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INVESTIGATING DEVIATIONS FROM OVERALL POROSITY−PERMEABILITY TRENDS

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ABSTRACT

A key parameter in assessing subsurface geothermal potential is the flow rate of hot water at depth. Flow rates are difficult to predict but have a straight-forward relationship to permeability and porosity. Though porosity variations are obtained from well logs, other methods have to be utilised for estimating the permeability, and commonly porosity−permeability correlations based on conventional core analysis are applied. However, porosity−permeability plots generally show large scatter, and deviations from a well-defined porosity−permeability trend are often observed. It is such deviations that we aim to understand in terms of texture, facies variations and diagenetic processes.

The Upper Triassic – Lower Jurassic Gassum Formation in Denmark has been chosen for the investigation of the porosity and permeability relationships. The Gassum Formation forms the most extensive reservoir for geothermal exploitation in Denmark. Furthermore, the formation is the primary reservoir for the most recent geothermal wells. It is dominated by extensive shoreface sandstones with minor intervals of estuarine and fluvial sandstones, marine and lacustrine mudstones.

For the Gassum Formation, the overall porosity−permeability relationship can be expressed by a power function. More well-defined trend lines appear, however when grouping the sediment according to grain size. Parameters such as grain size, sorting, grain shape, mineral composition, clay content and diagenetic cements all influence the permeability, and the aim is to determine to what degree they can explain the deviations from the overall porosity−permeability trend. Multivariate analyses are applied to identify the parameters that have the greatest influence on porosity and permeability. The outliers are investigated petrographically in order to find explanations for the deviation from the typical porosity−permeability trend. Micro-scale anisotropy is one factor that is found to have an effect on permeability. The permeability difference between horizontal and vertical plugs is typically due to lower permeability perpendicular to the bedding, for example due to lamination in the sediment. Micro-scale anisotropy, probably due to enlargements of small depositional variations by cementation along relatively minor fluid boundaries, also seems to have a strong influence on permeability in horizontal direction.

INTRODUCTION

Accurate prediction of reservoir properties is equally important for geothermal prospects as for hydrocarbon reservoirs. Several local consumer-owned combined heat and power plants in Denmark are currently considering geothermal energy as a supplement to conventional gas- and coal-fired plants. Such small consumer-owned plants are financially very vulnerable to failure; i.e. the geological prognosis and the first geothermal well have to be successful.

Porosity and permeability are crucial parameters when evaluating the quality of potential reservoirs for geothermal or multidisciplinary use. Although, porosities can be calculated from well logs; information on permeability cannot be obtained in this way. Precise porosity and permeability values are obtained by conventional core analysis. By comparing porosity−permeability trends from different wells it is possible to predict the reservoir permeability between wells. Permeabilities estimated from such overall porosity-permeability trends should be regarded as qualified but not necessarily accurate estimates. Understanding deviations from such trends are important in order to minimise the risk of predicting erroneous permeabilities.

The aim of this initiative is thus to create a database with linked information on porosity, permeability, texture, mineralogy (detrital and authigenic), depositional facies, burial depth and post-depositional processes (mechanical compaction, diagenesis). The database, which does not yet include all cored intervals of the Gassum Formation, will gradually be expanded and continuously updated as

new wells are drilled. Factors influencing the general porosity−permeability trends will be highlighted, but the outliers that deviate from the overall trend will receive equal attention. The focus is on the Gassum Formation, which is the most extensive potential reservoir sandstone onshore Denmark and occurs at present-day burial depths from 550 to 3360m (Mathiesen et al. 2009). The formation is mineralogical relatively uniform though with some provenance variations and its depositional environments include fluvial, estuarine, lagoonal, shoreface and offshore (Nielsen 2003; Weibel et al. 2011). The basin is not influenced by overpressure or hydrocarbon filling of reservoirs and is therefore ideal for investigating the variable factors influencing the porosity−permeability trends.

It is essential for the present study to improve the understanding of the mechanisms controlling the overall porosity−permeability trends and also the deviations from the general trends. Improved understanding will help in assessing when the porosity−permeability trends can be applied and when they are not functional or should be used with caution. In this way we expect to contribute to the final objective of our investigations, which is to develop a method that can estimate permeability of the entire formation by scaling up from cored intervals, and via well logs tied to seismic data provide reliable predictions of reservoir properties between wells.

GEOLOGICAL BACKGROUND

The Danish part of the Norwegian−Danish Basin was formed by crustal stretching in Late Carboniferous − Early Permian times between the stable Precambrian Baltic Shield and the Ringkøbing−Fyn High consisting of shallow basement highs (Fig. 1; Vejbæk 1989; Michelsen and Nielsen 1991, 1993). The extension phase was followed by regional subsidence governed by thermal cooling during the Mesozoic and resulted in deposition of sandstones, mudstones, evaporites and carbonates in a wide range of environments with thicknesses up to 5−9 km (Bertelsen 1980; Michelsen et al. 2003). The climate gradually changed from dominantly arid to semi-arid during the Early–Mid Triassic to become more humid during the Rhaetian. Lacustrine and sabkha deposition was terminated by an Early Norian marine transgression that probably came from the south (Nielsen 2003). The Gassum Formation represents extensive sheets of shoreface sandstones and associated paralic sediments deposited during short-lived forced regressions in Rhaetian−Hettangian time (Hamberg and Nielsen 2000; Nielsen 2003). Stepwise deepening took place during the Early Jurassic until fully marine conditions were developed.

