Porosity–Permeability prediction by diagenetic forward modelling: Case study from Gassum Formation, Denmark

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ABSTRACT

High-quality pre-drill predictions of reservoir properties are essential to evaluate the chance of success before drilling costly geothermal wells. The porosity and permeability of geothermal reservoirs can be predicted by combining knowledge of the petrography, provenance, depositional environment, and burial history. In this study we use diagenetic forward modelling (Touchstone and T>Map software systems), where the evolution of compaction, cementation, and the resulting reservoir properties are simulated from time of deposition until present-day. In this way, geothermal exploration in areas with little subsurface knowledge can be aided by utilizing diagenesis models based on data-rich areas with detailed geological information.

We simulated reservoir quality for four stratigraphic surfaces within the Gassum Formation. Input includes model configurations for depositional facies associated with each of the two main sediment provenance areas and maps of the distributions of these facies as well as for temperature and effective stress at times ranging from deposition to present-day. The facies maps are constructed in a sequence stratigraphic framework based on interpretations of wireline logs, sedimentological cores, and provenance analysis by geochronology. These data serve as the basis for delineating a provenance mixing zone between the quartz-rich and feldspar-rich sediments associated with the two different provenances. In addition, the forward diagenetic modelling utilizes information from seismic mapping and basin modelling. Output from the modelling system includes distributions in porosity and permeability. These results can be used to assess the feasibility of the Gassum Formation as a geothermal reservoir in areas that are considering the integration of geothermal heat into their energy system. The model results also can help to examine the profitability of targeting the Gassum Formation versus shallower or deeper reservoirs.

1. INTRODUCTION

Sandstones of the Upper Triassic – Lower Jurassic Gassum Formation possess excellent reservoir quality for geothermal exploitation for district heating in many parts of Denmark. However, in some areas the reservoir quality is poor due to reduced porosity and permeability from extensive diagenetic alteration. The large range in reservoir quality reflects substantial differences in the magnitude and nature of compaction and cementation that occur in response to variations in sand composition and texture at deposition, depositional environment, and burial history. The mineralogical composition of the sandstones is influenced by the type and location of sediment source areas and depositional environments, and these compositional differences strongly impact diagenetic reactions during burial. The maximum burial temperature and amount of Neogene uplift of the Gassum Formation varies across the country resulting in regional variation in the extent of diagenetic alteration.

2. METHODS

The petrography of the Gassum Formation sandstones was studied by optical microscopy and scanning electron microscopy (SEM). The mineralogy was quantified by point counting in thin sections, supplemented by SEM mineral mapping. Porosity and permeability were measured by standard core analysis. Depositional environments were interpreted in cores. The 3D basin modelling was made by PetroMod™ software (Schlumberger) of the burial, temperature, and effective stress histories. The diagenesis modelling was made by Touchstone™ software (Geocosm) that uses a forward modelling approach to predict reservoir quality of sandstones (Lander and Walderhaug 1999, Lander et al. 2008, Taylor et al. 2022). The Touchstone models were extended onto maps by T>Map™ software (Geocosm) using 3D basin models such that reservoir properties can be simulated for many timesteps.

3. RESULTS AND DISCUSSION

Petrographic analysis of the Gassum Formation has revealed that the framework grain composition differs much across the Norwegian–Danish Basin (Weibel et al. 2017). In the northwestern part of the basin, both quartz and feldspar grains are common, including many types of feldspar, while quartz is dominant in the southeastern part of the basin, in addition to smaller amounts of K-feldspar (Fig. 1). This mineralogical difference is caused by provenance contrasts of the sediments supplied from different entry points, as revealed by zircon U-Pb geochronology (Olivarius et al. 2022). Sediment in the NW area was sourced directly from the Fennoscandian Shield, whereas sediment in the SE area was sourced from both Fennoscandia and the Variscan Orogen, and it may have been reworked from Upper Palaeozoic sediments. Sediments in the NW area were supplied from the north/northeast, while sediments in the SE area were derived from the east/southeast. The area in which the sediment supplied from the different sources mixed in the basin depended on the distribution of the depositional environments and the location of the coastline, so it changed repeatedly throughout the deposition of the Gassum Formation. The provenance mixing zone shows the inferred area where sediment supplied from the different source areas became mixed in the basin, here exemplified by the Pre-TS3 surface (Fig. 1).

