for gases. Gulf Pub. Co.

Book presenting a compilation in tabular form and in Mollier diagrams of the thermodynamic properties of different gases, including CO2. High value.

Gaus, I. (2010). "Role and impact of CO_2–rock interactions during CO_2 storage in sedimentary rocks." International Journal of Greenhouse Gas Control 4(1): 73-89.

This article discusses methodologies for assessing CO_2–rock interactions in 6 potential areas (or phases) of concern: (1) interactions during the injection phase and in the near well environment, (2) long-term reservoir and cap rock interactions, (3) CO_2–rock interactions along leakage pathways (well, cap rock and fault), (4) CO_2–rock interactions causing potable aquifer contamination as a consequence of leakage, (5) water–rock interactions caused by aquifer contamination through the CO_2 induced displacement of brines, and (6) engineered CO_2–rock interactions. The driving processes of CO_2–rock interactions are discussed as well as their potential impact in terms of changing physical parameters. Moderate value.

Gaus, I., Audigane, P., André, L., Lions, J., Jacquemet, N., Durst, P., Czernichowski-Lauriol, I., Azaroual, M., (2008). Geochemical and solute transport modelling for CO_2 storage, what to expect from it? International Journal of Greenhouse Gas Control, Volume 2, Issue 4, Pages 605-625.

This paper provides an overview of geochemical and solute transport modelling for CO_2 storage, and highlights data requirements, challenges, and gaps up up to 2008. High value.

Harvey, A. H., (1996). Semiempirical Correlation for Henry's Constants over large temperature ranges. AIChE J. 42, 1491

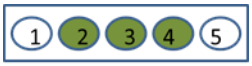
This study recasts a semiempirical correlation for aqueous Henry's constants in a form requiring no density or fugacity evaluations. Henry's Law is commonly used to describe the solubility of gases in liquids at low and moderate partial pressures. The correlation presented here is applicable over larger temperature ranges. High value.

Peng, D., Y., and Robinson, D., B., (1976). A new two-constant Equation of State. Ind. Eng. Chem., Fundam., Vol. 15, No. 1.

This important work presents the development of the most broadly used EoS in CO_2 injection processes. This is a two-constant equation of state in which the attractive pressure term of the semi-empirical van der Waals equation has been modified is outlined. Examples of the use of the equation for predicting the vapor pressure and volumetric behavior of singie-component systems, and the phase behavior and volumetric behavior of binary, ternary, and multicomponent systems are given. The proposed equation combines simplicity and accuracy. It performs as well as or better than the Soave-Redlich-Kwong equation in all cases tested and shows its greatest advantages in the prediction of liquid phase densities. High Value.

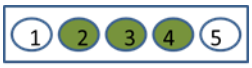
2.3 Geochemistry

André, L., Audigane, P., Azaroual, M., Menjoz, A., 2007, Numerical modeling of fluid-rock chemical interactions at the supercritical CO_2-liquid interface during CO_2 injection into a carbonate reservoir, the Dogger aquifer (Paris Basin, France), Energy Conversion and Management, Volume 48, Issue 6, Pages: 1782-1797.



Simulation study comparing the reactivity of CO_2 saturated water with the reactivity of supercritical CO_2. Results imply that supercritical CO_2 injection is weakly reactive, with a limited modification of well injectivity. Moderate value.

Azaroual, M., L. Andre, Y. Peysson, J. Pironon, D. Broseta, F. Dedecker, P. Egermann, J. Desroches, J. Hy-billiot (2012), Behavior of the *CO_2* injection well and the near wellbore during carbon dioxide injection in saline aquifers, TOUGH Symposium, September 2012, LBNL, Berkeley, CA.



Numerical simulation study aiming to understand physico-chemical processes, dryout of thenear-wellbore porous media and reactivity of highly evaporated residual brines retained by capillary and osmotic forces in the pores, and petrophysical and geomechanical impacts of coupled processes. High-moderate value

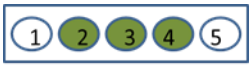
Gaus, I., M. Azaroual, and others, (2005). Reactive transport modelling of the impact of CO_2 injection on the clayey cap rock at Sleipner (North Sea). Chemical Geology 217(3–4): 319-337.

Reactive transport modelling study to assess the impact of major geochemical reactions between CO_2, the cap rock formation water, and the cap rock mineralogy on the porosity of the cap rock at Sleipner (37 °C, 101.3×10^5 Pa). A slight decrease of the porosity was predicted which might improve the sealing capacity of the cap rock, but this porosity change was found to be restricted to the lower meters, even in the most reactive case. High value.

Gaus, I., Audigane, P., André, L., Lions, J., Jacquemet, N., Durst, P., Czernichowski-Lauriol, I., Azaroual, M., (2008). Geochemical and solute transport modelling for CO_2 storage, what to expect from it? International Journal of Greenhouse Gas Control, Volume 2, Issue 4, Pages 605-625.

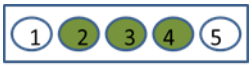
This paper provides an overview of geochemical and solute transport modelling for CO_2 storage, and highlights data requirements, challenges, and gaps up to 2008. High value.

Jun, Y.-S., D. E. Giammar and C. J. Werth (2012). Impacts of Geochemical Reactions on Geologic Carbon Sequestration. Environmental Science & Technology.



Simulation study to understand the impact of key geochemical reactions on GCS performance, the multiphase reactive transport of CO_2, and the management of environmental risks. Moderate value.

Muller, N., Qi, R., Mackie, E., Pruess, K., Blunt, M.J., (2008). *CO_2* injection impairment due to halite precipitation. Energy Procedia **1**, 3507–3514



This paper presents an injection impairment study performed for the CO2SINK Project, a European Union research project on testing geological carbon storage near Ketzin, Germany . Core flood experiments showed that halite precipitates due to brine evaporating in dry super-critical CO_2. The phenomenon was studied with two research codes, TOUGH2 and a streamline-based simulator. Both codes predict substantial salt deposition close to the injection point, with associated severe injection impairment. Simulations also suggest that simple reservoir engineering measures, such as a brief (hours) preflush with fresh water, can mitigate adverse effects. High-moderate value.

Newell, D. L.; Carey, J. W., (2012).Experimental evaluation of wellbore integrity along the cement-rock boundary. Environ. Sci. Technol., DOI: 10.1021/es3011404.

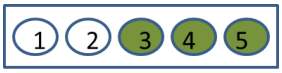
Experimental study comprised of multiphase (supercritical CO_2-brine) corefloods that simulate a leakage pathway along the cement/rock interface. A composite core constructed of oil-well cement and siltstone separated by a simulated damage zone (defect) containing ground cement and siltstone was flooded with brine + $scCO_2$ at 10 MPa and 60 °C parallel to the defect. Microscopy revealed leaching and erosion along the defect, a carbonation front extending 5 mm into the cement, parallel to the damage zone, and no change in the dimensions of the defect. High-moderate value.

Pruess, K. (2011). Integrated modeling of CO_2 storage and leakage scenarios including transitions between super- and subcritical conditions, and phase change between liquid and gaseous CO_2." Greenhouse Gases: Science and Technology **1**(3): 237-247.

In this paper, the authors describe and demonstrate simulation capabilities that can cope with several phase conditions in brine-CO_2 systems, including (1) description of thermophysical properties of aqueous and CO_2-rich phases as functions of temperature, pressure, salinity and CO_2 content, including the mutual dissolution of CO_2 and H_2O, (2) transitions between super- and subcritical conditions, including phase change between liquid and gaseous CO_2, (3) non-isothermal effects associated with phase change, mutual dissolution of CO_2 and water, and de-

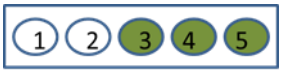
compression effects; and (4) the effects of dissolved NaCl, and the possibility of precipitating solid halite, with associated porosity and permeability change. High-moderate value.

Pruess, K. and N. Müller (2009). Formation dry-out from CO_2 injection into saline aquifers: 1. Effects of solids precipitation and their mitigation. Water Resour. Res. 45(3): W03402.



Numerical simulation study to evaluate the main physical mechanisms affecting the dry-out and salt precipitation process: (1) displacement of brine away from the injection well by injected CO_2, (2) dissolution (evaporation) of brine into the flowing CO_2 stream, (3) upflow of CO_2 due to gravity effects (buoyancy), (4) backflow of brine toward the injection point due to capillary pressure gradients that oppose the pressure gradient in the CO_2-rich ("gas") phase, and (5) molecular diffusion of dissolved salt. High-moderate value.