The Gassum Formation is widely distributed with thicknesses of 50–150 m in central and distal areas of the Danish part of the Norwegian−Danish Basin, thickening locally in association with salt-structures and major faults (up to 300 m in the Sorgenfrei−

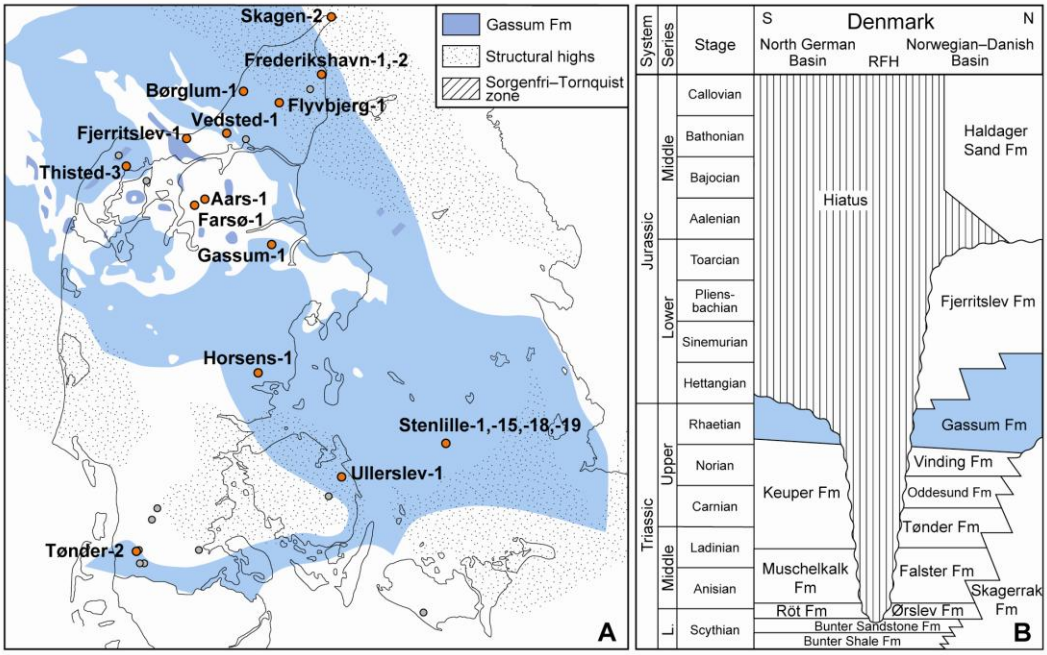

Fig. 1: ***A.*** *Map of Denmark showing the regional potential for geothermal exploitation of the Triassic−Jurassic formations. Modified after Mathiesen et al. (2009).* ***B.*** *Stratigraphic scheme of the Danish onshore Triassic and Jurassic sediments. Simplified after Clausen and Pedersen (1999), Michelsen and Clausen (2002) and Nielsen (2003).*

Tornquist Zone) and thinning or absent on the structural highs, such as the Skagerrak−Kattegat Platform and the Ringkøbing−Fyn High (Fig. 1). The Gassum Formation consists of shoreface, fluvial, estuarine, lacustrine, lagoonal and marine facies (Nielsen 2003). The fluvial facies association includes sandstones, mostly medium- to coarse-grained, occasionally fine-grained, moderately sorted with subangular to subrounded grains. The estuarine channel and tidal creek facies association comprises fine- to medium-grained sandstones, occasionally coarse-grained, and contains abundant mudstone clasts and common mudstone drapes on foresets. The lagoonal sandstones are well-sorted and fine-grained, and commonly contain organic debris. Shoreface and foreshore deposits range from fine-grained, or very fine-grained sandstones to coarse siltstones, and contain occasional thin beds of coarse-grained sandstones, pebbles and claystone clasts.

The present-day burial depth of the cored Gassum Formation varies from approximately 850 m (Frederikshavn-2), through 1200 m (Thisted-3), 1450 m (Børglum-1), 1500 m (Stenlille-1), 1650 m (Stenlille-18), 2000 m (Vedsted-1), 2900 m (Farsø-1) and to 3300 m (Aars-1). The maximum burial depth is derived by correction for Neogene uplift; this correction varies from 550 m to 700 m for the studied wells (Japsen et al. 2007).

METHODS

Two types of dataset have been applied in the present investigations, a dataset based on conventional core analysis and another dataset representing combined petrographic and conventional core analyses, which includes point counting of thin sections made from cut offs of the plugs applied for porosity and permeability measurements.

Porosity and permeability measurements

The porosity and permeability were measured according to the API RP-40 standard (API 1998). Gas permeability was measured at a confining pressure ~ 2.8 MPa (400 psi), and at a mean N_2 gas pressure of ~ 1.5 bar (bar absolute) = 0.15 MPa (permeabilities below 0.05 mD were measured using a bubble flowmeter). He-porosity was measured at unconfined conditions. The measured effective porosity corresponds to the total porosity, as most reservoir rocks contain only few isolated pores (API 1998). Typically, a fine match can be obtained between log-derived and plug measured porosity, though absolute values deviate.