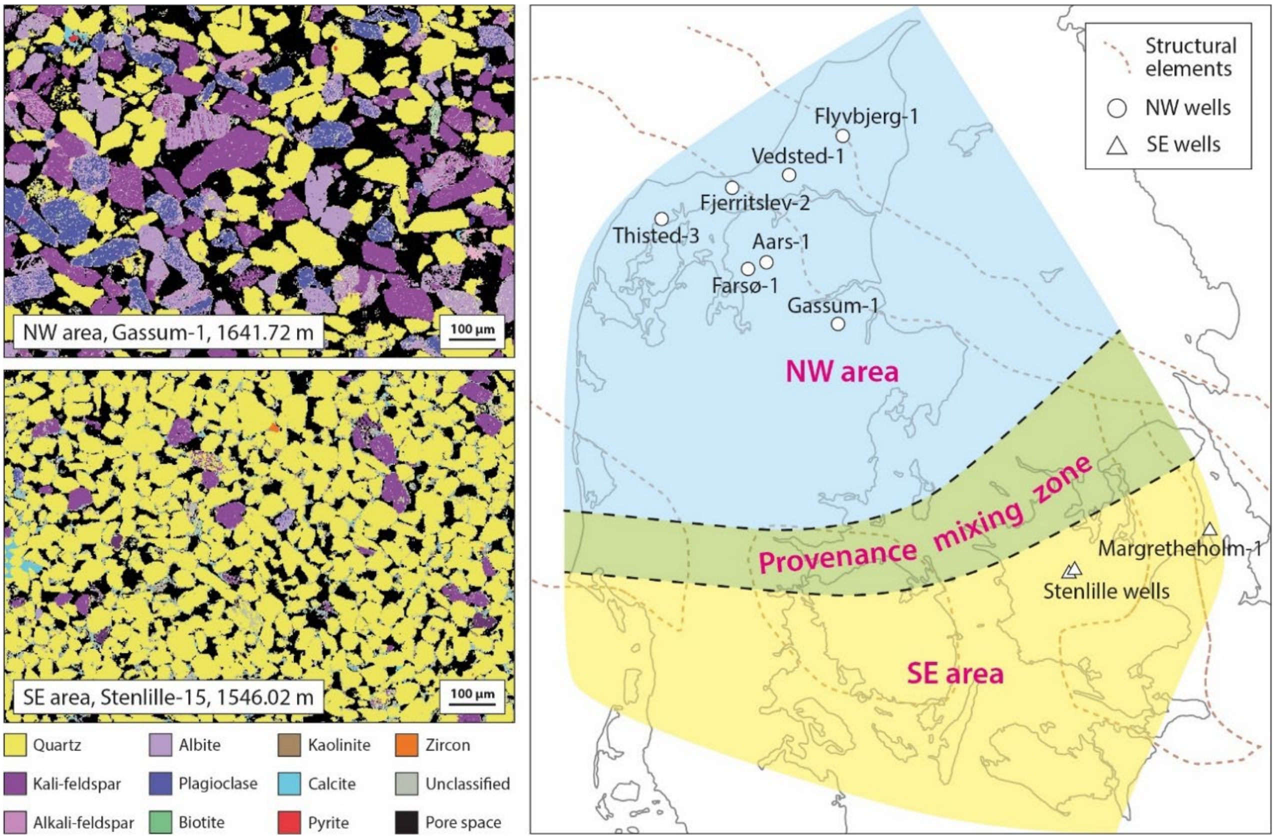

Figure 1. SEM mineral maps showing the mineralogical composition of the Gassum Formation (Olivarius et al. 2022). Provenance differences are causing the much larger quartz content and smaller feldspar content in the SE area than in the NW area. The inferred provenance mixing zone for the Pre-TS3 surface is shown.

Facies maps of selected time intervals during deposition of the Gassum Formation are reconstructed by sequence stratigraphy using core descriptions, wireline logs, and provenance analysis. In this way, sediment transport directions and distribution of depositional environments could be interpreted. Two sequence stratigraphic surfaces are included here (Fig. 2), defined as TS3 and MFS4 by Nielsen (2003). The Pre-TS3 sediments topped by the transgressive surface TS3 are an example of sand deposition across most of the basin in a short period before the transgressive flooding. The MFS4 sediments represent a maximum flooding surface with maximal overstepping of the basin margins causing limited sand deposition and widespread deposition of marine mud. The sand forming the best geothermal reservoirs was primarily deposited in the fluvial, estuarine, and shoreface facies, while less sand was deposited in the lacustrine, lagoonal, and paralic facies.