Pruess, K., (2009). Formation dry-out from CO_2 injection into saline aquifers: 2. Analytical model for salt precipitation. Water Resour. Res. 45, W03403.

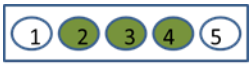


In this paper the author derives an equation that directly relates gas saturation at the dry-out front to temperature, pressure, and salinity dependence of fluid properties. The author derived this equation from a mass balance for water dissolved into the flowing CO_2 stream and a consideration of saturation profiles from the Buckley-Leverett fractional flow theory. High value.

Pruess, K., Spycher, N., (2007). ECO2N—a fluid property module for the TOUGH2 code for studies of CO_2 storage in saline aquifers. Energy Convers. Manage. 48 (6), 1761–1767.

This paper presents a description of ECO2N, which is a fluid property module for the TOUGH2 simulator (Version 2.0) that was designed for applications involving geologic storage of CO_2 in saline aquifers. It includes a comprehensive description of the thermodynamics and thermophysical properties of H_2O–NaCl–CO_2 mixtures that reproduces fluid properties largely within experimental error for the temperature, pressure and salinity conditions of interest. High-moderate value.

Pruess, K., C. Oldenburg, and G. Moridis, (1999). TOUGH2 User's Guide, Version 2.0, Report LBNL-3134, Lawrence Berkeley National Laboratory, Berkeley, Calif.



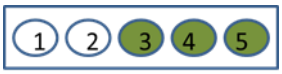
User guide. TOUGH2 is a general-purpose numerical simulation program for multi-dimensional fluid and heat flows of multiphase, multicomponent fluid mixtures in porous and fractured media. Chief application areas are in geothermal reservoir engineering, nuclear waste isolation

studies, environmental assessment and remediation, and flow and transport in variably saturated media and aquifers. High value.

Shao, H.; Ray, J. R.; Jun, Y.-S. Dissolution and precipitation of clay minerals under geologic CO_2 sequestration conditions: CO_2–brine–phlogopite interactions. Environ. Sci. Technol. 2010, 44 (15), 5999–6005.

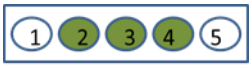
In this work, both fluid/solid chemistry analysis and interfacial topographic studies were conducted to investigate the dissolution/precipitation on phlogopite ($KMg_3Si_3AlO_{10}(F,OH)_2$) surfaces under GCS conditions (368 K, 102 atm) in 1 M NaCl. Phlogopite served as a model for clay minerals in potential GCS sites. High-moderate value.

Zeidouni M., Pooladi-Darvish M., Keith D., (2009). Analytical solution to evaluate salt precipitation during CO2 injection in saline aquifers, International Journal of Greenhouse Gas Control, Volume 3, Issue 5, September 2009, Pages 600-611.



This study develops a model which treats the vaporization of water and dissolution of CO_2 in radial geometry. Next, the model is used to predict salt precipitation. The combined model is then extended to evaluate the effect of salt precipitation on permeability in terms of a time-dependent skin factor. Finally, the analytical model is corroborated by application to a specific problem with an available numerical solution, where a close agreement between the solutions is observed. The authors use the results to examine the effect of assumptions and approximations made in the development of the analytical solution. High-moderate value.

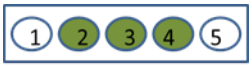
Zhang, G., E.I. Villegas (2012), Geochemical reactive transport modeling in oil and gas industry- Bussiness drivers, challenges and solutions, TOUGH Symposium, September 2012, LBNL, Berkeley, CA.



This paper discusses the business drivers, evaluate the challenges, and propose solutions for applications of RTM technology in the oil and gas industry, using real examples such as water injection, CO2 injection (CCS or EOR), and water-alternate gas injection (WAG). High-moderate value.

2.4 Thermal modeling

Daughty, C., Freifeld, B., 2013, Modeling CO_2 injection at Cranfield, Mississippi: Investigation of methane and temperature effects, Greenhouse Gases: Science and Technology, DOI: 10.1002/ghg.1363



Field/modeling study where results are compared with temperature observations made in the field with a Distributed Temperature Sensor (DTS) system, suggesting that a well-defined thermal response reached the near observation well within the seven-month monitoring period, but not the more distant observation well. High-modetare value.

Jordan, Preston and Doughty Christine. (2009). Sensitivity of CO_2 migration estimation on reservoir temperature and pressure uncertainty. Energy Procedia 1, 2825-2832.

Numerical simulation study showing that the relative ultimate plume size is almost directly proportional to the relative difference in brine and CO_2 density (buoyancy flow). The majority of the difference in plume size occurs during and shortly after the cessation of injection. High-moderate value.

Tao, Q., Bryant, S. L., and Meckel, T. A. (2013). Modeling above-zone measurements of pressure and temperature for monitoring CCS Sites. International Journal of Greenhouse Gas Control.

This study presents a simple set of coupled analytical models that enable diagnosis of above-zone monitoring data. Concurrent pressure and temperature measurements are especially valuable because they independently constrain the effective permeability of a leakage path along wellbore. High-moderate value.

2.5 Geomechanical modeling

Chiaramonte, L., Zoback, M. D., Friedmann, J., Stamp, V., (2008). "Seal integrity and feasibility of CO_2 sequestration in the Teapot Dome EOR pilot: geomechanical site characterization." Environmental Geology, Volume 54, Issue 8, pp.1667-1675, doi: 10.1007/s00254-007-0948-7

This paper presents a report of a preliminary investigation of seal integrity at Teapot Dome oil field, Wyoming, USA, with the objective of predicting the potential risk of CO_2 leakage along reservoir-bounding faults. High-moderate value.

Gemmer, L., O. Hansen, and others, (2012). Geomechanical response to CO_2 injection at Krechba, In Salah, Algeria. First Break 30(2): 79-84.

This article discusses the geomechanical modelling of the rock mechanical response to CO_2 injection at the Krechba gas field in Algeria arguing that key factors to understanding are the sensitivity of the model to the initial stress field and the rock-mechanical properties of the fault/fracture zones. High value.

Hawkes, C. D., P. J. McLellan, and others, (2004). Geomechanical Factors Affecting Geological Storage of CO_2 in Depleted Oil And Gas Reservoirs: Risks And Mechanisms. Gulf Rocks 2004, the 6th North America Rock Mechanics Symposium (NARMS), June 5 - 9, 2004 , Houston, Texas, American Rock Mechanics Association.

This paper provides a review of the geomechanical factors affecting the hydraulic integrity of the bounding seals for a depleted oil or gas reservoir slated for use as a CO_2 injection zone. Equations are given which are helpful for identifying the key parameters that govern these geomechanical factors, and further enable first-order estimates of the risks that they pose to bounding seal integrity. The results of this review are compiled into a table that summarizes key geomechanics-related risks, the mechanisms associated with these risks, and approaches to assess and mitigate them. High value.

Morris, J. P., Hao, Y., Foxall, W., McNab, W., (2010), A study of injection-induced mechanical deformation at the In Salah CO2 storage project, International Journal of Greenhouse Gas Control, Elsevier, doi:10.1016/j.ijggc.2010.10.004

This paper is a simulation study of the hydromechanical response in the vicinity of the KB-502 CO_2 injection well at the Krenchba gas field at In-Salah (Algeria). The authors simulated the mm-scale uplift of the overburden associated with the injection and compared the results with observed ground surface deformation measured by InSAR. High-moderate value.

Rinaldi, A., and Rutqvist, J., (2013) Modeling of deep fracture zone opening and transient ground surface uplift at vKB-502 CO_2 injection well, In Salah, Algeria, International Journal of Greenhouse Gas Control 12 (2013) 155–167.

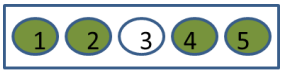
This paper presents a study of the transient evolution of uplift at the Krechba gas field at In Salah (Algeria) by comparing injection rate to the field Interferometric Synthetic Aperture Radar (InSAR) data using the displacement in the satellite line-of-sight. This is the first industrial scale

on-shore CO_2 storage demonstration project, and is also known for satellite-based ground-deformation monitoring data of remarkable quality. High value.