Texture

Grain size corresponding to the conventional core analysis was determined from sedimentary core descriptions. Sorting, based on visual evaluation of the plugs, is occasionally given. Average grain size, sorting and grain shape were described for each thin section with corresponding porosity and permeability analyses. The sorting classes were evaluated by use of sorting comparators (Longiaru 1987) defined for eight relative phi classes that range from very well sorted to poorly sorted. The phi values range from 0 for very well sorted sand to 2.0 for poorly−very poorly sorted sand.

Petrography

Sedimentary rocks impregnated with blue epoxy, for easy identification of porosity, were prepared as polished thin sections. The polished thin sections were etched and stained with sodium cobaltinitrite for K-feldspar identification. Mineralogy, petrographic relations, texture, average grain size, sorting and grain shape were described for each thin section. Modal compositions of the sandstones were obtained by counting a minimum of 500 points in each thin section. Supplementary studies of crystal morphologies and paragenetic relationships were performed on gold-coated rock chips mounted on stubs and on carbon-coated thin sections using a Phillips XL 40 scanning electron microscope (SEM). The electron beam was generated by a tungsten filament operating at 17 kV and 50-60 µA.

Multivariate analysis

Multivariate analysis by principal component analysis (PCA) was performed using the program Solo 2007-2008, Eigenvector with the objective to determine general relations between porosity, permeability and other factors, such as petrography, facies and burial depth. PCA analysis was chosen as it does not require a normal distributed and independent dataset. Each attribute (each element) was mean centralised prior to the analysis. The PCA model was validated by a test set, which was generated by splitting the dataset in two (every second according to depth) and applying one as a test set. In general, models are based on 6 or less principal components, as long as 60% of the variation in the dataset can be described.

Log interpretation

The wireline logs from two selected wells (Farsø-1 and Stenlille-1) were analysed to carry out a lithological interpretation and a petrophysical evaluation of the potential reservoir section, in this case the Gassum Formation. The lithological interpretation was based primarily on the gamma ray (GR) log combined with information from cuttings and core descriptions. The Gassum Formation commonly contains radioactive minerals other than clay, which complicates reliable lithological interpretation from the GR log alone, and information from supplementary sources (other petrophysical well-logs, cores, SWCs etc.) is thus needed. In the

Stenlille-1 well, the porosity has been determined from a shale-corrected density log and the porosity interpretation calibrated to core porosity data. No porosity or resistivity logs were acquired for the Gassum Formation in the Farsø-1 well and the porosity curve is thus based solely on the core porosity values. Outside the cored interval the porosity can only be assessed on the basis of the GR log as no other pertinent logs have been run in this interval, and in this context a direct correlation between the GR log response and the porosity has been assumed.

Alternative methods must be applied for estimating the permeability. The Gassum Formation has been cored in several wells located throughout the basin, and conventional core analysis data from these wells form the basis for correlating plug porosity−permeability measurements on a regional scale. Correlation of core porosity and permeability data is typically ambiguous, thus additional trend lines are suggested to account for the uncertainty. In all, three lines define the relation between porosity and permeability, minimum and maximum trends to account for uncertainty limits and an average case.

RESULTS

These investigations are based on two types of dataset representing the Gassum Formation in the eastern part of the Norwegian−Danish Basin. The dataset on conventional core analysis data for all cored wells has been subdivided according to grain size, sorting and plug orientation. The other dataset of combined petrographical-porosity−permeability analyses has been investigated by multivariate analysis in order to evaluate the potential influence of a variety of factors on the porosity and permeability.

Porosity and permeability

Conventional core analysis data from the Gassum Formation forms one dataset, which is subdivided into three groups according to grain size: 1. medium (- coarse) grained sandstone, 2. fine-grained sandstone and 3. siltstones, clayey and heterolithic sandstones. The overall porosity−permeability trends vary with grain size, i.e. the permeability is lower at the same porosity with decreasing grain size (Figs 2A & 2B). The lowest permeabilities are found in the siltstones, clayey and heterolithic sandstones, reflecting both the finer grain size and a lower degree of sorting (Fig. 2C). In general, heterolithic sandstone seems poorly sorted, though the individual laminae may be well-sorted.

Sorting parameters are available for a less comprehensive dataset. Subdivision of fine- and medium-grained sandstones into groups of very well sorted, well sorted, moderately sorted and poorly sorted gives surprisingly no apparent variation in the porosity−permeability trends (Figs 3A & 3B).

Petrography

The Gassum Formation consists of well to moderately sorted, fine- to medium-grained sandstones, with subordinate coarse-grained sandstones. Heterolithic sandstone intervals are common, but have not been in focus in this investigation. Grain shape is typically subrounded to subangular.

The formation consists mainly of subarkoses. The feldspar abundance varies across the basin and feldspar is relatively more abundant in the north-western part than in the eastern part of the studied area. Rock fragments are relatively rare in the formation. Mudstone clasts and allogenic clays occur in several samples, though in some wells infiltrated drilling mud cannot be distinguished from allogenic clay during point counting. Feldspar dissolution and alteration to kaolinite is common especially in fluvial and estuarine deposits. Early carbonates are typically siderite or calcite, which seem to be more abundant in the marine and lagoonal facies than in the fluvial and estuarine facies. In the deeply buried sandstones, ankerite is the dominant carbonate cement, though quartz diagenesis is important in quartz-rich and carbonate-poor samples. Stylolite typically occludes the porosity around the stylolitic seams and leads quartz precipitation in the nearby pore spaces. Authigenic clay minerals include ubiquitous kaolinite, illite and local chlorite cement.

