Geothermal reservoir quality prediction from diagenesis modelling

Margrethe Thorup Nielsen[1], Mette Olivarius[1], Rikke Weibel[1], Anders Mathiesen[1], Joachim Tremosa[2], Linda Bonnell[3], Lars Henrik Nielsen[1]

[1] GEUS, Geological Survey of Denmark and Greenland, Øster Voldgade 10, 1350 Copenhagen K, Denmark

[2] BRGM, Bureau de Recherches Géologiques at Minières, Orléans, France

[3] Geocosm, Durango, Colorado, USA

mol@geus.dk

Keywords: Diagenesis modelling, reservoir quality, mechanical compaction, burial depth, quartz cement, porosity-reduction.

ABSTRACT

The Danish subsurface is excellent for geothermal exploitation with its km-thick sedimentary successions of locally proved geothermal applicability. However, it is a challenge to find the geothermal reservoirs with optimum combination of the highest possible temperatures and sufficiently high porosity and permeability. The best reservoirs seem to be restricted to a depth of c. 1–3 km. The geothermal gradient is c. 25–30°C/km resulting in significant mineralogical alteration and cement precipitation in the sandstones (diagenesis) with large impact on porosity and permeability in the deeper part of the basin. Therefore, it is important to make reliable predictions of the reservoir quality before selecting locations for new geothermal plants.

Diagenesis modelling is here applied to make qualified pre-drill estimates of reservoir properties. Input parameters from a comprehensive database based on analyses of well cores include stratigraphic division, depositional facies, grain-size distribution, detrital mineralogy, cement types, grain coat coverage, porosity, permeability, provenance, burial history and temperature indicators. The temperature is confined by vitrinite reflectance, homogenization temperatures from fluid inclusions in quartz overgrowths and oxygen isotope composition of carbonate cements. The diagenesis model, based on the modelling tool Touchstone, is compared with generalized mechanical compaction curves from other studies and results from the modelling software SURP. These modelling software's can calculate the forward evolution of porosity induced by individual contributions of mechanical compaction and diagenesis.

The calibrated forward diagenesis modelling is used to estimate the temporal and spatial distribution of reservoir properties while applying basin modelling. Our research has identified a number of correlations that make the modelling of the sandstone reservoirs possible, when taking into account the influences of provenance and depositional environment on mineralogy, as well as the influences of mineralogy and temperature regime on diagenesis, the influence of burial depth on temperature regime and the influence of diagenesis on the reservoir properties.

1. INTRODUCTION

In the Danish Basin, the present burial depth of the Gassum Formation is shallower than the maximum burial depth, due to post-depositional inversion and uplift which resulted in erosion of 500-1000 meters of overburden (Japsen and Bidstrup 1999; Nielsen 2003; Japsen et al. 2007). For evaluation of the degree of diagenesis, the amount of time at a certain temperature is of key importance, as longer time at higher temperatures will result in more pronounced precipitation of e.g. quartz cement. This means that a reliable estimate of the burial history is crucial when aiming at predicting reservoir quality.

The reservoir quality of the Gassum Formation sandstones is influenced primarily by their burial depth, which affects both the degree of mechanical compaction and chemical diagenesis. Secondarily, the depositional environment and climate influence the detrital mineralogy, which in the end determines the diagenetic evolution of the sandstone (Weibel et al. 2017a, b). Previous studies of the Gassum Formation onshore Denmark has shown that for shallow burial (<1500 m present depth), mechanical compaction is the main factor controlling the porosity, whereas deeper burial depth results in larger influence of the chemical diagenesis such as quartz and carbonate cementation.

One of the great advantages of diagenesis modelling is that it can combine burial history with petrographical observations. For this study, a comparison of SURP and Touchstone software's was chosen in order to evaluate the performance of different modelling approaches. Input parameters from a comprehensive database based on analyses of well cores include stratigraphic division, depositional facies, grain-size distribution, mineralogy, cement types, grain coat coverage, porosity, permeability and burial history.

The Touchstone software is developed by Geocosm and has previously been proven useful for evaluation of reservoir quality in several hydrocarbon settings (e.g. Akpokodje et al. 2018; Taylor et al. 2015; Walderhaug et al. 2000). The Touchstone modelling focuses mainly on compaction and quartz kinetics. The SURP modelling tool is developed by BRGM (Bureau de Recherches Géologiques at Minières) and has been used for unpublished hydrocarbon reservoir studies (Tremosa et al., *in prep.*). The SURP modelling applies a combination of compactional evaluation and thermodynamic calculations based on PHREEQC. Neither the Touchstone nor the SURP modelling tools have until now been applied for geothermal reservoirs.

The overall aim is to be able to use diagenesis modelling for reservoir quality predictions in undrilled areas of the Danish area for appraisal of new geothermal prospects.

2. GEOLOGICAL BACKGROUND

The Norwegian-Danish Basin formed as a result of rifting in the Late Cretaceous – Early Carboniferous (Vejbæk, 1997). The basin is limited towards the south by the Ringkøbing–Fyn High and towards the north by the Fennoscandian Border Zone. During the Triassic and Jurassic, thick deposits accumulated during thermally controlled subsidence. The sedimentary material was mainly supplied from Mesozoic erosion of the uplifted Fennoscandian basement and Paleozoic cover (Zeck et al., 1988).