Ringrose, P. S., D. M. Roberts, et al. (2011). Characterisation of the Krechba CO_2 storage site: Critical elements controlling injection performance. Energy Procedia **4**(0): 4672-4679.

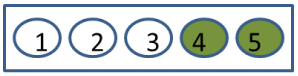
This article evaluates geologic features controlling CO_2 injection performance. The main findings are that structural geological and rock mechanical aspects are most critical in the early injection phase, while characterisation of the pore space, combined with the dynamically created fracture permeability, becomes more important when considering the medium to long-term effects (10–1000 years) including geochemical, fluid dynamical and geomechanical aspects. When considering the quantity and type of data that are needed to sufficiently characterise this CO_2 storage site, high quality 3D seismic proves to be highly valuable (despite its relatively high cost). For the pore space characterisation, core samples from both the reservoir and the caprock are vital in order to calibrate and properly interpret static and dynamic well data. Finally, monitoring datasets, including well-head gas and tracer data, time-lapse seismic data, and satellite (InSAR) monitoring data need to be interpreted and only bring true value when utilised with detailed geological descriptions and models of the subsurface. High value.

Ringrose, P., A. S. Mathieson, and others, (2013). The In Salah CO_2 storage project: lessons learned and knowledge transfer. Energy Procedia.



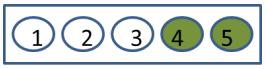
In this study, the authors summarize the key elements of the project life-cycle and identify 3 key lessons learned from this demonstration project and how they can be applied to other major GCS projects: (1) The need for detailed geological and geomechanical characterization of the reservoir and overburden, (2) The importance of regular risk assessments based on the integration of multiple different datasets, and (3) The importance of flexibility in the design and operation of the capture, compression, and injection system. *High value.*

Rutqvist, J. and C. F. Tsang (2002). A study of caprock hydromechanical changes associated with CO_2-injection into a brine formation. Environmental Geology 42(2-3): 296-305.



This paper reports on a numerical study of hydromechanical changes during a deep underground injection of supercritical CO_2 in a hypothetical brine aquifer/caprock system. Results show that most hydromechanical changes are induced in the lower part of the caprock near its contact with the injection zone, whereas the sealing mechanism of the upper part may remain intact, despite an injection pressure close to the lithostratic stress value. Moderate value.

Rutqvist, J., J. T. Birkholzer, and others, (2008). "Coupled reservoir–geomechanical analysis of the potential for tensile and shear failure associated with CO_2 injection in multilayered reservoir–systems." International Journal of Rock Mechanics and Mining Sciences 45(2): 132-143.



This is a failure analysis modeling study that evaluates factors affecting the potential for breaching a geological CO2-storage system. The paper also evaluates methods for estimating the maximum CO2-injection pressure that could be sustained without causing such a breach. To these ands, coupled reservoir–geomechanical simulations were conducted to study the potential for tensile and shear failure—e.g., tensile fracturing and shear slip along pre-existing fractures—associated with underground CO2-injection in a multilayered geological system. High-moderate value.

Streit, J. E., A. F. Siggins, et al. (2005). Predicting, monitoring and controlling geomechanical effects of CO_2 injection. Greenhouse Gas Control Technologies 7. Oxford, Elsevier Science Ltd**:** 643-651.

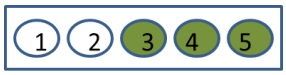
This is a book chapter presenting a discussion on the effects of pore-fluid pressure change on effective stresses in porous reservoir rock. High value.

3. Monitoring, Verification, and Accounting (MMV)

3.1 Flood Performance

3.1.1 Field data integration and reservoir modeling

Akbarabadi, M. and Piri M., (2011). Geologic storage of Carbon Dioxide: An experimental study of permanent capillary Trapping and relative permeability. Department of Chemical & Petroleum Engineering, University of Wyoming. This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Austin, Texas, USA 18-21 September.

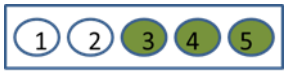


Experimental study presenting results on the effects of hysteresis on permanent capillary trapping and relative permeability of CO2/brine systems. High value.

Arts, R., Eiken, O., Chadwick, R.A., Zweigel, P., Van Der Meer, L., and Kirby, G.A. 2004. Seismic monitoring at the Sleipner underground CO_2 storage site (North Sea). In: Baines, S. and Worden, R.J. (Eds.) Geological Storage for CO_2 emissions reduction. Geological Society, London, Special Publication 233, 181-191.

This study presents some aspects of the interpretation of the first two seismic surveys acquired at Sleipner, the first industrial scale CO_2 storage project. the first repeat survey was completed in October 1999 and the second in October 2001. The presence of CO_2 beneath thin intra-shale layers within the reservoir has caused significant changes both in reflection amplitudes (up to a factor 10) and in travel time (more than 40ms) through the CO_2 plume (the velocity push-down effect). High value.

Arts, R.; Chardwick R.A.; Eiken, Ola; Thibeau, Silvain and Nooner Scott. 2008. Ten years' experience of monitoring CO_2 injection in the Utsira Sand at Sleipner, offshore Norway in First Break. Vol 26, 65-72. http://www.ldeo.columbia.edu/~snooner/Nooner/Publications_files/fbjan08_05.pdf

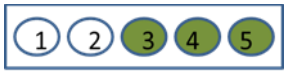


Summary article outlining the experiences gained at this site, especially with respect to monitoring of CO2 migration in the subsurface. High-moderate value.

Bachu, Stefan and Bennion Brant. 2008. E, Effects of in-situ conditions on relative permeability characteristics of CO_2-brine systems, Environmental Geology, June 2008, Volume 54, Issue 8, pp 1707-1722

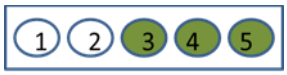
This paper presents a summary and interpretation of results of experimental measurements of relative permeability and other displacement characteristics of CO_2-brine systems for sandstone, carbonate and shale formations in central Alberta in western Canada. The tested formations are representative of the in-situ characteristics of deep saline aquifers in compacted on-shore North American sedimentary basins. The results show that the capillary pressure, interfacial tension, relative permeability and other displacements characteristics of CO_2-brine systems depend on the in-situ conditions of pressure, temperature and water salinity, and on the pore size distribution of the sedimentary rock.

Bennion, B., Bachu, S., (2008), Drainage and imbibition relative permeability relationships for supercritical CO_2/brine and H_2S/brine systems in intergranular sandstone, carbonate, shale, and anhydrite rocks, SPE Reservoir Evaluation Engineering, 11, 487-496, DOI: 10.2118/99326-PA.



This paper presents the detailed experimental equipment and protocols, and the results of a series of relative permeability measurements conducted at full reservoir conditions using supercritical pure CO_2 and H_2S on samples of intercrystaline sandstone, carbonate, shale, and anhydrite rocks from the Wabamun and Zama areas in Alberta, Canada, where large CO_2 sources and several acid-gas-injection operations exist. Results of the relative permeability measurements are presented for each fluid and rock type. The results provide a valuable dataset for the evaluation and simulation of acid gas disposal and CO_2 sequestration projects. High value.

Cavanagh, A. and P. Ringrose (2011). "Simulation of CO_2 distribution at the In Salah storage site using high-resolution field-scale models." Energy Procedia 4(0): 3730-3737.



Simulation study using an invasion percolation modelling approach to simulate the CO2 migration process assuming capillary limit conditions. The field-scale model involves 56 million cells with dimensions of 10x10x2 meters. This high-resolution model captured the reservoir heterogeneity with respect to both the fault and fracture distributions. The simulation results highlight the role that high-resolution heterogeneous field-scale models can play in developing a comprehensive storage monitoring program. High-moderate value.

Cavanagh, Andrew. 2011. Calibration and prediction of the Sleipner CO_2 plume from 2006 to 2012. American Geophysical Union, Fall Meeting 2011, abstract #H42C-04. http://adsabs.harvard.edu/abs/2011AGUFM.H42C.04C

This is a satellite surveys (InSAR) study showing subtle surface deformation and well data analysis (gas geochemistry and tracers). These data was used to interpret the pressure and gas distribution. The authors conclude that the simulation results are reasonably consistent with the inferred CO2 distribution after 5 years of injection, and indicate that the current distribution of CO2 is principally

related to the fracture network. The simulation results highlight the role that high-resolution heterogeneous field-scale models can play in developing a comprehensive storage monitoring program.

