

GHGT-11

Werkendam, the Dutch natural analogue for CO₂ storage – long-term mineral reactions

Mariëlle Koenen, Laura J. Wasch, Marit E. van Zalinge and Susanne Nelskamp

*TNO, Princetonlaan 6, P.O. Box 80015, 3508 TA Utrecht, the Netherlands
e-mail address: marielle.koenen@tno.nl*

Abstract

The Werkendam (WED) and Barendrecht-Ziedewij (BRTZ) gas fields are CO₂- and CH₄-bearing stratigraphic equivalents in the Netherlands. A comparison in petrographic characteristics and burial histories of the two fields is performed to investigate long-term mineral reactions induced by the presence of CO₂. The mineral relations in BRTZ are used as a CO₂-free reference for WED. However, the results show that the differences in paragenetic sequence between the two fields are partially due to different temperature evolutions and fluid influxes. The mineral relations that can be linked to the presence of CO₂ in WED are the partial dissolution of anhydrite and feldspar and the precipitation of siderite, quartz and potentially minor dolomite. The amount of CO₂ sequestered in siderite (and potentially dolomite) is small. PHREEQC geochemical modelling was able to simulate the observations of the mineral reactions induced by carbonized brine. Yet, a sensitivity study on the type of illite used in the model, and the inclusion of minor minerals showed that significantly different reactions can be induced. Furthermore the presence and type of Fe-minerals determines if and how much siderite forms. This shows that careful selection of initial mineralogy is required as model input. In one model run mineral reactions were predicted which are known from petrographic studies not to occur under the applied conditions. Hence, besides careful mineral selection, an expert opinion on diagenetic processes is necessary to guide the model towards the proper mineral reactions.

© 2013 The Authors. Published by Elsevier Ltd.
Selection and/or peer-review under responsibility of GHGT

Keywords: CO₂ storage; natural analogue; mineral reactions; diagenetic history, burial history, PHREEQC modeling

1. Introduction

Geological storage of CO₂ in a depleted gas field or an aquifer is one of the measures identified by the European Commission and the Dutch government to reduce CO₂ emissions in the coming decades. When CO₂ is injected into a reservoir, it will partially dissolve into the formation water, thereby forming

carbonic acid. As a result the equilibrium conditions of the rock-water-gas system change and mineral reactions start to proceed. Particularly the precipitation of CO₂ sequestering minerals is important for efficient and safe long-term storage of CO₂ in geological reservoirs. Partly, these mineral reactions are believed to be very slow and will occur over geological time scales only [1]. Experimental studies investigating geochemical reactions only cover a limited time scale and are highly dependent on experimental conditions [2]. Geochemical modelling studies, on the other hand, are able to predict the reactions on a much longer time scale. However, these models are prone to significant uncertainties [3]. Another way to study long-term mineral reactions induced by the presence of CO₂ is to look at natural CO₂ fields, the so-called natural analogues. A few natural analogues are studied up to now (e.g. [5, 6, 7 and 8]). Long-term mineral reactions are however case specific. The Netherlands' most important natural analogue is the Werkendam (WED) field. This field has the highest CO₂ content (~75%) of the currently known gas fields and the reservoir is representative of potential Dutch CO₂ storage reservoirs.

In this study, which is part of the Dutch research program CATO-2, we compared rock samples of the Werkendam field with samples of the Barendrecht-Ziedewij (BRTZ) field. The latter is a CH₄-bearing stratigraphic equivalent of the Werkendam field. The goal was to define the paragenetic sequence and subsequently to unravel the diagenetic history of the reservoirs. The comparison of the two fields will support the determination of reactions which are induced by the CO₂ in WED. Additionally, the potential to simulate petrographic observations by means of PHREEQC geochemical modelling was investigated.

2. Samples and methodology

We constructed a general geological setting based on publicly available data of the Werkendam and Barendrecht-Ziedewij gas fields. The data is available at the Dutch oil and gas portal www.nlog.nl.