The focus of this study is on the Gassum Formation, which function as geothermal reservoir for two Danish geothermal plants and has a high potential for future geothermal prospects due to its large distribution with optimum burial depth (e.g. Nielsen 2003; Weibel et al. 2017a). The sandstones in the Gassum Formation comprise fluvial and shallow deposits formed by a series of relative sea level falls during the Upper Triassic – Lower Jurassic. The formation is widely distributed in the Danish area and has thicknesses of 50–150 m in central and distal parts of the Danish Basin and up to 300 m along the Sorgenfrei – Tornquist fault zone, but is absent on most of the Ringkøbing–Fyn High due to later erosion (Fig. 1; Nielsen & Japsen, 1991; Nielsen, 2003). The Gassum Formation is overlain by the thick, uniform marine mudstones of the Fjerritslev Formation, which forms a competent caprock unit (Nielsen, 2003; Weibel et al., 2014). The present day burial depths encountered in wells vary from 550 to 3350 m. Though, the maximum burial depth of the formation is deeper with estimated depths of down to 4 km due to later erosion of the overburden as a result of a Late Cretaceous – Early Paleogene inversion combined with a regional Neogene uplift in the northeastern part of the area (Japsen and Bidstrup 1999; Weibel et al. 2017b).

The sandstones of the Gassum Formation are mainly well sorted subarkoses and arkoses (Friis, 1987) of fine to medium grain size. The permeability largely follows a grain-size trend for the shallowly buried sandstones (<1500 m) with higher permeabilities in coarser sandstones (Weibel et al. 2017b). Exceptions are samples with high amounts of detrital clays or early siderite cement, which result in low porosities and permeabilities. At deeper burial (>1500 m), the grain-size has less influence on porosity and permeability. Here, the cementation of the sandstone (quartz and carbonate), which increases in abundance with burial depth, is of larger importance for the reservoir quality, resulting in lower porosity and permeability at greater maximum burial depth. Early continuous chlorite-coatings has locally retarded quartz precipitation and thus resulted in porosities and permeabilities higher than the general trend, whereas locally abundant illitic clays (fluvial deposits) have had the opposite effect (Weibel et al., 2017b).

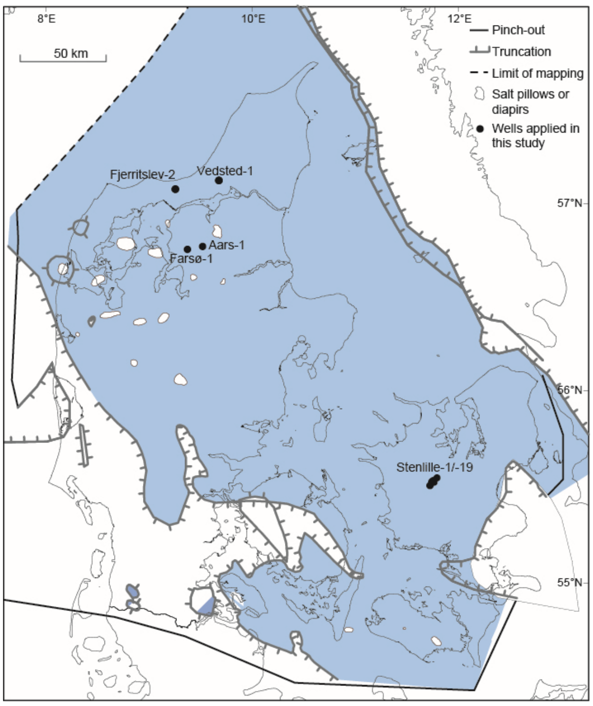


Figure 1: Map showing the distribution of the Gassum Formation (blue) and location of the investigated wells (modified after Weibel et al. 2017a).

3. METHODS

In order to evaluate the compaction modelling , samples from shallow wells (1430–1780 m depth) in the Stenlille area were applied. For evaluation of both compaction and quartz cementation in intermediately buried sandstones, samples from the Vedsted-1 and Fjerritslev-2 wells (1780–2300 m depth) were applied. For evaluation of the modelling of compaction and quartz cementation in deep wells, sandstones from the Farsø-1 and Aars-1 wells (2850–3360 m depth) were applied.

For each sample, routine core analysis was performed and a thin section was prepared from the same plug. The polished thin sections were studied by transmitted and reflected light microscopy. Point count data (80 samples in total) were collected via counting of minimum 500 points excluding porosity in each thin section. The mean grain diameter in each thin section was obtained by measurement of minimum 100 grains intersecting three or more arbitrary straight lines. Since thin section grain-size analysis underestimates the dimensions relative to sieving analysis, the diameters of the measured grains were applied for calculation of mean grain size and degree of sorting. The grain-size nomenclature is applied according to the Wentworth Class (Wentworth 1922). Sorting is defined as a graphic standard deviation (Trask 1930) calculated from the thin section grain size distribution. Grain coat coverages were visually estimated and controlled for a subset of data by manual measurements on back-scatter electron micrographs from scanning electron microscopy.

Basin maturity modelling

Basin maturity modelling is used as a tool for integration of geological, geophysical, geochemical and petrophysical data and serves as a framework for testing numerous hypotheses concerning origin and evolution of the basin, the processes herein and the geological development of its petroleum resources. The object of the basin modelling is normally to investigate thermal maturity of the potential source rock, as timing and extent of source rock maturation is crucial to understand petroleum systems (*e.g*. Magoon and Dow, 1994).