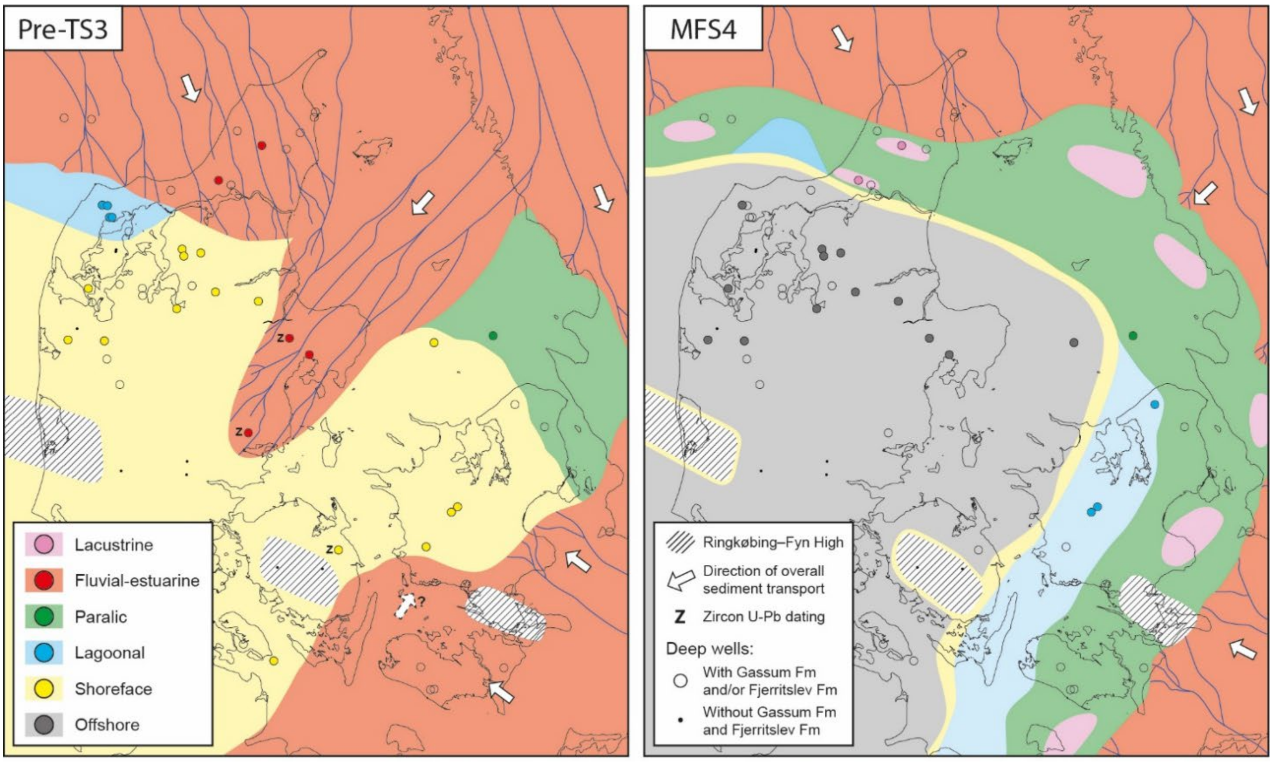

Figure 2. Facies maps for two selected intervals of Gassum Formation that have been reconstructed based on sequence stratigraphic correlations between the shown wells. The facies maps represent the intervals of Pre-TS3 (transgressive surface) and MFS4 (maximum flooding surface).

Diagenesis modelling is applied to estimate the reservoir properties of the Gassum Formation reservoir in undrilled areas where geothermal energy may be exploited for district heating. The provenance, climate, and depositional environments control the mineralogy of the deposited sediment, and the burial history controls the degree of diagenesis that the sediment is exposed to. The Gassum Formation has experienced a variable amount of subsidence in different parts of the basin, resulting in large differences in the diagenetic development. Furthermore, the Neogene exhumation of the whole area has removed a succession of up to c. 1 km (Japsen et al. 2007, Petersen et al. 2008), so the maximum burial depth must be taken into account to estimate the amount of diagenesis.

The provenance-controlled difference in quartz/feldspar ratio across the basin affects the reservoir quality of the sandstones, since they behave differently during diagenesis. For example, feldspar alteration during burial causes clay formation, whereas high quartz content results in extensive quartz overgrowths at deep burial. Thus, the type and amount of the dominant minerals that precipitate during diagenesis are different in the NW versus SE area. The effect on the reservoir properties is simulated by establishing a provenance mixing zone in the diagenesis modelling, where the models established for the NW and SE areas are being mixed.

The climate controls the degree of weathering, while the depositional environments affect the grain size, sorting, and the subsequent type of diagenetic alterations. For example, calcite and siderite precipitate at shallow burial and most abundantly in the marine sands such as the shoreface facies, and the minerals transform to ankerite at deeper burial of c. 2 km, causing a decrease in reservoir properties.