In both gas fields the Triassic Röt Fringe Sandstone Member was partly cored. This member is located at 2727-2768 m and 2650-2690 m TVD in wells WED-03 and BRTZ-01 respectively and constitutes part of the reservoir interval. We selected seven sandstone samples from fluvial lithofacies from each field. XRD analyses are performed and thin sections made by PanTerra Geoconsultants. The thin sections are studied by Scanning Electron Microscopy (Tescan Miralmh FEG-SEM) with and without cathodoluminescence detector (Centaurus).

We used basin modelling to develop realistic burial histories and temperature evolutions of the two fields. Potential differences in temperature evolution need to be taken into account when the diagenetic histories of the two fields are compared. To perform 1D modelling of the burial and temperature history, the software PetroMod v11 of Schlumberger was used. Basic data requirements for the modelling are the present-day geometry, lithological description of the layers based on true vertical depths, the formation properties, absolute ages for stratigraphic layers, times of non-deposition and erosion, boundary conditions such as paleo-surface temperature, heat flow and water depth. The model is calibrated using the current temperature, maturity of organic matter and compaction data [9]. The rock sequence in well BRTZ-01 is cut by 2 normal faults, cutting out a significant sedimentary sequence. Faults cannot easily be included in the model. To prevent the simulation of severe, false erosion periods we used well BRTZ-03 to determine the burial history of the Barendrecht-Ziedewij field. The faults in well WED-03 did not result in missing strata.

Geochemical batch modelling was performed using PHREEQC in order to simulate the CO₂-brine-mineral reactions in WED. The approach of the modelling was to investigate which model conditions need to be applied to simulate the paragenetic sequence observed in the samples. In this approach it is assumed that the microscopic observations and interpretation are correct. The BRTZ mineralogy was equilibrated with CO₂ at a high partial pressure to see whether the same mineral reactions would be predicted as observed in WED.

3. Geological setting and history

The Werkendam and Barendrecht-Ziedewij gas fields are located near the area of Rotterdam, the Netherlands. Both WED and BRTZ are onshore fields in the structural geological element West Netherlands Basin (WNB) and they are approximately 25 km apart. The reservoirs are of Triassic age, consisting of the Röt Fm., Solling Fm. and Main Buntsandstein (subgroup). Two gas samples were taken from WED, from the Röt Fringe Sandstone Member (Röt Fm) at a depth of ~2858 m along borehole (ah) and from the Hardegens Fm. (Main Buntsandstein) at a depth of ~2925 m ah. The two samples have a similar composition with an average CO₂ concentration of 75%. The gas sample of BRTZ contains only 0.8% CO₂. Bottom hole pressure in WED is 280 bar and the downhole temperature is ~115°C. WED is the only known reservoir in the WNB containing such a high CO₂ concentration.

WNB is a small inverted basin [10] located in the southern North Sea province, bounded to the north by the Central Netherlands Basin and the Broad Fourteens Basin and to the south by the London-Brabant Massif [11]. During the late Carboniferous thick layers of organic material were deposited that became the main source rock for CH₄-gas in the Triassic sandstone reservoirs [12]. At the end of the Carboniferous sedimentation stopped due to uplift related to the Variscan orogeny. Between Late Permian and Middle Jurassic sedimentation continued and mainly clastic sediments were deposited [12]. The WNB experienced a late Kimmerian rifting event (Late Jurassic – Early Cretaceous) during which the basin was filled with ~2500 m sediments [13]. The Triassic Bunter sandstones formed tilted half blocks which are able to trap gas [12]. The rifting event also initiated volcanism in the basin [14]. During the Early Cretaceous the major faulting ceased [12]. During Late Cretaceous to Early Tertiary times the WNB was influenced by the Alpine orogeny, which caused three inversion pulses (Late Cretaceous, Paleocene and Eocene/Oligocene). During the first two pulses pre-existing faults were reversely reactivated. The latest pulse caused no reactivation of the faults, just uplift [13]. The amount of uplift within the WNB differs per subarea [9]. Both the BRTZ and WED gas fields are located in the Triassic tilted half blocks (formed during late Jurassic and modified during Cretaceous/Tertiary inversion) [12].