Basin maturity modeling is in this study conducted as 1D modeling, using the PetroMod (IES®, Integrated Exploration Systems GmbH, Aachen, Germany; v2016.2) software on five wells all situated within the Danish onshore area (Fig. 1). The 1D basin modelling tool combines a wide range of geological, geophysical, geochemical and petrophysical data into a conceptual model that contains all of the key elements. The aim of the 1D basin modelling is to organize and integrate the knowledge and understanding of the geological development in order to deliver input data for the Touchstone and SURP modelling tools (burial history, temperature history etc.).

Based on the defined tectonic-stratigraphic framework defined in the Danish onshore area, the selected wells were divided into layers or events allowing the 1D PetroMod to quantify all important basin processes as a function of time, including maturity parameters such as temperature and vitrinite reflectance. The 1D PetroMod model calibrates maturity using either the EASY%R_o (Sweeney and Burnham, 1990) or the Basin%Ro (Nielsen et al., 2015) vitrinite reflectance models to determine the thermal evolution of the basin. The calculated temperature history is based upon standard mathematical approximations of heat flux in sedimentary basins through time, which is expressed as the heat flow (HF) model, together with surface temperature through time, composition and thickness of the sedimentary infill, potential erosion and timing (Japsen and Bidstrup 1999; Nielsen 2003; Japsen et al. 2007). The paleo-heat flow history is calibrated against vitrinite reflectance well temperature data.

Touchstone

The Touchstone™ modelling software (Lander and Walderhaug 1999) is a forward modelling approach to predict reservoir quality based on burial history inputs and measured rock properties. The input parameters are petrographic data, routine core analyses in combination with temperature and pressure calibrated burial histories. The focus has in this case been on the temperature evolution history.

For the Stenlille area (shallow burial), the model was optimized for compaction and microporosity, only. Microporosity was included in order to predict total porosity. For the two other areas, intermediate and deep burial; Vedsted-Fjerritslev and Farsø-Aars, respectively), the model was optimized for compaction, paragenesis, replacement, quartz kinetics, microporosity and permeability. Prior to model optimization and prediction, a normal run was set up. The initial results from this run were then used for an optimization run for the calibration of the model after which a prediction run was performed. A full description of the setup of the Touchstone modelling can be found in Lander and Walderhaug (1999) and Lander et al. (2008).

SURP

The SURP code (Tremosa et al., in prep.) is under development at BRGM to account for both thermo-hydro-mechanical and mineralogical effects and their reciprocal influence during the burial of a 1D sedimentary pile. It includes the influence of temperature and pressure evolution on diagenetic mineral reactions and the influence of the porosity variations by mineralogical precipitations and dissolution, the fluid pressure and the effective stress in the sedimentary pile. The SURP code consists of a coupling between the thermo-hydro-mechanical calculations, made using a Python code source, and the IPHREEQC geochemical calculation code (Charlton & Parkhurst, 2011), used for the thermodynamic and mineralogical calculations. The mineral evolution is calculated assuming a thermodynamic equilibrium between the pore water and the mineral assemblage forming the rock. The calculated diagenetic evolution is then driven by the temperature changes but also depends on the pore water composition. During the sediment burial, the porosity evolves both because of the mechanical compaction of the rock and because of the mineral precipitations and dissolutions. It is then possible to distinguish the individual effects of compaction and diagenesis on porosity evolution.

4. RESULTS

Petrography of the Gassum Formation

The sandstones of the Gassum Formation are mainly subarkoses and arkoses according to the classification of McBride (1963). The feldspar content is generally low in the eastern part of Denmark, which is known from the Stenlille wells, compared with higher contents in the western part of Denmark, where the Aars-1, Farsø-1, Vedsted-1 and Fjerritslev-2 wells are located. Furthermore, albite becomes more abundant with increasing burial depth. Plutonic rock fragments, mica and heavy minerals occur in smaller amounts.

The dominant cementing phases in the Gassum Formation is siderite and calcite cement in shallowly buried parts, though quartz and ankerite cement in deeply buried sandstones (Fig. 2). The maximum abundance of quartz cement increases with burial depth. The abundance of grain coating clays vary independently of burial depth, since the clay rims comprise both detrital and authigenic clays.

The detrital composition and cementing phases of the Gassum Formation and their relationship with depositional environment and burial depth are described in more details by Friis (1987) and Weibel et al. (2017a, b).

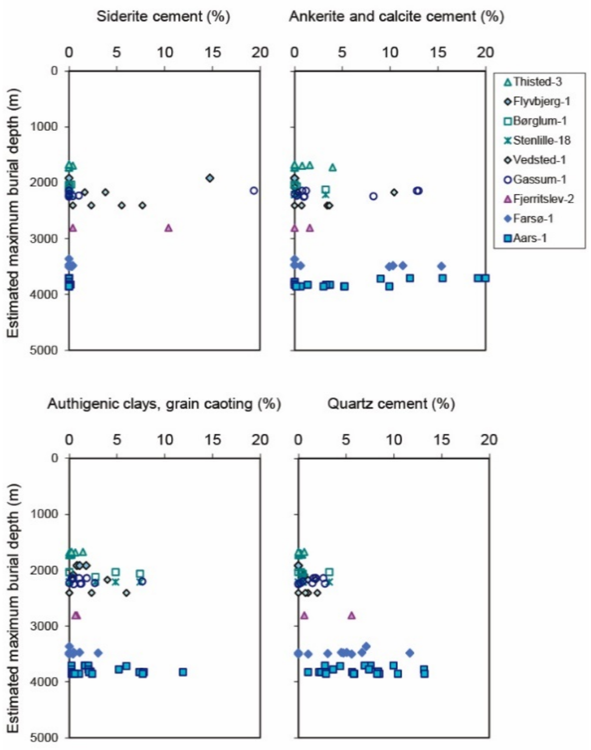


Figure 2: Abundance of cementing phases with estimated maximum burial depth. Note that the maximum abundance of siderite is in shallowly buried sandstones, and that the maximum quartz cement content increases with burial (modified from Weibel et al. 2017b).