Multivariate analysis

Compared to quartz arenites, the diagenetic changes are more diverse in subarkoses, as observed in the Gassum Formation. Multivariate analysis has therefore been used in order to identify overall relationships between petrography and porosity−permeability values.

Multivariate analysis of the combined petrographical−porosity−permeability dataset shows that the first principal component (PC1) describes the variation in porosity and permeability versus burial depth (Fig. 4). This tendency is quite clear though PC1 describes only 19% of the variation in the dataset. It is noteworthy that porosity estimates from two different methods, conventional core analysis ("Porosity") and from modal analysis by point counting ("Primary Porosity"), plot closely (Fig. 4), though there can be a tendency to underestimate porosity by point counting. High porosity and permeability values are negatively correlated with burial depth and maximum burial depth, as they form opposite groups in the plot of loadings on principal components 1 and 2 (Fig. 4). The Thisted-3 well, representing the shallowest buried parts of the formation, is associated with high porosity, whereas

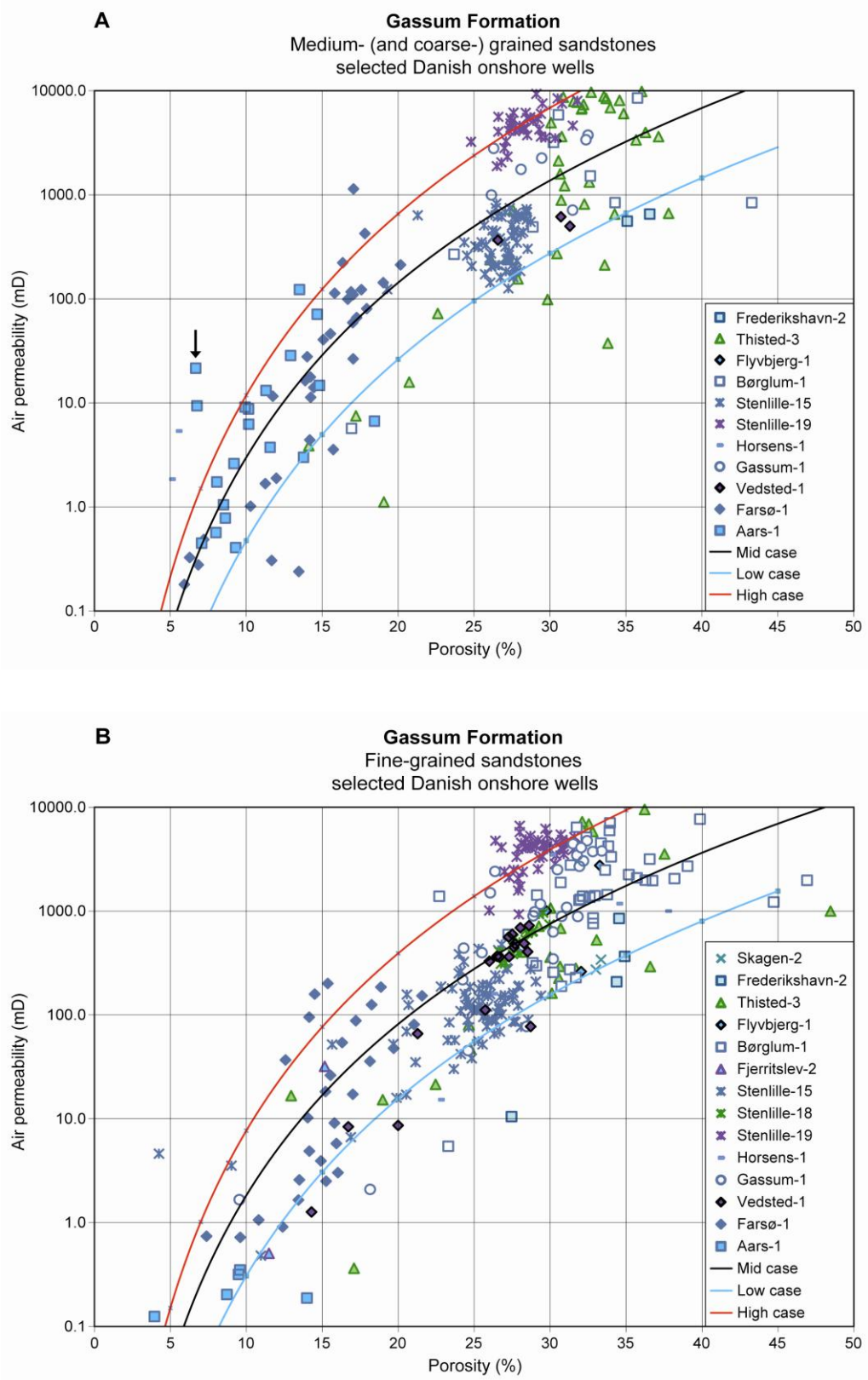

Fig. 2: Porosity and permeability trend and uncertainty bands (given by high and low cases) for the Gassum Formation based on conventional core analysis, ***A.*** *Medium- (and coarse-) grained sandstones,* ***B.*** *Fine-grained sandstones,* ***C.*** *Siltstones, clayey and heterolithic sandstones. Relatively high permeability due to fractured sample is marked by an arrow.*