Chadwick, R.A., Zweigel, P., Gregersen, U., Kirby, G.A., Holloway, S. and Johannessen P.N. 2004. Geological reservoir characterization of a CO_2 storage site: The Utsira Sand, Sleipner, northern North Sea. Energy 29, 1371-1381.

This paper draws some generic conclusions on reservoir characterization based on the Sleipner operation where CO_2 is being injected into the Utsira Sand. Regional mapping and petrophysical characterization of the reservoir, based on 2D seismic and well data, enable gross storage potential to be evaluated. Site-specific injection studies, and longer-term migration prediction, require precision depth mapping based on 3D seismic data and detailed knowledge of reservoir stratigraphy. Stratigraphical and structural permeability barriers, difficult to detect prior to CO_2 injection, can radically affect CO_2 migration within the aquifer. High-moderate value.

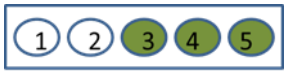
Chadwick, R.A., Arts, R., Eiken, O., Williamson, P., and Williams, G. (2006). Geophysical monitoring of the CO2 plume at Sleipner, North Sea: an outline review. In: Lombardi, S., Altunia, L.K., and Beaubien, S.E. (Eds.) Advances in the Geological Storage of Carbon Dioxide. Springer, Dordrecht, NATO Science, IV Earth and Environmental Sciences Vol. 65, 303-314.

This article presents the analysis of the famous time-lapsed seismic data acquired at the Utsira Sand, a major saline aquifer 1000m beneath the North Sea were CO_2 produced at the Sleipner gas field is being injected into. The volumes were acquired in 1994, prior to injection, and again in 1999, 2001 and 2002; seabed gravimetric data were also acquired in 2002. The CO_2 plume was imaged on the seismic data as a number of bright sub-horizontal reflections, growing with time, underlain by a prominent velocity pushdown. High value.

Doughty, C. Freifeld, B.M., Trautz, R.C., 2008, Site characterization for CO_2 geologic storage and vice versa: The Frio brine pilot, Texas, USA, as a case study, Environmental Geology, 54, 1635-1656.

Study that illustrates the concept of an iterative sequence in which traditional site characterization is used to prepare for CO_2 injection and then CO_2 injection itself is used to further site-characterization efforts, constrain geologic storage potential, and validate understanding of geochemical and hydrological processes. The Frio brine pilot was used as a case study. High value.

Hosseini, S. A., Lashgari, H., Choi, J. W., Nicot, J. P., Lu, J., Hovorka, S. D., 2013. Static and Dynamic Reservoir Modeling for Geological CO_2 Sequestration at Cranfield, Mississippi, U.S.A. International Journal of Greenhouse Gas Control. DOI: 10.1016/j.ijggc.2012.11.009



Study showcasing reservoir modeling as important process for improving our understanding of processes during and after CO_2 injection, and traditional rock and fluid characterization is the first step in building a static reservoir model. The paper highlights the integration of the observed pressure data to reduce the models uncertainty, and the validation of the models against saturation well logs and breakthrough times. There is also a discussion on methane exsolution and importance of residual saturations. High value.

Hovorka, S. D., Meckel, T.A., Treviño, R., 2013. Monitoring a Large-volume Injection at Cranfield, Mississippi - Project Design and Recommendations, International Journal of Greenhouse Gas Control.

Project summary paper of the SECARB Cranfield project, were more than 4 million metric tons of CO_2 have been monitored to observe multiphase fluid flow, to test technologies, to document permanence of storage, and to advance techniques for capacity estimation. High-moderate value.

Johnson, J. W. and others, 2012. Geochemical Monitoring. In B. Hitchon (Editor), Best Practices for Validating CO_2 Geological Storage, 119-154. Geoscience Publishing.

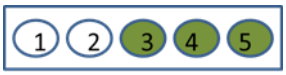
This is a book chapter describing the geochemical monitoring program and results of IEAGHG Weyburn-Midale CO_2 monitoring and storage project. The main recommendation lies on the use geochemical monitoring as part of any CO_2 storage program, as the time-lapse data acquired documents the progressive CO_2-induced departure from baseline conditions. High value.

White, D. and others, 2012. Geophysical Monitoring. In B. Hitchon (Editor), Best Practices for Validating CO_2 Geological Storage, 155-210. Geoscience Publishing.

This is a book chapter describing the geophysical monitoring program and results of IEAGHG Weyburn-Midale CO_2 monitoring and storage project. Results demonstrate effective qualitative mapping of the subsurface CO_2 plume. However, semi-quantitative CO_2 saturation estimates continue to be limited. Results also conclude that discriminating pressure effects from CO_2 saturation is feasible, but results are model dependent. High value.

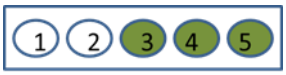
3.1.2 Geophysical methods

Ajo-Franklin, J. B., J. Peterson, J. Doetsch, T.M. Daley, (2013), High-resolution characterization of a CO_2 plume using crosswell seismic tomography: Cranfield, MS, USA. *International Journal of Greenhouse Gas Control (Impact Factor: 3.94). 10/2013; 18:*497-509. DOI:http://dx.doi.org/10.1016/j.ijggc.2012.12.018



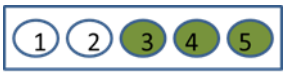
Analysis of results of a high-resolution time-lapse crosswell seismic survey carried out at a large-scale carbon storage pilot located in Cranfield, MS, USA. This study demonstrates that crosswell seismic imaging can be a powerful tool for detecting and mapping the distribution of injected CO_2 in the inter-well region. High Value.

Carrigan, C. R, Xianjin Yang, Douglas J. LaBrecque, Dennis Larsen,David Freemand, Abelardo L. Ramirez, William Daily, Roger Aines,Robin Newmark, Julio Friedmann, Susan Hovorka,. (2013), Electrical resistance tomographic monitoring of CO_2 movement in deep geologic reservoirs. International Journal of Greenhouse Gas Control, Elsevier, http://dx.doi.org/10.1016/j.ijggc.2013.04.016



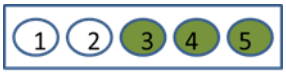
Time lapse electrical resistivity images were obtained successfully for more than one year by an experimental cross-well ERT system. The system operated during the injection of approximately one-million tons of CO_2 at a depth exceeding 3000 m in an oil and gas field in Cranfield, MS. This represents the deepest application of the method to date. High value.

Daily, W., Ramirez, A.L., LaBrecque, D.J., Nitao, J., (1992). Electrical resistivity tomography of vadose water movement. Water Resources Research 28 (5),1429–1442.



Field study to evaluate the capabilities and limitations of ERT to image underground structure and ground water movement in the vadose zone. Cross borehole electrical resistivity tomography (ERT) was used to image the resistivity distribution before and during two infiltration experiments. In both cases water was introduced into the vadose zone, and the change in resistivity associated with the plume of wetted soil was imaged as a function of time. High-moderate value.

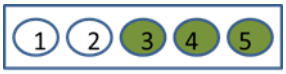
Daley, T.M., Ajo-Franklin, J.B., Doughty, C., (2011). Constraining the reservoir model of an injected CO_2 plume with crosswell CASSM at the Frio-II brine pilot. International Journal of Greenhouse Gas Control 5 (4), 1022–1030.



Field/modeling study using Crosswell CASSM (continuous active-source seismic monitoring) data. These data were acquired as part of the Frio-II brine pilot CO_2 injection experiment. To gain

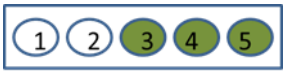
insight into the CO_2 plume evolution, the authors integrated the 3D multiphase flow modeling code TOUGH2 with seismic simulation codes via a petrophysical model that predicts seismic velocity for a given CO_2 saturation. Results of forward seismic modeling based on the CO_2 saturation distribution produced by an initial TOUGH2 model compared poorly with the CASSM data, indicating that the initial flow model did not capture the actual CO_2 plume dynamics. High-moderate value.

Daley, T.M., Myer, L.R., Peterson, J.E., Majer, E.L., Hoversten, G.M., (2008). Time-lapse crosswell seismic and VSP monitoring of injected CO_2 in a brine aquifer. Environmental Geology 54, 1657–1665.