Touchstone diagenesis modelling

Mechanical compaction

The initial porosity is assumed to be 36 % for the Aars-1 and Farsø-1 wells according to the applied model fit to experiments conducted by RQC (Consortium for Quantitative Prediction of Sandstone Reservoir Quality) established by Geocosm.

The Gassum Formation in the Stenlille area shows a relatively low reduction in porosity (from 35 % to 30 %) during the Jurassic and Lower Cretaceous due to the relatively low sedimentation rate (Fig. 3). The deposition of thick chalk units during the Upper Cretaceous has little effect on the resulting porosity (28 %) at a burial depth of 1580 m.

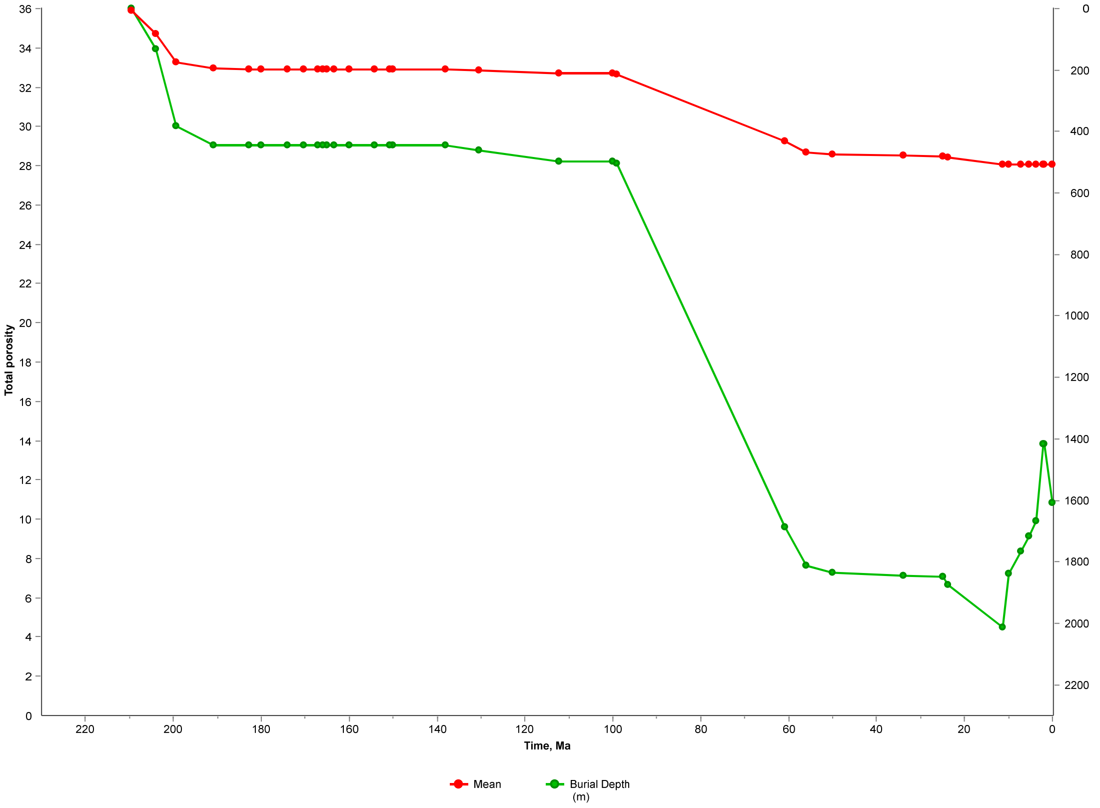
Quartz cementation

The Gassum Formation in the Farsø-1 and Aars-1 cores show a relatively high porosity-reduction (from 36 % to 25 %) due to mechanical compaction resulting from the deposition of the overlying part of the Gassum Formation (Fig. 3). A continued gradual porosity-reduction (from 25 % to 18 %) takes place during the low sedimentation rates of the overlying Jurassic and Lower Cretaceous sediments. This change into a slightly increased porosity-reduction rate during the Upper Cretaceous due to deposition of thick overlying chalk units. This porosity-reduction is coalescent with a temperature increase from 80 to 120°C and therefore includes the onset of quartz cementation. The resulting porosity is in average 10–11 % at burial depth of 2800–3200 m after mechanical compaction and quartz cementation. The modelled intergranular volume (IGV) fits well with the measured IGV from point counting (Fig. 4A).

The quartz cement abundance is calculated from the Touchstone model based on point counted data from the Aars-1 and Farsø-1 wells. Every second sample was used for calibration of the model and the rest were used as test samples. Plot of the modelled versus measured quartz cement abundance fits well for both calibrated and test data and thereby confirms the applicability of the model for quartz cementation.

Several iterations showed that fitting the burial and thermal history has major effects on the quantified abundance of quartz cement. The modelled quartz cement abundance fits well with the measured quartz cement abundance from point counting (Fig. 4B).