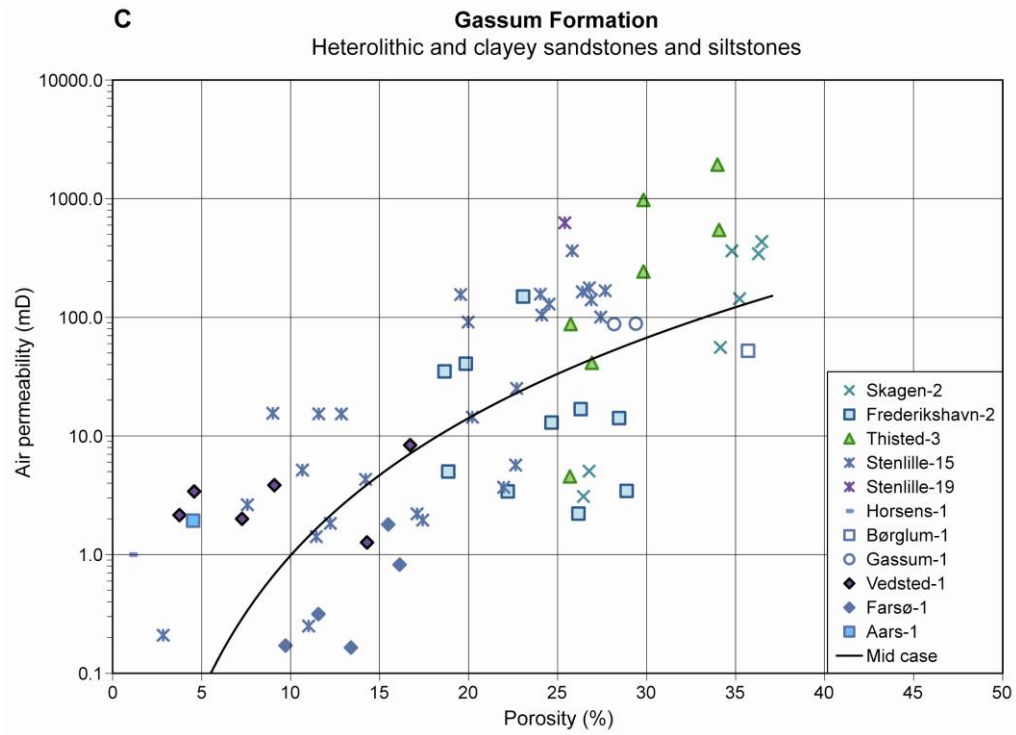

Fig. 2: Continued

the Aars-1, representing the deepest buried parts of the formation, plots together with high burial depth. Increased abundance of authigenic quartz, show the strongest association with increased burial depth. Other diagenetic features, such as carbonate cement, authigenic feldspar, kaolinite and secondary porosity are also negatively correlated to high porosity and permeability. The other diagenetic phases have less influence on the porosity and permeability, as they plot closer to the centre of PC1. High abundance of unaltered detrital K-feldspar is related to high porosity and permeability (Fig. 4).

The second principal component, describing 9 % of the variation of the dataset, is mainly defined by the difference in grain size and grain density (Fig. 4). Coarse grain sizes plot together with fluvial facies, abundant rock fragments and polycrystalline quartz, and authigenic phases such as feldspar, kaolinite and illite (Fig. 4). Fine grain sizes are instead associated with offshore and lagoonal facies, abundant heavy minerals, allogenic clays and carbonate cement, all of which results in an increased grain density (Fig. 4).

The third principal component describes the variation between sorting (and grain size) and abundance of organic matter and mica. The degree of sorting is given as sorting classes, where high phi values equals poorly sorted sediments. Sorting has, compared with burial depth, relatively small influence on the porosity, though increased phi values (i.e. poor sorting) plot opposite to high porosity and permeability (Fig. 4). The fine-grained sediments appear to be better sorted than the coarse sediments. The fine-grained sediments contain more mica and organic matter, which together with carbonate cement are associated with micro-anisotropy. Micro-anisotropy has a minor influence on the porosity and permeability (Fig. 4).

Tidal creek and shoreface facies plot relatively close to the centre of the loadings of the first principal component and seem to be less affected by low porosity and permeability than fluvial, offshore and lagoonal facies (Fig. 4). Fluvial facies are not related to high porosity and permeability, but instead group together with coarse grain sizes, abundant detrital polycrystalline quartz and authigenic phases such as kaolinite, illite and feldspar (Fig. 4). Lagoonal and offshore facies are associated with high grain density, abundant transparent and opaque heavy minerals, anatase and carbonate cement (Fig.4).

Petrographical investigation of outliers/outlying points

Coupled sets of relatively high and low permeability and almost similar porosity, have been compared in order to understand the differences. Coarse-grained samples from the Aars-1 well tend to lie in the upper part of the porosity–permeability uncertainty band, despite the presence of kaolinite in some of the pores. Some coarse-grained samples, however, lie in the lower part of the porosity–permeability trend, as the

pores are filled with illitised mica, along with kaolinite (Figs 5A & 5B). This particular type of illitised mica is found in fine- to medium-grained shoreface sandstones in the Børglum-1 well and coarse-grained fluvial sandstones in the Aars-1 well and is in both cases associated with reduced permeability and unaffected porosity (compare Fig. 6A with 6B).