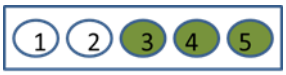
Field study where seismic surveys successfully imaged a small scale CO_2 injection (1,600 ton) conducted in a brine aquifer of the Frio Formation near Houston, Texas. These time-lapse borehole seismic surveys, crosswell and vertical seismic profile (VSP), were acquired to monitor the CO2 distribution using two boreholes (the new injection well and a pre-existing well used for monitoring) which are 30 m apart at a depth of 1,500 m. The crosswell survey provided a high-resolution image of the CO2 distribution between the wells via tomographic imaging of the P-wave velocity decrease (up to 500 m/s). The simultaneously acquired S-wave tomography showed little change in Swave velocity, as expected for fluid substitution. High value.

Daley, T.M., Solbau, R.D., Ajo-Franklin, J.B., Benson, S.M., (2009). Continuous active source seismic monitoring of CO2 injection in a brine aquifer. Geophysics 74, Q27–Q40.



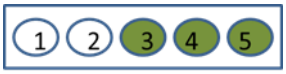
Field study based on continuous crosswell seismic monitoring of a small-scale CO2 injection. The study was carried out with a novel tubing-deployed piezoelectric borehole source. This piezotube source was deployed on the CO_2 injection tubing, near the top of the saline aquifer reservoir at 1657-m depth, and allowed acquisition of crosswell recordings at 15-minute intervals during the multiday injection. The change in traveltime recorded at various depths in a nearby observation well allowed hour-by-hour monitoring of the growing CO_2 plume via the induced seismic velocity change. High value.

LaBrecque, and others, (2004). Autonomous Monitoring of Fluid Movement Using 3-D Electrical Resistivity Tomography, JEEG, September 2004, Volume 9, Issue 3, pp. 53–62



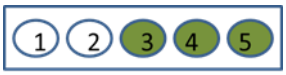
This paper compares different strategies for collecting three-dimensional (3-D) data sets. The authors discuss the critical design aspects of the system and the importance of using integrated hardware for data collection, and software for data interpretation. Moderate value.

LaBrecque, D.J., Yang, X., (2001). Difference inversion of electrical resistivity tomography data – a fast inversion method for 3-D in-situ monitoring. Journal of Environmental and Engineering Geophysics 6 (2), 83–89.



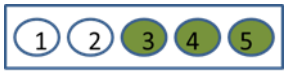
This article presents a new three-dimensional (3-D) inversion algorithm, which was developed for electrical resistivity tomography (ERT). The new algorithm was optimized for in-situ monitoring applications. Moderate value.

Lazaratos, S.K., Marion, B.P., (1997). Crosswell seismic imaging of reservoir changes caused by CO_2 injection. The Leading Edge 16, 1300–1306.



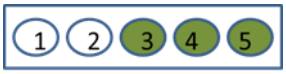
This paper presents a time-lapse geophysics study for the monitoring of enhanced-oil-recovery processes with crosswell data. The authors conclude that because data with frequencies up to a few kilohertz can often be collected with the crosswell geometry, the method can potentially offer imaging resolution of the order of a few feet. Such resolution is often necessary for time-lapse investigation to be useful in building reservoir models and for accurately describing fluid flow in heterogeneous reservoirs. High-moderate value.

Lei, X., Xue, Z., (2009). Ultrasonic velocity and attenuation during CO_2 injection into water-saturated porous sandstone: measurements using difference seismic tomography. Physics of the Earth Planetary Interiors 176 (3–4), 224–234.



In this paper the authors conducted laboratory-based seismic measurements with a dense sensor array at ultrasonic frequencies during the injection of CO_2 into a water-saturated sandstone specimen. The resulting high-quality seismic data enabled detailed determination of the relative velocity and attenuation coefficient of the compressional wave using difference seismic tomography, which directly inverses time-lapse changes in rock properties from time-lapse changes in observed data. High-moderate value.

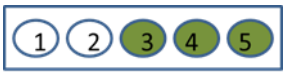
Nakagawa, S., Kneafsey, T.J., Daley, T.M., Freifeld, B.M., Rees, E.V., (2011). Laboratory seismic monitoring of supercritical CO_2 flooding in sandstone cores using the Split Hopkinson Resonant Bar technique with concurrent X-ray CT imaging. In: 1st International Workshop on Rock Physics, August 7–12, 2011, Golden, CO.



Laboratory experiment to investigate the feasibility of seismic methods for CO_2 saturation estimation in CO_2 saline storage sites. Because of strong contrasts in density and elastic properties between brine and CO_2 at reservoir conditions, seismic methods are among the most

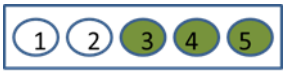
commonly employed techniques for this purpose. However the relationship between seismic (P-wave) velocity and CO_2 saturation is not unique because the velocity depends on both wave frequency and the CO_2 distribution in rock. In the laboratory, the authors conducted measurements of seismic properties of sandstones during supercritical CO_2 injection. Seismic responses of small sandstone cores were measured at frequencies near 1 kHz, using a modified resonant bar technique (Split Hopkinson Resonant Bar method). High-moderate value.

Ramirez, A. L., Carrigan, C R; Newmark, R L ; Aines, R and Friedmann, S. J., (2009). Application of ERT for tracking CO_2 plume growth and movement at the SECARB Cranfield site, presented at: 8th Annual Conference on Carbon Capture & Sequestration, Pittsburgh, PA, United States, May 4-7.



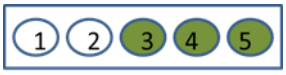
Field study describing the installation of Electrical Resistance Tomography (ERT) at the SECARB Cranfield, MS. sequestration site. The ERT is installed to track the development of an injected subsurface CO_2 plume. This is the deepest subsurface application of this method to date. High value.

Saito, H., Nobuoka, D., Azuma, H., Xue, Z., Tanase, D., (2006). Time-lapse crosswell seismic tomography for monitoring injected CO_2 in an onshore aquifer, Nagaoka, Japan. Exploration Geophysics 37, 30–36.



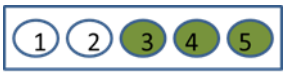
This paper reports the results of the crosswell seismic tomography conducted at the Nagaoka site, Japan. The crosswell seismic tomography measurements were carried out three times; once before the injection as a baseline survey, and twice during the injection as monitoring surveys. The velocity tomograms resulting from the monitoring surveys were compared to the baseline survey tomogram, and velocity difference tomograms were generated. The velocity difference tomograms showed that velocity had decreased in a part of the aquifer around the injection well, where the injected CO_2 was supposed to be distributed. The authors also found that the area in which velocity had decreased was expanding in the formation up-dip direction, as increasing amounts of CO_2 were injected. High value.

Shi, J.-Q., Xue, Z., Durucan, S., (2007). Seismic monitoring of supercritical CO_2 injection into a water-saturated sandstone: interpretation of P-wave velocity data. International Journal of Greenhouse Gas Control 1, 473–480.



This paper reports on an integrated laboratory and numerical simulation study of ultrasonic P-wave velocity response to supercritical CO_2 displacement of pore water in Tako sandstone. The analysis of dynamic velocity data recorded using an array of piezoelectric transducers mounted on a core sample showed that the P-wave velocities at different positions displayed a similar trend in time, i.e., an initial sharp fall followed by a more gradual decline . High-moderate value.

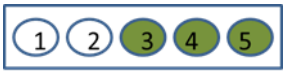
Silin, D., Tomutsa, L., Benson, S.M., Patzek, T.W., (2011). Microtomography and pore-scale modeling of two-phase fluid distribution. Transport in Porous Media 86 (2), 495–515.



This study shows a pore-scale visualization of carbon dioxide flooding experiments performed at a reservoir pressure. The visualization was conducted through synchrotron-based X-ray microtomography (micro CT) at the Advanced Light Source (ALS) line 8.3.2 at the Lawrence Berkeley National Laboratory, and produced three dimensional micron-scale-resolution digital images of the pore space of the reservoir rock along with the spacial distribution of the fluids. High-moderate value.