The CO₂ carbon isotope value of -4.4‰ relative to the PDB standard suggests either a magmatic origin or CO₂ from heating of carbonates underlying the reservoir [15]. Either way, the presence of CO₂ would be related to the volcanic activity which occurred 140 to 130 million years ago.

4. Diagenetic history

4.1. Paragenetic sequence

Quartz and K-feldspar are the most abundant detrital minerals of both WED and BRTZ. The rocks are porous and locally cemented with anhydrite and siderite. XRD results combined with SEM and EDX analyses show some mineralogical differences which are consistent between the WED and BRTZ samples. The samples from WED contain on average >10 wt% more quartz and slightly more illite. They contain slightly less feldspar and significantly less dolomite and anhydrite. The samples from BRTZ contain on average 4.7 wt% kaolinite, which is not present in any WED sample.

Petrographic analyses show complex diagenetic mineral relations for both fields. Particularly the relative timing of clay mineral formation with respect to other diagenetic minerals is not clear. Nonetheless, we found important differences and similarities in the paragenetic sequences. These are described below for each type of mineral. Keep in mind that they are interpretations based on a small set of rock samples.

Quartz – BRTZ has two phases of syntaxial overgrowth. A small phase predates and a larger phase postdates anhydrite precipitation and major compaction. In WED major syntaxial overgrowth occurred before, and euhedral quartz crystals precipitated after anhydrite and siderite cementation.

Feldspar – In both fields K-feldspar overgrowth predates major compaction and cementation. Albitization of detrital grains occurred to a great extent. Feldspar grains are partially dissolved, or replaced by kaolinite and illite in BRTZ and WED respectively.

Kaolinite – Kaolinite is the dominant clay mineral in BRTZ and is probably mainly authigenic. Secondary kaolinite replaces micas and feldspars.

Illite – In BRTZ some illitization of kaolinite occurred. Illite is much more abundant in WED and occurs as feldspar replacement, pore-filling cement and within clay-rich clasts.

Dolomite – Occurs as euhedral minerals within pores, they have Fe-rich rims. In BRTZ dolomite postdates illite and predates siderite. In WED the Fe-rich rims show signs of partial dissolution, with subsequent Fe-poor dolomite overgrowth. The latest phase seems to predate siderite cementation but relative timing is difficult to determine.

Siderite – In BRTZ small anhedral siderite crystals form along with kaolinite as mica alteration product. Pore-filling siderite encompasses dolomite crystal, predates anhydrite cement (Figure 1) and postdates quartz overgrowth. In WED siderite is abundant and probably represents different phases of growth. Late phase siderite cementation postdates anhydrite cementation and subsequent anhydrite dissolution (Figure 1).

Anhydrite – In both fields anhydrite occurs as local, pore-filling cement. Dissolution features are observed. These are more extensive in WED (Figure 1).

Barite – A late phase of barite cementation is observed in WED. It postdates quartz cement and siderite.

APS (Aluminium Phosphate Sulphate minerals) – REE-rich APS are abundant, large and euhedral in WED. In BRTZ they are present as small, anhedral grains and far less abundant. Timing is difficult to ascertain.

4.2. Burial and temperature history

The burial and temperature histories of WED and BRTZ are presented in Figure 2. WED experienced major subsidence during Jurassic and Lower Cretaceous. This subsidence can be linked to the Jurassic-Cretaceous rifting event. The amount of subsidence decreased in the Upper Cretaceous, and might be correlated to end of the rifting. The maximum burial depth of the Röt Fringe sandstone was reached