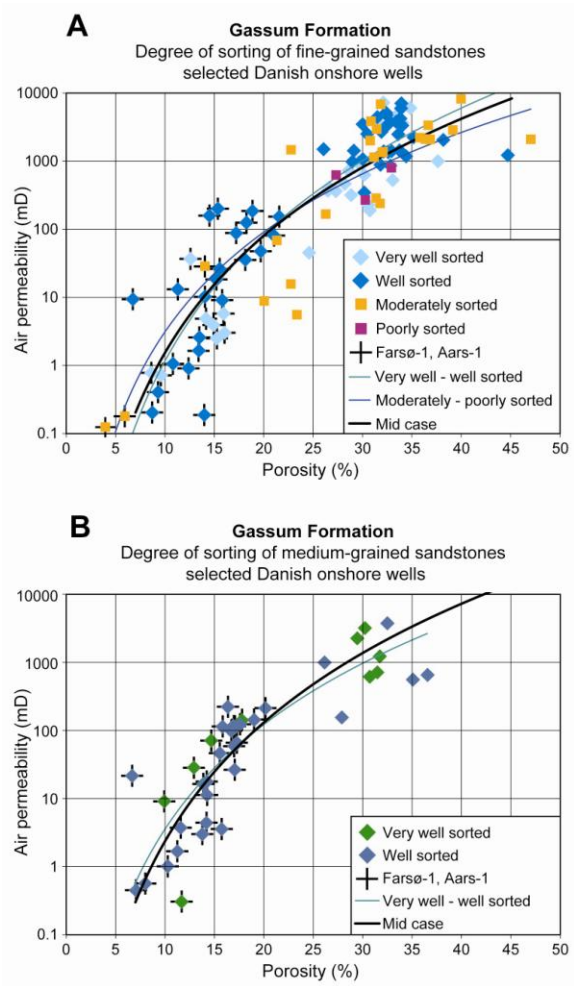

Fig.3: Porosity and permeability relationships for different sorting classes of the Gassum Formation, based on conventional core analysis, ***A.*** *Fine-grained sandstones,* ***B.*** *Medium-grained sandstones.*

Some fine-grained sandstones display micro-anisotropy due to deformed laminae of mica, organic matter or cement, which reduces the permeability much more than porosity. Siderite cement, associated with mica-rich laminae, in the Frederikshavn-2 well, and mica deformation zones (incipient stylolite formation) in the Farsø-1 well are both examples of this phenomenon (compare Fig. 6C with 6D, and 6E with 6F).

Even though the dataset has been subdivided into three grain-size groups, the coarsest sandstones will lie in the upper part of the porosity–permeability uncertainty band, whereas the finest grained sand-stones will be positioned in the lower part of the trends. The position of the Stenlille wells in Fig. 2B exemplifies this observation, as the very fine- to fine-grained sandstones of the Stenlille-15 well generally have lower porosities and permeabilities than the fine- to medium-grained sandstones of the Stenlille-19 well.

In fractured samples, the permeability is controlled by fractures and not the sandstone matrix. In some cases it can be difficult to identify these fracture measurements, especially if a thin mica or clay lamina is accompanied by microscopic fractures. Valid measurements may be disregarded and invalid values may be accepted, as the nature of the clay or mica lamiae is difficult to evaluate without the help of thin sections. Relatively high permeabilities are in some cases related to fractures associated with mica laminae in otherwise intensively carbonate-cemented sandstones (Fig. 2A).

EXAMPLES OF PERMEABILITY ESTIMATES FROM LOGS

Interpretation of well log data was implemented to extend the evaluation of porosity and permeability to the un-cored parts of the Gassum formation. The well-sections of Stenlille-1 and Farsø-1, which differ with respect to both burial depth of the formation and depositional setting, have been chosen to illustrate variations in porosity and permeability relative to burial depth. The Stenlille-1 well records shallow burial of the Gassum Formation (1500 m), whereas the Farsø-1 well represents deep burial (2900 m). In both wells, the log-derived porosity is calibrated to core porosity data, and a reasonably good match between log and core data is obtained (Figs 6A & 6B.

The permeability has not been drill-stem or flow tested in any of the wells, but the permeability may be estimated from porosity–permeability relations established for the Gassum Formation as described above. A regional dataset was used for establishing a reliable relationship between porosity and permea-bility, because the amount of available core analysis data is limited for any well and may only reflect few specific facies (i.e. the Stenlille-1 well in Fig. 2). In both the Farsø-1 and Stenlille-1wells, the Gassum Formation sandstones are predominantly medium-grained and consequently the porosity–permeability trend for medium-grained sand-stones (Fig. 2A), has been used to estimate permeability variations. The permeability and its uncertainty range, here defined as average (mid case) divided by or multiplied with 5 as a first approximation, are thus derived from the