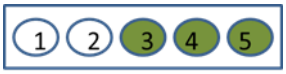
3.1.3 Gravity

Alnes, Harvard; Eiken, Ola; Nooner, Scott; Sasagawa, Glenn; Stenvold, Torkjell and Zumberge, Mark. (2011). Results from Sleipner gravity monitoring: Updated density and temperature distribution of the CO2 plume. Energy Procedia. Vol. 4, 5504-5511



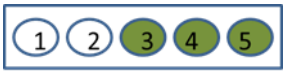
In this study the authors analyzed and accounted for multiple sources of changes in gravity to obtain an estimate of in situ *CO_2 density. The 2002–2009 gravity change was used to constrain the rate of dissolution of CO_2 into the formation water. Dissolved CO_2 is invisible in seismic data. The contribution from gravimetric data proved valuable for monitoring this process, which is important for long-term predictions of the CO_2 stored in the Utsira Fm. The authors gave an upper bound on the dissolution rate of 1.8% per year. High-moderate value.*

Chen, T., John F. Ferguson, Carlos L.V. Aiken, and Jerry Brady, (2005). Real-time data acquisition and quality control for gravity surveys. *The Leading Edge,* 24, 702-704



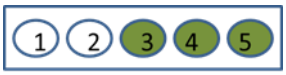
This paper presents procedures for quality control of gravity data acquisition. "In most gravity surveys, gravity and position data are usually collected, stored, and processed separately. They are either recorded manually in a field notebook or in the memories of the instruments with subsequent data entry or download to a computer for processing. However, this has several disadvantages; in particular, most instrument interfaces are too crude to continuously monitor the measurement and thus detect problems in the field, such as meter malfunctions. This means that the separate recording of the gravity and position data is prone to problems such as station misidentification, transcription errors, or even missing records". Moderate value.

Ishido, T., T. Tosha, C. Akasaka, Y. Nishi, M. Sugihara, Y. Kano, S. Nakanishi, (2011) Changes in geophysical observations caused by CO2 injection into saline aquifers, Energy Procedia, 4 (2011), pp. 3276–3283



In this paper, the authors use geophysical postprocessors to calculate the resulting temporal changes in the earth-surface distributions of microgravity, self-potential (SP), apparent resistivity (from MT surveys) and seismic observables. Moderate value.

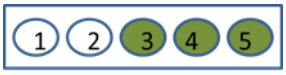
Nooner, S. L., O. Eiken, C. Hermanrud, G.S. Sasagawa, T. Stenvold, M.A. Zumberge, (2007). Constraints on the in situ density of CO2 within the Utsira formation from time-lapse seafloor gravity measurements IJGGC, 1 (2007), pp. 198–214



In this study, gravity measurements were made over the Utsira injection site in 2002 and 2005 on top of 30 concrete benchmarks on the seafloor in order to constrain the in situ CO_2 density. Moderate value.

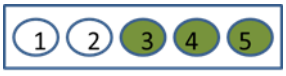
3.1.4 Wireline logging

Brie, A., F. Pampuri, A. Marsala, and O. Meazza (1995), Shear sonic interpretation in gas bearing sands, paper 30595-MS presented at Annual Technical Conference and Exhibition, Soc. of Pet. Eng., Dallas, Tex., 22–25 Oct.



In this paper the authors develop a model that can be solved to evaluate gas volume from compressional and shear slownesses. Data sets were acquired and analyzed on Vp/Vs versus Atc crossplots. Trends were identified in sands and shales and were matched with semi-empirical correlations based on the Gassmann formalism. These trends can be used to quality control shear logs and for quicklook lithology interpretation. High-moderate value.

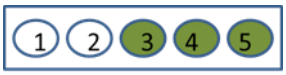
Caspari, E., Muller, T.M., Gurevich, B., 2011. Time-lapse sonic logs reveal patchy CO_2 saturation in-situ. Geophysical Research Letters 38, L13301.



Based on time-lapse sonic and neutron porosity logs from the Nagaoka CO_2 sequestration experiment, a P-wave velocity-saturation relation at reservoir depth is retrieved. It does not coincide with either of the end-member models of uniform and patchy saturation but falls in between even if realistic error estimates for the host rock properties are considered. Assuming a random distribution of CO_2 patches it is shown that the mechanism of wave-induced flow can be

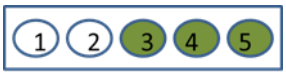
evoked to explain this velocity-saturation relation. Characteristic CO_2 patch size estimates range from 1 to 5 mm. Such mesoscopic heterogeneity can be responsible for attenuation and dispersion in the well logging frequency band. High value.

Quinlan, T. M., and others, (2007). Evaluation of the Carbon Dioxide Response on Pulsed Neutron Logs. SPE-159448-MS



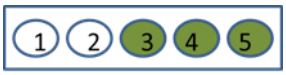
This paper presents examples of commercial and experimental tools in clastic and carbonate environments are presented. The examples show how CO_2 can be quantified and demonstrate critical design requirements for successful pulsed neutron logging campaigns. The authors outline the lessons learned and make recommendations for the design of logging programs and interpretation of the acquired data in stand-alone or in time-lapse modes. High value.

Sakurai, S., and others, (2005). Monitoring Saturation Changes for *CO_2* Sequestration: Petrophysical Support of the Frio Brine Pilot Experiment. Society of Petrophysicists & Well Log Analysts, SPWLA-2005-YY



Field study where a pulsed neutron tool was selected as the primary log for monitoring saturation changes through change of thermal neutron absorption cross-section. Wireline logs were run to estimate lithology and porosity, as well as to confirm structural dip using the borehole imaging tool. The wireline formation tester was used to sample formation water. The C/O ratio measurement and dipole acoustic tool were also used to estimate saturation changes. Baseline logs of these tools were recorded as preinjection values. High value.

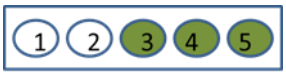
Xue, Z., Tanase, D. and Watanabe, J. 2006. Estimation of CO_2 saturation from time-lapse CO_2 well logging in an onshore aquifer, Nagaoka, Japan, Exploration Geophysics, 37, p19-29.



In this field study CO_2 breakthrough was identified by induction, sonic, and neutron logs. By sonic logging, the authors confirmed P-wave velocity reduction that agreed fairly well with a laboratory measurement on drilled core samples from the Nagaoka site. The authors successfully matched the history changes of sonic P-wave velocity and estimated CO_2 saturation after breakthrough in two observation wells out of three. High value.

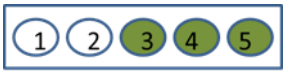
3.1.5 Temperature monitoring

Daughty, C., Freifeld, B., 2013, Modeling CO_2 injection at Cranfield, Mississippi: Investigation of methane and temperature effects, Greenhouse Gases: Science and Technology, DOI: 10.1002/ghg.1363



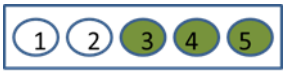
Field/modeling study where results are compared with temperature observations made in the field with a Distributed Temperature Sensor (DTS) system, suggesting that a well-defined thermal response reached the near observation well within the seven-month monitoring period, but not the more distant observation well. High-modetare value.

Liebscher, A., Möller, F., Bannach, A., Köhler, S., Wiebach, J., Schmidt-Hattenberger, C., Weiner, M., Pretschner, C., Ebert, K., Zemke, J. 2013. Injection operation and operational pressure-temperature monitoring at the *CO_2* storage pilot site Ketzin, Germany - Design, results, recommendations. International Journal of Greenhouse Gas Control, *15*, 163-173, 10.1016/j.ijggc.2013.02.019.



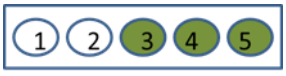
Field experiment at the Ketzin pilot site, in the German Federal State of Brandenburg about 25 km west of Berlin, where bottom hole pressure (BHP), bottom hole temperature (BHT) and distributed temperature sensing (DTS) were monitored along the injection tubing of an injection well, BHP for two observation wells (from March 2010 to October 2011) and above-zone pressure monitoring in a shallow observation well. High value.

Núñez-López, V., 2011, Temperature monitoring at SECARB Cranfield Phase 3 site using distributed temperature sensing (DTS) technology. GCCC Digital Publication Series #11-10.



This study presents Distributed Temperature Sensing (DTS) data acquired before and during CO2 injection at the Cranfield site. Fiber optic cables were deployed along two observation wells to help observe the evolution of the CO_2 plume within the injection zone. The author concludes that DTS can be useful as a complimentary monitoring tool, whith the advantage over a temperature gauge is that it provides continuous information over the entire length of a well. However, the gauge readings seem to be more stable. High-moderate value.