A Stenlille area



B Aars-1

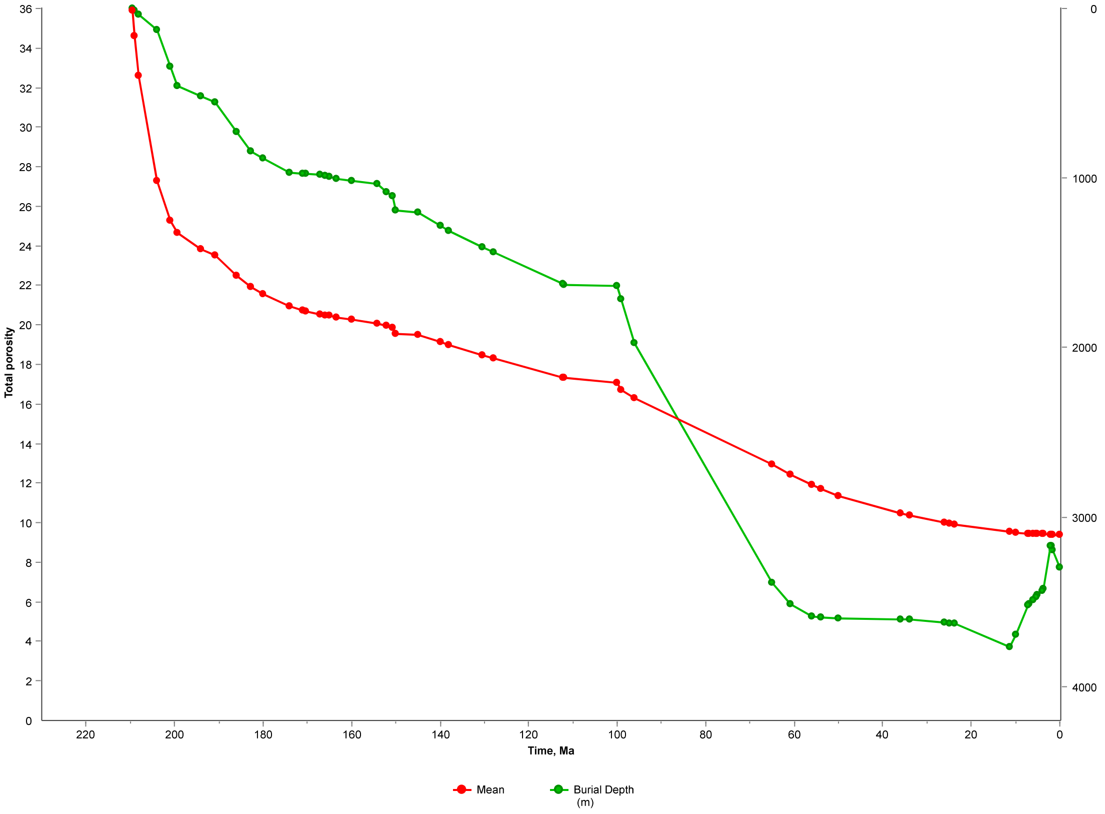


Figure 3: Touchstone modelled porosity evolution given in percentage (in red) and PetroMod modelled **burial history (in green) in meter for the Stenlille area (A) and the Aars-1 well (B).**

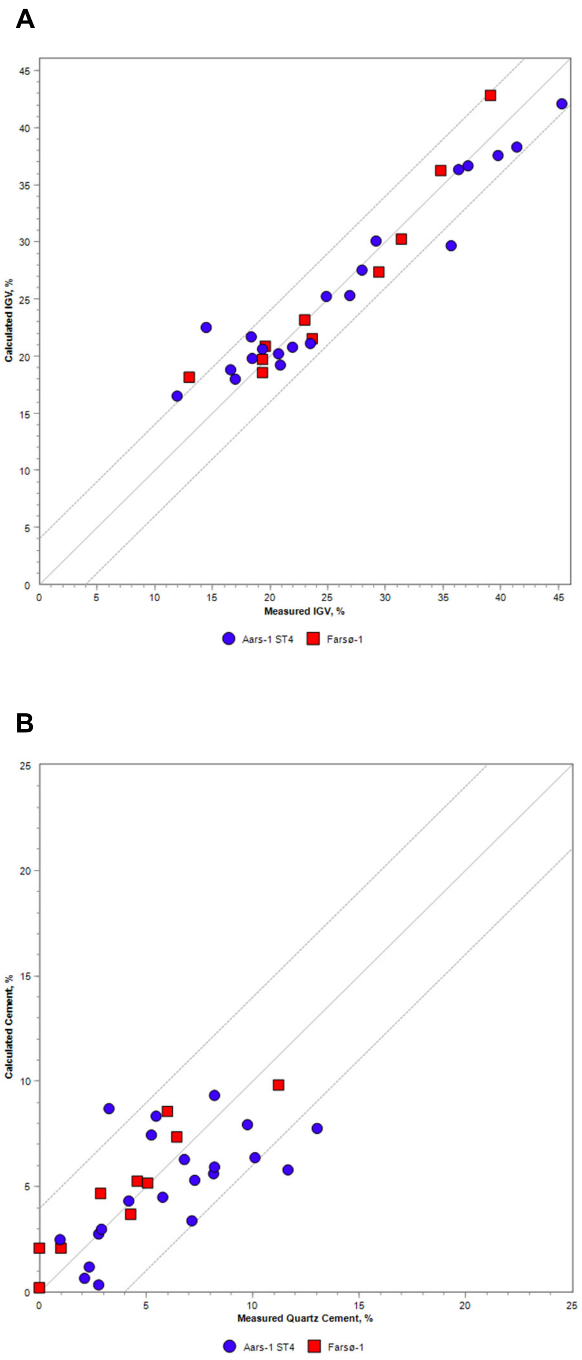


Figure 4: Comparison of calculated (from the Touchstone model) and measured (from point counting of thin sections) intergranular volume – IGV (A) and quartz cement abundance (B).