All these factors are taken into account in the diagenesis modelling, where the combined effect on the reservoir properties is estimated. The diagenesis models were calibrated to petrographic data, core analyses data and burial histories from the Gassum Formation, and the facies maps linked to sequence stratigraphic surfaces were used to integrate the distribution of depositional environments in the prediction of porosity and permeability. The simulated total porosity for the Pre-TS3 surface for several timesteps during burial and until present day including uncertainty estimates is shown in Fig. 3. The variation across the Danish area shows how the provenance, burial depth, and depositional environments all influence the resulting reservoir properties.

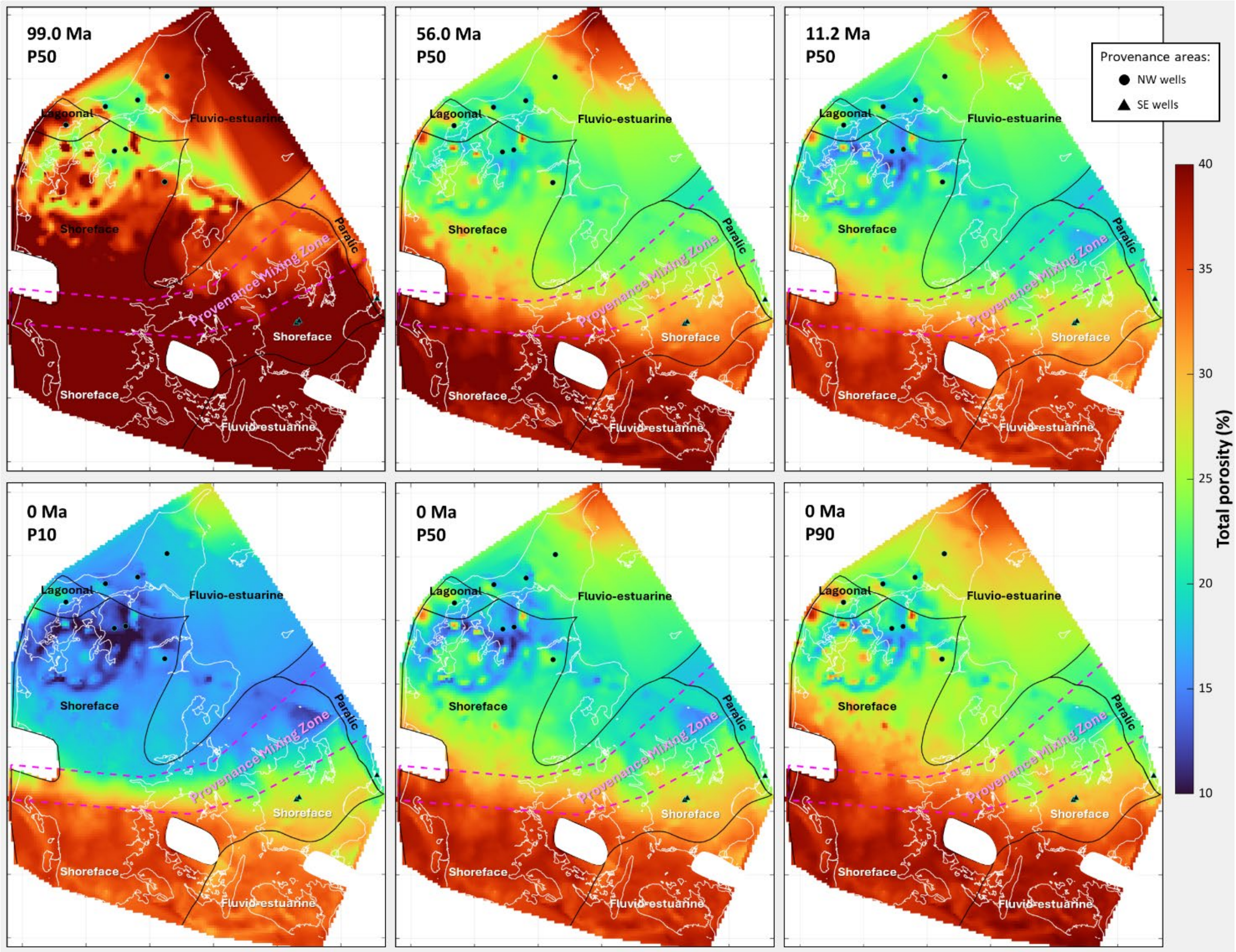

Figure 3. Total porosity estimates for the Pre-TS3 surface made by diagenesis modelling. It is shown for four timesteps from 99 Ma to present day for P50, and for P10, P50, and P90 for present day.

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