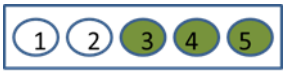
Jordan, Preston and Doughty Christine. 2009. Sensitivity of CO_2 migration estimation on reservoir temperature and pressure uncertainty. Energy Procedia 1, 2825-2832.



Numerical simulation study showing that the relative ultimate plume size is almost directly proportional to the relative difference in brine and CO_2 density (buoyancy flow). The majority of

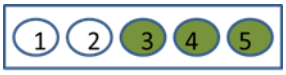
the difference in plume size occurs during and shortly after the cessation of injection. High-moderate value.

Tao, Q., Bryant, S. L., and Meckel, T. A. (2013). Modeling above-zone measurements of pressure and temperature for monitoring CCS Sites. International Journal of Greenhouse Gas Control



This study presents a simple set of coupled analytical models that enable diagnosis of above-zone monitoring data. Concurrent pressure and temperature measurements are especially valuable because they independently constrain the effective permeability of a leakage path along wellbore. High-moderate value.

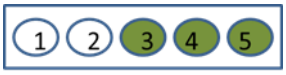
Alnes, Harvard; Eiken, Ola; Nooner, Scott; Sasagawa, Glenn; Stenvold, Torkjell and Zumberge, Mark. 2011. Results from Sleipner gravity monitoring: Updated density and temperature distribution of the CO2 plume. Energy Procedia. Vol. 4, 5504-5511



In this study the authors analyzed and accounted for multiple sources of changes in gravity to obtain an estimate of in situ *CO_2 density. The 2002–2009 gravity change was used to constrain the rate of dissolution of CO_2 into the formation water. Dissolved CO_2 is invisible in seismic data. The contribution from gravimetric data proved valuable for monitoring this process, which is important for long-term predictions of the CO_2 stored in the Utsira Fm. The authors gave an upper bound on the dissolution rate of 1.8% per year. High-moderate value.*

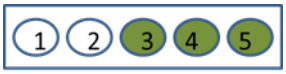
3.1.6 Pressure monitoring

Chabora, E.R., Benson, S.M., 2009. Brine displacement and leakage detection using pressure measurements in aquifers overlying *CO_2* storage reservoirs. EnergyProcedia 1, 2405–2412.



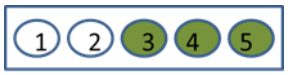
This paper presents a wide range of geologic settings and injection parameters is evaluated from which a generalized correlation is constructed to relate the hydrologic properties of the storage reservoir and seal to the magnitude of expected pressure buildups associated with brine migration across the seal. This correlation, referred to as the detection factor (DF), provides insight into the feasibility and interpretation of pressure changes measured in zones overlying CO_2 storage reservoirs as a means of monitoring and leakage detection. High-moderate value.

Meckel T.A. and Hovorka S.D., 2010. Above-Zone Pressure Monitoring as a Surveillance Tool for Carbon Sequestration Projects. SPE International Conference on CO_2 Capture, Storage, and Utilization. New Orleans, Louisiana, USA, 10–12 November 2010.



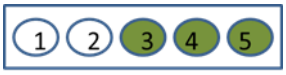
Study conducted to test the "above zone" monitoring technique. Monitoring pressure stratigraphically above the injection interval has been proposed as a fit-to-purpose technique to document performance of confining system and degree of isolation provided by existing wellbore completions. To test the technique under field conditions, data have been collected over a >24-month period beginning in July 2008 during a continuous industrial-scale CO_2 injection at an enhanced oil recovery (EOR) site at Cranfield Field, Mississippi.

Nicot, J. P., Hosseini, S.A., and Solano, S.V., 2011. Are single-phase flow numerical models sufficient to estimate pressure distribution in CO_2 sequestration projects? Proceedings of the 10th International Conference on Greenhouse Gas Control Technologies GHGT10, September 19-23, 2010, Amsterdam, The Netherlands, Energy Procedia. 4, 3919-3926. GCCC Digital Publication #11-14.



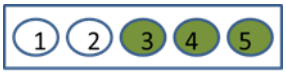
This paper investigates using single-phase flow numerical models to describe compositional flow processes. Previous work already showed that results from the CMG-GEM and MODFLOW numerical codes are very similar away from the injection zone given some minor modifications in the input file of the single-phase flow code. The authors present a more thorough scoping analysis aiming at establishing the proposition that single-phase flow models (CMG-IMEX), given some simple treatment, can predict pressure increase as well as more complex compositional flow models (CMG-GEM). High value.

Nogues, J.P., Nordbotten, J.M., Celia, M.A., 2011. Detecting leakage of brine or CO_2 through abandoned wells in a geological sequestration operation using pressure monitoring wells. Energy Procedia 4, 3620-3627.



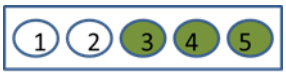
In this study the authors evaluate the gains of using pressure-monitoring wells and the limitations given by specific accuracy thresholds of the measuring device. They also try to answer the question of where these monitoring wells should be placed to optimize the objective of a monitoring scheme. The authors believe these results can ultimately lead to practical design strategies for monitoring schemes, including quantitative estimation of increased probability of leak detection per added observation well. High-moderate value.

Liebscher, A., Möller, F., Bannach, A., Köhler, S., Wiebach, J., Schmidt-Hattenberger, C., Weiner, M., Pretschner, C., Ebert, K., Zemke, J. (2013): Injection operation and operational pressure-temperature monitoring at the CO2 storage pilot site Ketzin, Germany - Design, results, recommendations. International Journal of Greenhouse Gas Control, *15*, 163-173, 10.1016/j.ijggc.2013.02.019.



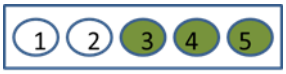
Field experiment at the Ketzin pilot site, in the German Federal State of Brandenburg about 25 km west of Berlin, where bottom hole pressure (BHP), bottom hole temperature (BHT) and distributed temperature sensing (DTS) were monitored along the injection tubing of an injection well, BHP for two observation wells (from March 2010 to October 2011) and above-zone pressure monitoring in a shallow observation well. High value.

Tao, Q., Bryant, S. L., and Meckel, T. A. this issue. Modeling above-zone measurements of pressure and temperature for monitoring CCS Sites. International Journal of Greenhouse Gas Control.



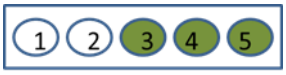
This study presents a simple set of coupled analytical models that enable diagnosis of above-zone monitoring data. Concurrent pressure and temperature measurements are especially valuable because they independently constrain the effective permeability of a leakage path along wellbore. High-moderate value.

Tao, Q., Bryant, S.L., Meckel, T.A. and Luo, Z., 2012. Wellbore leakage model for above-zone 36 monitoring at Cranfield, MS. Carbon Management Technology Conference. Orlando, 37 Florida, USA, 7-9 February.Tao and others, 2012.



In this paper the authors model the wellbore leakage by coupling the flow in wellbore and a diffusion model in the above zone sand layer. Matching the pressure data yields an effective wellbore permeability in order of tens of darcies. This corresponds to a large flow rate along the pathway which would very likely raise the temperature in the above zone. They conclude that leakage from the injection zone is very small. The observed pressure increases in the monitoring well are attributed to larger-scale geomechanical phenomena. High-moderate value.

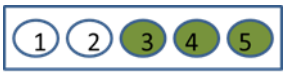
Zeidouni, M., and Pooladi-Darvish, M. 2012a. Leakage characterization through above-zone pressure monitoring: 1—inversion approach: Journal of Petroleum Science and Engineering, v. 98-99, p. 95–106.



A test to characterize leakage from a reservoir using pressure monitoring is presented. The leakage inverse problem is parameterized and the solution uniqueness is investigated. Solution

stability studied based on relative sensitivity coefficients and correlation matrix. Confidence interval over which the leakage parameters vary in response to data error is estimated. High-moderate value.

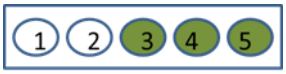
Zeidouni, M., and Pooladi-Darvish, M. 2012b. Leakage characterization through above-zone pressure monitoring: 2—design considerations with application to CO_2 storage in saline aquifers: Journal of Petroleum Science and Engineering, v. 98-99, p. 69–82.