SURP diagenesis modelling

Porosity evolution

An initial porosity of 35 % was applied in order to be comparable with the other diagenesis model. According to the mechanical compaction model, the porosity decreases rapidly (from 35 to 25 %) during the first 1000 m of burial (Fig. 5). The porosity decreases slowly from 25 % to 22 % during the succeeding burial to 2000 m and remains relatively constant around 22 % during continued burial. However, when both compaction and chemical diagenesis is considered, the porosity is reduced slightly more (from 35 to 22 %) at 1000 meters burial depth (Fig. 5). A gradual porosity-decrease from 22 % to 13 % continues during burial from 1000 m to 3800 m, when applying the combined diagenesis and compaction model.

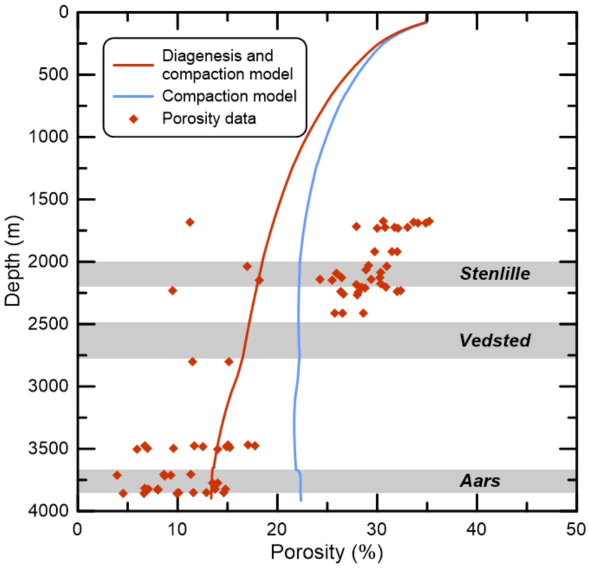


Figure 5: SURP modelled porosity evolution from compaction model and from a combined compaction and diagenesis model, which is compared with plug porosity measurements of samples with petrographical information.

Cementation

The SURP diagenesis model show the combined effect of all modelled cementing phases (Fig. 6). During the burial of the Gassum Formation, the diagenetic evolution of the sandstone is calculated thanks to the coupling in SURP between the thermo-hydro-mechanical calculations and the PHREEQC geochemical code. The diagenetic evolution is driven by the temperature increase during burial and depends on the thermodynamic equilibrium between the formation water chemistry and the mineralogical assemblage.

For the Gassum Formation sandstone, in agreement with the petrographical observations, the dissolution of mica (muscovite) and K-feldspar primary phases is simulated. Because of these dissolving minerals, kaolinite is the first secondary phase to precipitate and is the most abundant silicate cement in the first 1000–1500 m of burial. Precipitation of quartz and chlorite is initiated in the first 1000 m and increases gradually in abundance with burial depth. At 1500 meters burial depth, quartz is the most likely cement to form and an amount of 3 % of authigenic quartz is simulated in the deepest well. Illite begins precipitation at a burial depth of 3800 m.

Regarding the carbonates, a progressive replacement of siderite by ankerite is simulated, considering siderite as primary phase. At approximately 2250 m burial depth, ankerite cement becomes more abundant than siderite.

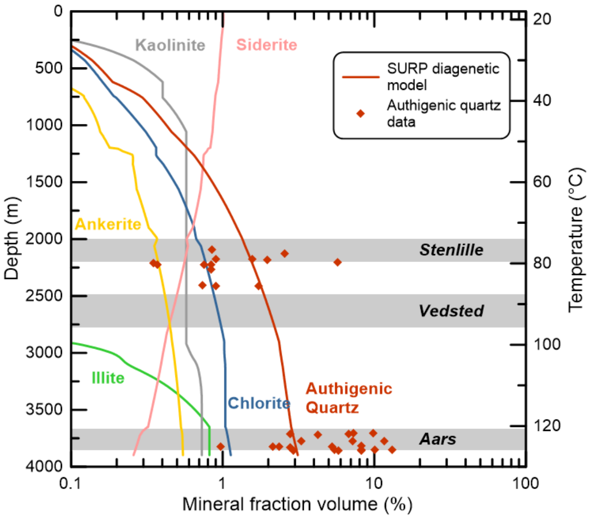


Figure 6: SURP modelled abundance of cementing phases according to burial depth. Especially authigenic quartz is one of the most important cementing phases and its abundance is compared with quartz cement abundance from point counting data.

5. DISCUSSION

One of the main objectives with the diagenesis modelling of the Gassum Formation is to investigate at which depth quartz cementation must be expected to have destroyed the geothermal reservoir. A relatively low number of cored intervals of the Gassum Formation are from the depth range of 2500–3500 m estimated maximum burial (Fig. 2). Major chemical changes may occur in this depth interval. The deeper part of the depth-interval corresponds to intensive quartz cementation in the North Sea Basin (e.g. Burley et al., 1989; McBride, 1989; Walderhaug, 1990; Giles et al., 1992).

The Touchstone model for Stenlille shows that the porosity changes can be modelled for the shallowly buried Gassum Formation solely by mechanical compaction. Porosity of intermediately and deeply buried parts of the Gassum Formation must be modelled by a combination of mechanical compaction and quartz cement precipitation in the Touchstone model. Since quartz is one of the major porosity occluding cements in the Gassum Formation (Friis 1987; Weibel et al. 2017b), the quartz cement abundance is crucial for predicting the impact of diagenesis on the reservoir properties.