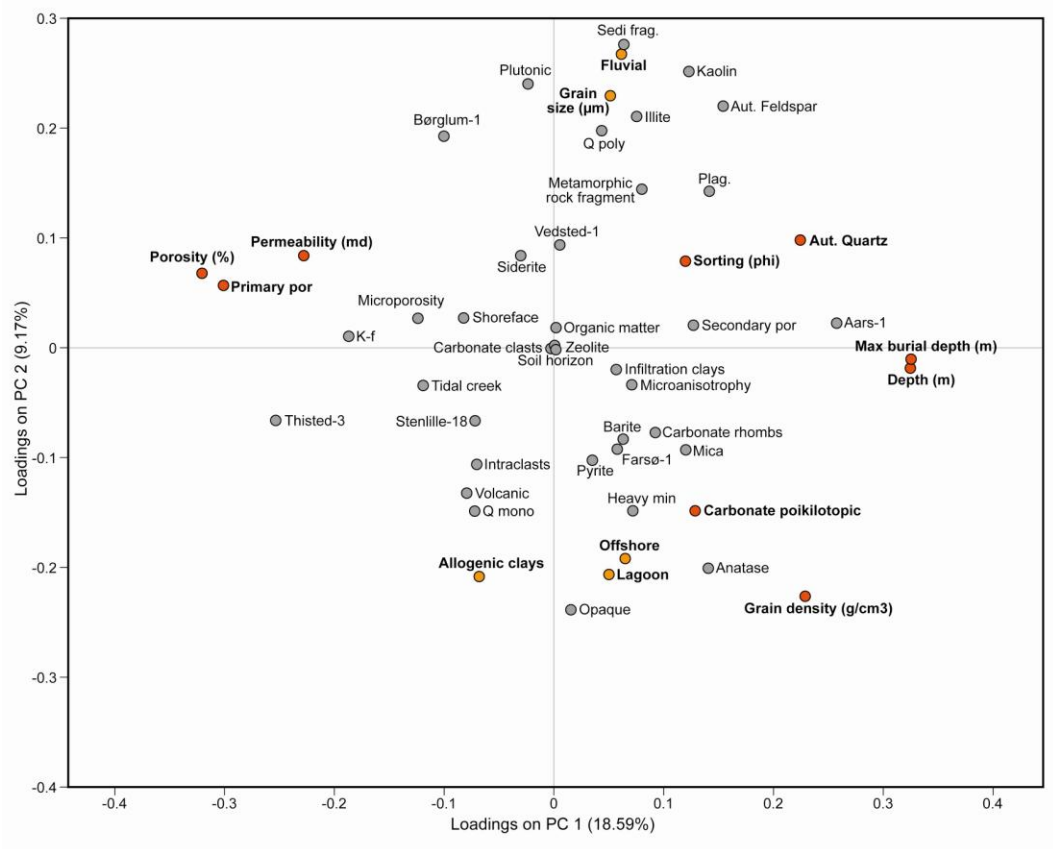

Fig. 4: Multivariate analysis of 50 samples from the Gassum Formation with combined petrography and porosity and permeability measurements. Loadings plot of the first and second principal component (PC1 and PC2) describes respectively 19% and 9% of the variation in the petrographical dataset. PC1 is defined by the variation in porosity−permeability versus burial depth and burial-related diagenesis. PC2 describes the variation between grain size, grain density, facies and facies related diagenesis.

porosity using mathematical expressions defined by the trend lines shown in Fig. 2A:

Low case: $PERM\_log = 292000 \cdot (PHIE)^{5.7905}$
Mid case: $PERM\_log = 1460000 \cdot (PHIE)^{5.7905}$
High case: $PERM\_log = 7300000 \cdot (PHIE)^{5.7905}$

where the log-derived permeability (PERM_log) is in milliDarcy (mD), and the porosity (PHIE) is a fraction. The use of three trend lines (corresponding to a low, mid and high case) expresses the larger uncertainty range associated with permeability estimates contrary to porosity calculations. The core permeability data have been compared to the 'envelope' defined by three log-derived permeability curves, and a reasonably good match has been obtained. The permeability range in the Stenlille-1 well is generally 100–1000 mD, and in the Farsø-1 well significantly lower, i.e. 0.1–500 mD. In the Farsø-1 well, however, a number of outliers showing very low core permeabilities are observed, indicating that the permeability in certain intervals cannot be honoured by the permeability 'envelope' defined by the log-derived permeability curves.

DISCUSSION

Multivariate analysis of the petrographical dataset and subdivision of the conventional core analysis dataset from the eastern part of the Norwegian−Danish Basin has been undertaken as the first step in a study of the relation between porosity and permeability on one side and multiple parameters on the other side. Investigations of the outliers and comparison of samples from the high and low cases, respectively, have revealed when the general trend cannot be applied. The more well-understood the porosity−permeability trends are, the more precisely will the log-derived permeability estimates become. The overall porosity−permeability relationships of the Gassum Formation are best fitted to a power function. A linear relation between porosity and permeability may be applied for the shallow buried parts only. Diagenetic alterations in the deeper buried parts generally reduce the permeability relatively more than the porosity and the data therefore fit to a power function. Outliers can in several cases be related to intensive diagenetic alterations.