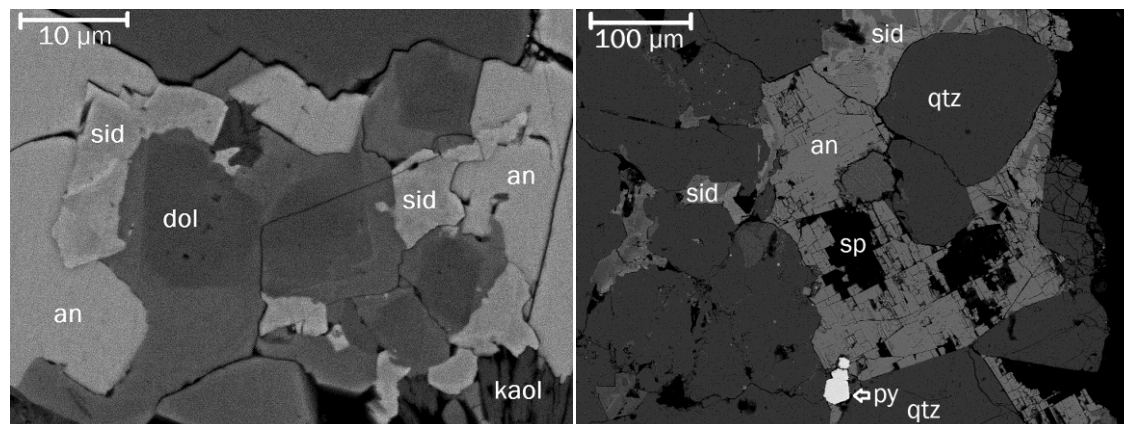


Figure 1. BSE image of BRTZ (left) and WED (right) sample. Note the different scales. BRTZ: Dolomite precipitation followed by siderite and then anhydrite. WED: partially dissolved anhydrite cement, surrounded by patchy zoned siderite cement. An = anhydrite, sid = siderite, kaol = kaolinite, sp = secondary pore, qtz = quartz, py = pyrite.

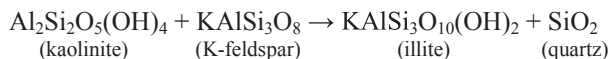
during the Upper Cretaceous and was >3000 m. At the end of the Cretaceous the inversion caused major uplift, resulting in the erosion of most of the Cretaceous and Palaeocene sediments. The uplift can be correlated to the first two Alpine inversion pulses and eroded >1000 m. After this major uplift gradual burial continued. The last inversion pulse occurred at the Eocene/Oligocene boundary, uplifting the rock sequence by approximately 200 m.

In BRTZ subsidence was slower during the Kimmerian rifting than in WED. A slight uplift of approximately 300 m occurred during the Lower Cretaceous. Major uplift in the Upper Cretaceous, as interpreted for WED, is not observed (Figure 2).

4.3. Integration and interpretation

Most diagenetic mineral reactions are strongly influenced by temperature [16]. We used the temperature dependency of the reactions to fit the paragenetic sequence onto the burial graph (Figure 2). Important (tectonic) events are also included.

K-feldspar overgrowth occurs early in the diagenesis of sandstones and can precipitate along with kaolinite at a temperature <50°C [17]. Illitization of kaolinite starts at temperature >70°C [16] and increases significantly between 120 and 140°C. K⁺ is supplied by K-feldspar dissolution and the reactions are accompanied by quartz precipitation [18]:



Since the peak temperature of WED was ~140°C during the Upper Cretaceous, illitization of kaolinite was completed. The difference in burial history between WED and BRTZ can therefore explain the absence of kaolinite in WED. Euhedral dolomite precipitation occurs at temperatures ~100°C [16]. Small amounts of carbon can be supplied by thermal decay of organic matter [15]. Due to the fast burial of WED, dolomite precipitation occurred earlier than in BRTZ. In BRTZ dolomite is followed by and closely related to siderite precipitation. Also minor quartz overgrowth, probably associated with K-feldspar and kaolinite conversion to illite [18], occurs after dolomite precipitation. According to [16] anhydrite cementation during burial diagenesis is the result of circulating evaporite-related pore waters. At the end of the Alpine inversion CO₂ probably accumulated in the field, resulting in a dissolution phase which affected the feldspars and anhydrite. The late stage siderite and quartz cementation in WED is