Strategies to enhance leak characterization through above-zone pressure monitoring are studied. The value of information provided by each strategy is assessed. Placement of monitoring wells is discussed considering requirements of CO_2 storage applications. A graphical method is introduced to obtain leak parameters using a function of pressure derivative. High-moderate value.

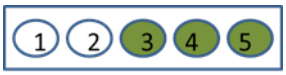
3.2 Shallow and surface monitoring

Brady, J. L., John F. Ferguson, John E. Seibert, Tianyou Chen, Jennifer L. Hare, Carlos V.L. Aiken, Fred J. Klopping, John M. Brown, (2004), Surface Gravity Monitoring of the Gas Cap Water Injection Project - Prudhoe Bay, Alaska, SPE Annual Technical Conference and Exhibition, 29 September-2 October 2002, San Antonio, Texas 77513-MS, DOI 10.2118/77513-MS.



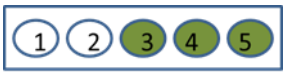
This paper presents this monitoring technique as an essential component of the surveillance program for the approved Gas Cap Waterflood Project (GCWI) at Prudhoe Bay. This paper discusses both inverse modeling of time differenced gravity maps and four test surveys that have been completed to perfect the gravity measurement technique. Moderate value.

Kharaka, Y., and others. 2009. Changes in the chemistry of shallow groundwater related to the 2008 injection of CO_2 at the ZERT field site, Bozeman, Montana. Environmental Earth Sciences. DOI: 10.1007/s12665-009-0401-1



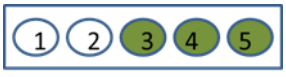
Field experiment where approximately 300 kg/day of food-grade CO_2 was injected through a perforated pipe placed horizontally 2–2.3 m deep during July 9–August 7, 2008 at the MSU-ZERT field test to evaluate atmospheric and near-surface monitoring and detection techniques applicable to the subsurface storage and potential leakage of CO_2. High-moderate value.

Romanak, K. D., Smyth, R. C., Yang, C., Hovorka, S. D., Rearick, M., and Lu, J., (2012). Sensitivity of groundwater systems to CO_2: application of a site-specific analysis of carbonate monitoring parameters at the SACROC CO_2-enhanced oil field. International Journal of Greenhouse Gas Control, v. 5, no. 1, p. 142– 152.



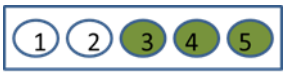
This is a field study and geochemical modeling of a shallow aquifer, situated above a long-running (>35 years), large-scale (~250 km^2) CO_2-enhanced oil recovery site (SACROC oil field), which were conducted to determine how the aquifer might react to input of injectate CO_2. The analysis indicates that dedolomitization (dolomite dissolution with concurrent calcite precipitation) is the dominant native geochemical process and calcite dissolution cannot be assumed to result from CO_2 input. High value.

Romanak, K. D., Zhang, T., Gilbert, K., Yang, C., Bennett, P., and Hovorka, S., (2010). Evaluation of CO_2, He, C1-C5 gaseous hydrocarbons at an engineered CO_2 injection, Cranfield, Mississippi. GCCC Digital Publication Series #10-04.



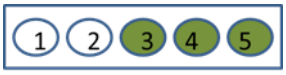
Field study where samples from 2 observation wells (~3000m depth) were continuously collected at the Cranfield site over 30 days using a pressure-loop U-Tube sampler and analyzed by gas chromatography. A gas mixing model with two end members and He to calculate mixing fractions during the course of CO_2 injection was used to characterize the origin of the sampled gas during the observation period. Mixing of gases from heterogeneous CO_2 invasion, assumed to occur, 1) during transport of the CO_2 plume to the observation wells due to aquifer heterogeneities, and 2) in the wellbore during sampling, is one of the main physical processes. Deviations from the model may identify chemical processes between injected and reservoir gases and brine. High-moderate value.

Romanak, K.D., Bennett, P. C., Yang, Changbing, Hovorka, S.D., (2012). Process-based approach to soil gas monitoring at geologic carbon storage sites. Geophysical Research Letters. 39, L15405, doi:10.1029/2012GL052426



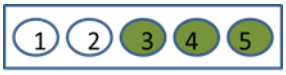
This study presents a novel process-based approach to identify the source CO_2 detected in soil gas and differentiate biogenic CO2 from CO2 that has leaked from deep geologic storage reservoirs into the shallow subsurface. The ability to identify gas leakage into the vadose zone without the need for background measurements could decrease uncertainty in leakage detection and expedite implementation of future geologic CO_2 storage projects. High value.

Schlömer, S., I. Möller, M. Furche, 2014, Baseline soil gas measurements as part of a monitoring concept above a projected CO_2 injection formation—A case study from Northern Germany, International Journal of Greenhouse Gas Control. 01/2014; 20:57–72.
DOI:http://dx.doi.org/10.1016/j.ijggc.2013.10.028



Field application for the development of a continuous soil gas monitoring system, which requires little maintenance and includes an automatic data transfer. The authors report on a large data set recorded during a long-term (up to 4 years) continuous soil gas monitoring program completed during a case study in the Altmark area (Germany). Permanent monitoring stations were operated at 12 well sites and one reference location.

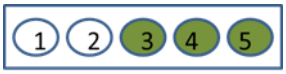
Spangler, L.H., and others, (2010), A shallow subsurface controlled release facility in Bozeman, Montana, USA, for testing near surface CO_2 detection techniques and transport models: or on-line journal article in pdf format, 967 KB, published by Springer with Open Access)



This paper describes a controlled field pilot has been developed in Bozeman, Montana, USA, to study near surface CO_2 transport and detection technologies. Controlled releases of CO_2 from the horizontal well were performed in the summers of 2007 and 2008, and collaborators from six national labs, three universities, and the U.S. Geological Survey investigated movement of CO_2

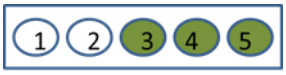
through the soil, water, plants, and air with a wide range of near surface detection techniques. An overview of these results is presented. High value.

Spangler, Lee. 2012. Overview of monitoring controlled releases. http://www.ieaghg.org/docs/General_Docs/Natr%20rel%20worksop/SPANGLER_SEC.pdf



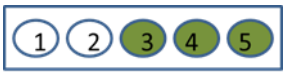
Overview of various CO_2 controlled releases and best practices. Moderate value.

Yang, C., Romanak, K.D., Hovorka S.D.; Trevino, R., Holt R.M., Linder J., Smith, F., Roeckner, F. Xia, Y., and Rickerts J. (2012). Large Volume CO_2 Injection at Cranfield Early Field Test of the SECARB Phase III: Near-Surface Monitoring, SECARB 7th Annual Stakeholders' Briefing http://www.secarbon.org/wp-content/uploads/2012/08_Romanak.pdf.



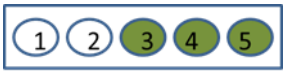
Report on three monitoring technologies were assessed: soil CO_2 concentration measurements, CO_2 flux measurements on the land surface, and multiple soil-gas component measurements. Results indicate that soil-gas-component measurements provide reliable information for gas-leakage detection. Methodologies of nearsurface monitoring developed in this study can be used to improve CO_2-leakage monitoring at other CO_2 sequestration projects

Yang, Changbing, Mickler, P. Reedy,R. Scanlon,B.R. and Larson, T., Assessing potential impacts of CO_2 leakage on Cranfield shallow groundwater chemistry with laboratory and field experiments. International Journal of Greenhouse Gas Control.



Report on 11 field campaigns for groundwater sampling at the Cranfield site. Moderate value.

Yang, F., Bai, B., Dunn-Norman, S. 2011. Modeling the effects of completion techniques and formation heterogeneity on CO_2 sequestration in shallow and deep saline aquifers, Environmental Earth Sciences, 64, 841-849, DOI: 10.1007/s12665-011-0908-0.



This work studied the effect of completion techniques and reservoir heterogeneity on CO_2 storage and injectivity in saline aquifers using a compositional reservoir simulator, CMG-GEM. Two reservoir models were built based on the published data to represent a deep saline aquifer and a shallow aquifer. The effect of various completion conditions on CO_2 storage was then discussed, including partial perforation of the reservoir net pay (partial completion), well geometry, orientation, location, and length. Moderate value.