The importance of constraining the thermal history in exhumed basins was emphasized by English et al. (2017). The Gassum Formation has experienced a minor Middle Jurassic uplift and erosion mainly in the western part of Denmark, and a major Neogene uplift of the northern and central part of Denmark (Japsen & Bidstrup, 1997; Nielsen, 2003; Japsen et al., 2007). Fitting the thermal and burial history has required several iterations and not until all mineralogical temperature indicators were applied could the quartz cement abundance be calculated for the deepest wells. However, this meant that the vitrinite reflectance data no longer corresponded with the EASY%R_o (Sweeney and Burnham, 1990) vitrinite reflectance model, but instead the Basin%Ro vitrinite reflectance model that is constructed to fit data from the Danish Basin (Nielsen et al., 2015).

The SURP model incorporates several cementing phases known from petrographical investigations. The modelled quartz abundance is in the lower end of the spectrum of the point counted data (Fig. 6). The sensibility of the SURP model towards variations in formation water chemistry, mineral abundances, initial porosity etc. is not known and needs to be evaluated further. Though the quartz cement abundance may be underestimated, other cementing phases are incorporated in the model, such as siderite, ankerite cement and clays minerals.

Carbonate cement abundance cannot be estimated from the Touchstone modeling tool and therefore has to be added manually to the model. The SURP modeling tool applies a thermodynamic approach and show reduced stability of siderite with burial succeeded by increased stability and precipitation of ankerite at burial depths > 2000 m (Fig. 6). This reflects perfectly the petrographically observed abundant siderite at shallow burial depth, though ankerite cement at deeper burial depths for example in the Aars-1 well (Weibel et al., 2017a, b).

The SURP diagenesis model suggest that kaolinite is the first precipitating authigenic phase. Early precipitation of kaolinite can be confirmed petrographically (Friis, 1987; Weibel et al., 2017a, b). However, the observation of early chlorite coatings cannot be imitated by the SURP model. Possibly, adjustment of formation water chemistry or an additional kinetic control on the mineral phase stability have to be considered, since chlorite coatings preferentially form in the estuarine environment (Weibel et al., 2017b). The modelled illite precipitation at burial depths > 3000 m corresponds well with petrographical observations.

6. CONCLUSIONS

The Touchstone modelling has confirmed that the porosity of shallowly buried Gassum Formation sandstones can be modelled by mechanical compaction. The porosity and the quartz cement abundance in intermediately and deeply buried sandstones can be modelled by a combination of mechanical compaction and quartz cementation. The risk of encountering carbonate-cemented sandstones must be added to the diagenesis model manually.

The SURP diagenesis model imitates most of the petrographically observed cementing phases, such as quartz, ankerite, siderite, kaolinite, illite and chlorite. The estimated temperature for precipitation of these phases fits generally with the petrographical observations. However, SURP model fails in estimating the correct abundances of these cementing phases.

Each diagenesis model has its advantages and disadvantages. Application of a combination of these models may narrow the uncertainty in predicting the reservoir properties of new geothermal prospects.

REFERENCES

Akpokodje, M., Melvin, A., Churchill, J., Burns, S., Morris, J., Kape, S., Wakefield, M. and Ameerali, R., 2018. Regional study of controls on reservoir quality in the Triassic Skagerrak Formation of the Central North Sea. In: Bowman, M., Levell, B. (Eds.), Petroleum Geology of NW Europe: 50 Years of Learning - Proceedings of the 8th Petroleum Geology Conference. *Geological Society of London*, 125–146.

Burley, S.D., Mullis, J., Matter, A., 1989. Timing diagenesis in the Tartan reservoir (UK North Sea): constraints from combined cathodo-luminescence microscopy and fluid inclusion studies. *Marine and Petroleum Geology* **6**, 98–120.

Charlton, S. R., and Parkhurst, D. L. (2011). Modules based on the geochemical model PHREEQC for use in scripting and programming languages. *Computers & Geosciences*, **37**, 1653–1663.

English, K.L., English, J.M., Bonnell, L.M., Lander, R.H., Hollis, C., Refern, R., Guirdham, C., Garnham, J., Cherif, R.Y. 2017. Controls on reservoir quality in exhumed basins – an example from the Ordovician sandstone, Illizi Basin, Algeria. *Marine and Petroleum Geology,* **80**, 203 –227.

Friis, H., 1987. Diagenesis of the Gassum Formation Rhaetian-Lower Jurassic, Danish Subbasin. *DGU Report* Series **A 18**, 41p.

Japsen, P. and Bidstrup, T., 1999. Quantification of late Cenozoic erosion in Denmark based on sonic data and basin modelling. *Bulletin of Geological Society of Denmark,* **46**, 79–99.

Giles, M.R., Stevenson, S., Martin, S.V., Cannon, S.J.C., Hamilton, P.J., Marshall, J.D., Samways, G.M., 1992. The reservoir properties and diagenesis of the Brent Group: a regional perspective. In: Morton, A.C., Haszeldine, R.S., Giles, M.R., Brown, S. (Eds.), Geology of the Brent Group, 61. *Geological Society of London Special Publication*, 289–327.