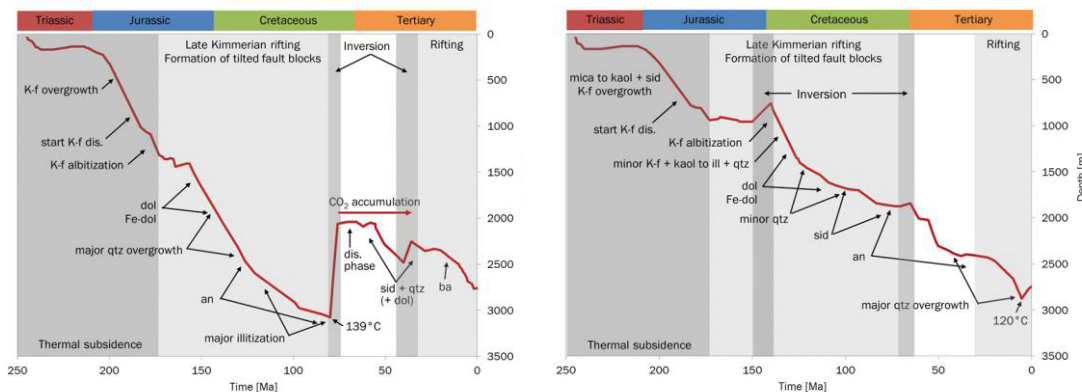


Figure 2. Paragenetic sequence and main events integrated with the burial history for WED (left) and BRTZ (right).

probably related to the presence of CO₂ and long-term pH buffering. The late stage dissolution and siderite/quartz precipitation are not observed in BRTZ. These events represent the main differences related to the presence of CO₂. The enhanced illitization of kaolinite could be partially due to the decreased formation brine pH.

5. Geochemical modeling

The observed mineral reactions in WED related to the CO₂ (black outline in Figure 2) are simulated by geochemical batch modelling using PHREEQC and the thermoddem database by BRGM [19]. The BRTZ formation water composition is computed by equilibrating surplus amounts of the minerals identified by XRD with brine. Subsequently the mineral composition (340 mol in total) and one kg brine (corresponding to 20% porosity and 50% water saturation) of BRTZ is equilibrated with CO₂ with a partial pressure of 280 bar. EDX analyses showed that illite is essentially iron-free and contains small amounts of magnesium. Magnesium-rich illite is initially used in the modelling. The precipitation of barite is not considered.

Equilibration of the present day BRTZ mineralogy with CO₂ and brine results in minor reaction of illite to kaolinite and microcline (Figure 3 (Mg-illite)). Illite is known to be the stable clay mineral at the applied conditions instead of kaolinite. Furthermore, microcline and kaolinite are unstable together at this temperature [16]. To investigate the stability of other types of illite, a model is run in which Mg-illite is replaced by Al-illite. This results in the reaction of albite, kaolinite and microcline to quartz and illite (Figure 3 (Al-illite)). Dividing the amount of illite over the Al and Mg variant gives results similar to the Al-illite, with in addition minor reaction of anhydrite, Mg-illite and CO₂ to dolomite (Figure 3 (Al-Mg-illite)). All three models result in negligible siderite precipitation. This can be explained by the lack of sufficient iron in the system. Several studies indicate the importance of iron containing minerals as iron source for siderite formation (e.g. [20, 21]). Assuming a potential iron source within the reservoir, petrographic analysis was used to select possible sources of iron within the BRTZ samples. Several minor iron containing minerals were identified. These are present in amounts below XRD detection limits but could be significant iron sources. The following minerals were used in the modelling: annite (biotite), hematite, goethite (Fe-oxide), ferrihydrite (Fe-hydroxide), ilmenite and pyrite (all 0.2 mol%). Figure 3 (right graph) shows the results of these model runs, in which both Al- and Mg-illite was included. All Fe-minerals individually yield the same reactions, including formation of siderite (Figure 3 (single Fe-

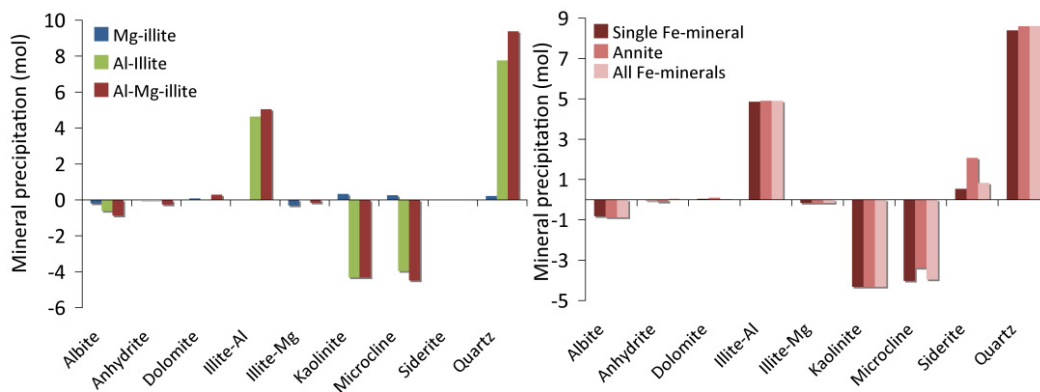


Figure 3. Modelling results. Left: Current mineral composition based on XRD measurements is equilibrated with CO₂. Sensitivity analysis on type of illite. Right: Fe-bearing minerals are added to the mineral composition with Al-Mg illite before equilibration.

mineral)). Addition of annite to the mineralogy, results in increased siderite precipitation. Modelling all Fe-minerals together (0.2 mol% in total), predicts a value in between (Figure 3 (All Fe-minerals)). The results indicate that several minerals observed in the BRTZ samples are able to supply iron for siderite formation, with annite potentially as the largest source. The three scenarios give equal results concerning the direction of the reactions, with the amount of siderite formation depending on the type and amount of iron minerals present. Another possible source of iron can be the influx of iron-rich fluids from outside the reservoir [22, 23].

6. Discussion

The petrographic study on BRTZ and WED sandstones shows significant differences in diagenetic history between the CO₂- and CH₄-bearing fields. The fields are not far apart and the selected sandstones are from similar lithofacies. We can therefore assume that the initial detrital mineralogy is similar, as well as the eogenetic conditions (shallow, depositional-environment related diagenesis). The main part of the paragenetic sequence in WED is interpreted to have occurred during burial diagenesis, before the influx of CO₂. Hence, the larger part of the differences in diagenesis between BRTZ and WED cannot be assigned to the presence of high CO₂ partial pressures. The burial histories, which show significant differences, probably had a large influence on the diagenetic histories. In addition, pore fluid chemistry plays a major role in diagenesis. The formation of faults and tilted half blocks during Kimmerian rifting could have generated fluid flow pathways, resulting in local differences in pore fluid chemistry. The presence of REE-rich APS minerals in WED suggest the influx of brine enriched in REE. The brine could result from carbonated fluids ascending along re-activated faults and volcanic rocks [7]. Volcanic rocks in the West Netherlands Igneous Centre, which includes WNB, are Early Cretaceous in age (140 – 130Ma) [14, 24]. They are related to the Late Kimmerian rifting and occur in the area around Werkendam [24].

Siderite and potentially the outer rims of dolomite represent the CO₂ sequestering minerals in WED. Particularly siderite is present very locally within the samples. A larger and more representative suite of sample analyses is required to calculate the amount of CO₂ sequestration by siderite. However, the amount of siderite and dolomite rims do not represent more than a few % of the total rock volume. Low amounts of CO₂ sequestration have also been found for other natural analogues. In the Fizzy field in the UK small amounts of dawsonite and dolomite are the sequestering minerals [6]. On the other hand, CO₂ sequestration is as high as several tens of volume percentages in a natural CO₂ field in the Songliao Basin in China [8]. Feldspar is generally thought to be the most important provider of cations for CO₂ sequestering minerals. In many natural CO₂ fields feldspars have not completely reacted, even after geological periods of time. Either reactions are much slower than generally considered, or the formation of carbonates is highly sensitive to the prevailing conditions beyond the presence of feldspar. According to [5] albite reaction to dawsonite occurs at high pH or high effective CO₂ pressure. Exceptional brine composition in equilibrium with feldspar could also explain the evident stability of these minerals [25].