Japsen, P., Green, P.F., Nielsen, L.H., Rasmussen, E.S., Bidstrup, T. 2007. Mesozoic-Cenozoic exhumation events in the eastern North Sea Basin: a multi-disciplinary study based on palaeothermal, palaeoburial, stratigraphic and seismic data. *Basin Research*, **19**, 451–490.

Lander, R.H., Walderhaug, O., 1999. Predicting porosity through simulating sandstone compaction and quartz cementation. *American Association of Petroleum Geologists Bulletin*, **83**, 433–449.

Lander, R. H., Larese, R. E. and Bonnell, L. M. 2008. 'Toward more accurate quartz cement models : The importance of euhedral versus noneuhedral growth rates'. American Association of Petroleum Geologists Bulletin 11(11), 1537–1563. Magoon, L.B., and W.G. Dow, 1994, The petroleum system, *in* L.B. Magoon and W.G. Dow, eds., The Petroleum System – From Source to Trap: *American Association of Petroleum Geologists Memoir*, **60**, 3–24.

Magoon, L.B., and Dow, W.G. 1994, The petroleum system, *in* L.B. Magoon and W.G. Dow, eds., The Petroleum System – From Source to Trap: *American Association of Petroleum Geologists Memoir*, **60**, 3–24.

McBride, E.F., 1963. A classification of common sandstones. *Journal of Sedimentary Research*, **33**, 664–669.

McBride, E.F. 1989. Quartz cementation in sandstones: a review. *Earth Science Review*, **26**, 69–112.

Nielsen, L.H. 2003. Late Triassic – Jurassic development of the Danish Basin and Fennoscandian Border Zone, Southern Scandinavia. In: Ineson, J. R. & Surlyk, F. (Eds.): The Jurassic of Denmark and Greenland. *Geological Survey of Denmark and Greenland Bulletin*, **1**, 459–526.

Nielsen, S.B., Clausen, O.R. and McGregor, E. 2015, Basin%Ro: A vitrinite reflectance model derived from basin and laboratory data: *Basin Research*, doi:10.1111/bre.12160

Sweeny, R.E. and Burnham, A.K. 1990: Evaluation of a simple model of vitrinite reflectance based on chemical kinetics. *American Association of Petroleum Geologists Bulletin*, **74**, 1559– 1570.

Taylor, T.R., Kittridge, M.G., Winefield, P., Bryndzia, L.T. and Bonnell, L.M., 2015. Reservoir quality and rock properties modeling - Triassic and Jurassic sandstones, greater Shearwater area, UK Central North Sea. *Marine and Petroleum Geology,* **65**, 1–21.

Trask, P.D., 1930. Mechanical analysis of sediments by centrifuge. *Economic Geology*, **25**, 581–599.

Tremosa, J., Gailhanou, H., Chiaberge, C., Castilla, R., Gaucher E. C., Lassin, A., Gout, C., Fialips, C., and Claret, F. (*in prep.*). Effects of smectite dehydration and illitisation on overpressures in sedimentary basins: a coupled chemical and thermo-hydro-mechanical modelling approach. *Journal of Geophysical Research: Solid Earth.*

Vejbæk, O.V., 1997. Dybe strukturer i danske sedimentære bassiner. *Geologisk Tidsskrift*, **4**, 1–31.

Walderhaug, O., 1990. A fluid inclusion study of sandstones offshore mid-Norway-possible evidence for continued quartz cementation during oil emplacement. *Journal of Sedimentary Petrology*. **60**, 203–210.

Walderhaug, O., Lander, R.H., Oelkers, E.H. and Nadeau, P.H., 2000. Modelling quartz cementation and porosity in reservoir sandstones. In: Worden, R.H. and Morad, S. (Eds.), Quartz Cementation in Sandstones: Special Publication 29 of the IAS. *John Wiley & sons*, 39–49.

Weibel, R., Kjøller, C., Bateman, K., Laier, T., Nielsen, L. H., Purser, G. 2014. Carbonate dissolution in Mesozoic sandstones as a response to CO_2 exposure at 70°C and 20 MPa. *Applied Geochemistry*, **42**, 1-15.

Weibel, R., Olivarius, M., Kjøller, C., Kristensen, L., Hjuler, M.L., Friis, H., Pedersen, P.K., Boyce, A., Andersen, M.S., Kamla, E., Boldreel, L.O., Mathiesen, A. and Nielsen, L.H., 2017a. The influence of climate on early and burial diagenesis of Triassic and Jurassic sandstones from the Norwegian-Danish Basin. T*he Depositional Record,* **3**, 60–91.

Weibel, R., Olivarius, M., Kristensen, L., Friis, H., Hjuler, M.L., Kjøller, C., Mathiesen, A. and Nielsen, L.H., 2017b. Predicting permeability of low-enthalpy geothermal reservoirs: A case study from the Upper Triassic – Lower Jurassic Gassum Formation, Norwegian–Danish Basin. *Geothermics*, **65**, 135–157.

Zeck, H.P., Andriessen, P.A.M., Hansen, K., Jensen, P.K. and Rasmussen, B.L., 1988. Paleozoic paleo-cover of the southern part of the fennoscandian shield-fission track constraints. *Tectonophysics*, **149**, 61–66.

Wentworth, C.K. 1922. A scale of grade and class terms for clastic sediments. *Journal of Geology*, **5**, 377–392.

ACKNOWLEDGEMENTS

The Innovation Fund Denmark is acknowledged for funding the project GEOTHERM (‘Geothermal energy from sedimentary reservoirs – Removing obstacles for large scale utilization’) (No. 6154-00011B), which allowed continued studies on diagenesis and geochemical modelling.