Geochemical modelling shows that the observed feldspar/anhydrite dissolution and siderite/quartz/dolomite precipitation as a result of CO₂-brine-rock interactions can be simulated. Also the illitization of kaolinite in the presence of K-feldspar is shown. However, the model results highly depend on the assumptions made. A number of input parameters are varied in a sensitivity study indicating that the presence of Al-illite and Fe-minerals are required to simulate the mineral reactions as observed in the petrographic study. Under the conditions applied in this run, the model predicted that the amount of siderite precipitation depends on the type and amount of (minor) iron containing minerals present. More detailed investigation and modelling is required to better constrain the amount and type of Fe-minerals

required to form the observed amount of siderite and possibly Fe-rich dolomite. Furthermore, the possibility of an external iron source needs to be explored.

To conclude, geochemical modeling is able to predict long-term mineral reactions and can therefore be a powerful tool in site specific research or reservoir screening. However, the input parameters need to be chosen with great care. Relatively simple XRD mineralogical analyses are not adequate as input. Detailed petrographic analyses are necessary. Also, an expert opinion on diagenetic processes is required to guide the modelling into the right direction.

The diagenetic history discussed in this paper is based on limited data and several assumptions. Further work will include the extension of the petrographic analyses. Isotopic analyses on carbonate minerals will be performed to verify the link between siderite and late stage dolomite in Werkendam, and the presence of CO₂. Future work could involve the extension of the geochemical modeling to investigate iron migration, redox processes and siderite precipitation.

7. Conclusions

The diagenetic histories of CH₄- and CO₂-bearing stratigraphic equivalents show similarities as well as important differences. Partially, these differences can be assigned to contrasts in the burial histories of the two reservoirs, including influx of fluids along specific migration paths. The presence of many large, well crystallized REE-rich Aluminium Phosphate Sulphate minerals suggest that REE-rich brine migrated into the Werkendam field along activated faults. The main differences which seem to be linked to the presence of high CO₂ partial pressures are the enhanced dissolution of feldspar minerals and anhydrite cement and the subsequent precipitation of siderite, dolomite and quartz. PHREEQC geochemical modeling was able to simulate the observations of the mineral reactions induced by carbonized brine. Detailed mineralogical input, including minor minerals not detected by XRD, and an expert opinion on diagenetic processes is necessary to simulate the true reactions. The mineralogical differences strongly affect the type of mineral reactions and the resulting amount of CO₂ sequestration predicted by geochemical modelling.

Acknowledgements

This research was carried out and will be continued in the context of the CATO-2-program. CATO-2 is the Dutch national research program on CO₂ Capture and Storage technology (CCS). The program is financially supported by the Dutch government (Ministry of Economic Affairs) and the CATO-2 consortium parties. We would like to thank Harmen Mijnlief, Jaap Breunese, Tim Tambach, Therese Maarschalkerweerd, Jan Timmner, Maarten Pluymaekers and Geert-Jan Vis from TNO, Maartje Hamers from Utrecht University and Jonathan Flores Colmenares from TU Delft for fruitful discussions and technical help. Furthermore, we want to thank Schlumberger for giving us the opportunity to use their software PetroMod in the context of this study.

References

- [1] Benson S and Cook P. Chapter 5: Underground geological storage. In: *IPCC special report on carbon dioxide capture and storage*, Cambridge University Press; 2005
- [2] Gaus I, Audigane P et al. Geochemical and solute transport modelling for CO₂ storage, what to expect from it? *International Journal of Greenhouse Gas Control* 2; 2008, p. 605-625
- [3] Dethlefsen F et al. Uncertainties of geochemical modeling during CO₂ sequestration applying batch equilibrium calculations.

Environmental Earth Sciences, 65 (4); 2012, p.1-13

- [5] Worden RH. Dawsonite cement in the Triassic Lam Formation, Shabwa Basin, Yemen: A natural analogue for a potential mineral product of subsurface CO₂ storage for greenhouse gas reduction. *Marine and Petroleum Geology* 23; 2006, p. 61-77
- [6] Wilkinson M, et al. CO₂-mineral reaction in a natural analogue for CO₂ storage – implications for modeling. *Journal of Sedimentary Research* 79; 2009; p. 486-494
- [7] Pudlo D et al. Petrophysical, facies and mineralogical-geochemical investigations of Rotliegend sandstones from the Altmark natural gas field in central Germany. *Energy Procedia* 4; 2011, p. 4648-4655
- [8] Liu N et al. Genesis of authigene carbonate minerals in the Upper Cretaceous reservoir, Honggang Anticline, Songliao Basin: A natural analogue for mineral trapping of natural CO₂ storage. *Sedimentary Geology* 237; 2011, p. 166-178
- [9] Nelskamp S and Verweij JM. Using basin modeling for geothermal energy exploration in the Netherlands – an example from the West Netherlands Basin and Roer Valley Graben. *TNO report TNO-060-UT-2012-00245*; 2012
- [10] De Jager J. Inverted basins in the Netherlands, similarities and differences. *Geologie en Mijnbouw/Netherlands Journal of Geosciences* 83; 2003, p. 355-366
- [11] Balen van RT. et al. Modelling the hydrocarbon generation and migration in the West Netherlands Basin, the Netherlands. *Geologie en Mijnbouw/Netherlands Journal of Geosciences* 79; 2000, p. 29-44
- [12] De Jager J et al. Hydrocarbon habitat of the West Netherlands Basin. In: *Geology of gas and oil under the Netherlands*. Edited by Rondeel et al.; 1996, p. 191-206
- [13] De Jager J. Geological development. In: *Geology of the Netherlands*. Edited by Wong et al.; 2007, p. 5-26
- [14] Sissing W. Palaeozoic and Mesozoic igneous activity in the Netherlands: a tectonomagmatic review. *Geologie en Mijnbouw/Netherlands Journal of Geosciences* 83 (2); 2004, p. 113-134
- [15] Wycherley H et al. Some observations on the origins of large volumes of carbon dioxide accumulations in sedimentary basins. *Marine and Petroleum Geology* 16; 1999, p. 489-494
- [16] Worden RH and Burley SD. Sandstone diagenesis: the evolution of sand to stone. In: *Sandstone diagenesis – Recent and ancient*; 2003, p.3-44
- [17] Bjørkum P.A. and Gjelsvik N. An isochemical model for formation of authigenic kaolinite, K-feldspar and illite in sediments. *Journal of Sedimentary Petrology* 58 (3); 1988, p. 506-511
- [18] Chuhan FA et al. The role of provenance in illitization of deeply buried reservoir sandstones from Haltenbanken and north Viking Graben, offshore Norway. *Marine and Petroleum Geology* 17; 2000, p. 673-689
- [19] Blanc P et al. THERMODDEM A DATABASE DEVOTED TO WASTE MINERALS. BRGM, Orléans, France. <http://thermoddem.brgm.fr>; 2007
- [20] Pham VTH et al. On the potential of CO₂-water-rock interactions for CO₂ storage using a modified kinetic model. *International Journal of Greenhouse Gas Control* 5 (4); 2011, p. 1002-1015
- [21] Kihm J et al. Hydrogeochemical numerical simulation of impacts of mineralogical compositions and convective fluid flow on trapping mechanisms and efficiency of carbon dioxide injected into deep saline sandstone aquifers. *Journal of Geophysical Research - B: Solid Earth* 117 (6); 2012 (in press)
- [22] Ardelan MV and Steinnes E. Changes in mobility and solubility of the redox sensitive metals Fe, Mn and CO at the seawater-sediment interface following CO₂ seepage. *Biogeosciences* 7 (2); 2010, p. 569-583
- [23] Rempel KU et al. An experimental investigation of trace element dissolution in carbon dioxide: Applications to the geological storage of CO₂. *Chemical Geology* 289 (3-4); 2011, p. 224-234
- [24] Bergen van MJ and Sissingh W. Magmatism in the Netherlands: expression of the North-west European rifting history. In: *Geology of the Netherlands*. Edited by Wong et al.; 2007, p. 197-221
- [25] Taylor TR et al. Sandstone diagenesis and reservoir quality prediction: Models, myths, and reality. *AAPG Bulletin* 94 (8); 2010, p.1093-1132