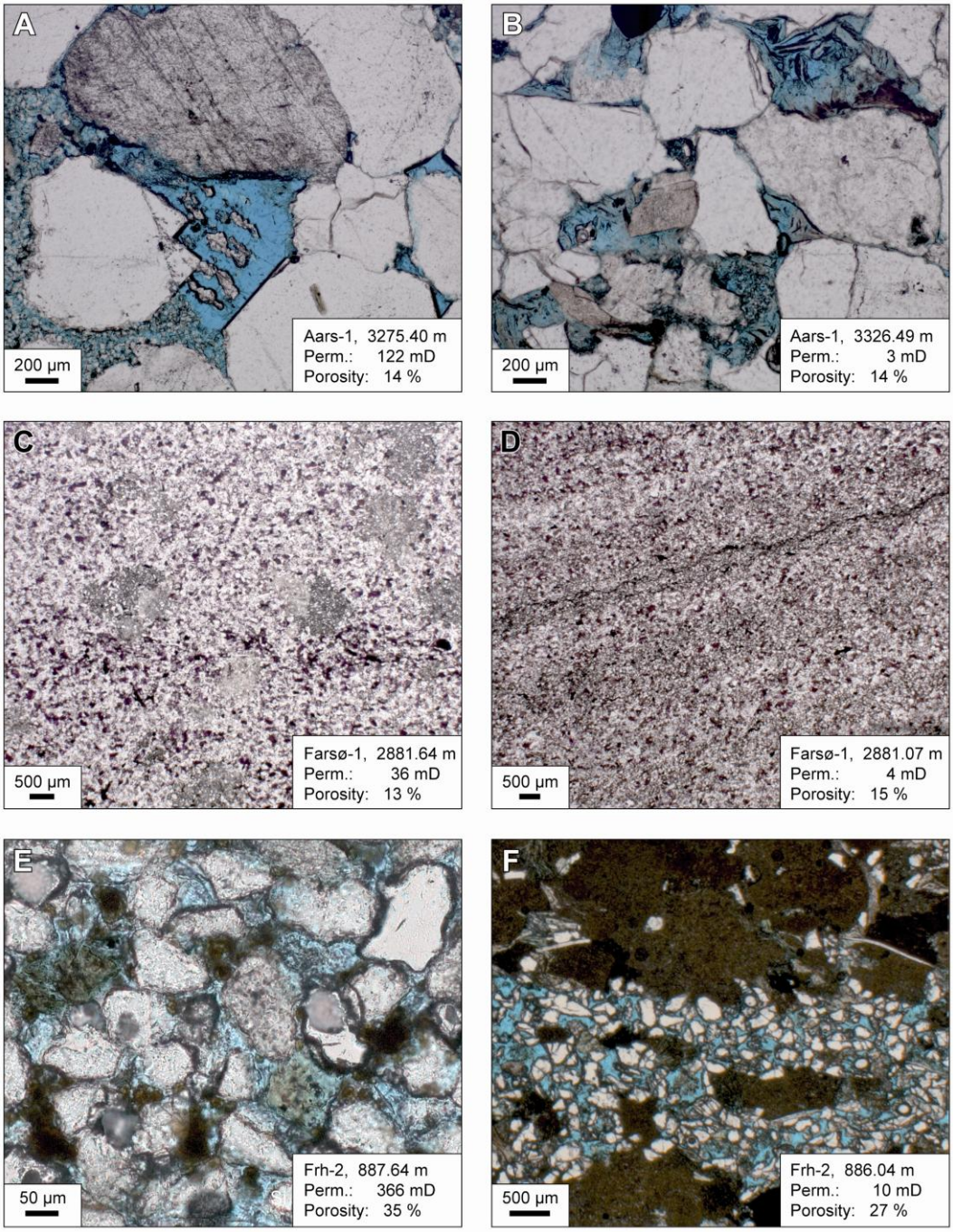

Fig. 5: Petrographic examples of the Gassum Formation. ***A.*** *Coarse-grained sandstone with quartz overgrowths and kaolinite in some of the open pore spaces, Aars-1, shoreface, 3275.40 m.* ***B.*** *Coarse-grained sandstone with quartz overgrowths, kaolinite and abundant illitised mica filling almost all pores, Aars-1, fluvial, 3326.49 m.* ***C.*** *Fine-grained sandstone with weak lamination, Farsø-1, lower shoreface, 2881.64 m.* ***D.*** *Fine-grained sandstone with strong micro-anisotropy due to deformed mica along zones of incipient stylolite formation, Farsø-1, lower shoreface, 2881.07 m. E. Dispersed siderite crystals, Frederikshavn-2, lower shoreface, 887.64 m.* ***F.*** *Intensive siderite cement associated with mica laminae, Frederikshavn-2, shoreface, 886.04 m.*

Parameters defining the general porosity−permeability trend

Grain size

Grain size has a strong influence on the porosity−permeability trends, as different general porosity−permeability trends were obtained for medium- (and coarse-) grained and fine-grained sandstones (Figs 2A & 2B). The effect of especially grain size and sorting on porosity and permeability of unconsolidated sand was shown by Beard and Weyl (1973). These initial sediment parameters define the sandstone properties until other factors, such as mechanical compaction and diagenesis related to higher temperatures and pressures, become more important. Therefore the difference between the two porosity−permeability trends of fine-grained and medium- (and coarse-) grained sandstones is smaller for the more deeply buried Gassum Formation (samples from the Aars-1 and Farsø-1 wells), where the diagenesis dominates the porosity and permeability more than the grain size.

The effect of sorting on the porosity−permeability trend seems to be less pronounced than the grain size when assessed on the basis of the subdivided conventional core analysis dataset (Fig. 3). However, multivariate analysis shows that the porosity and permeability plot opposite to poor sorting in the loadings plot of the first principal component (Fig. 5A) and consequently the degree of sorting seems to have some effect on the porosity and permeability. Visual evaluation of sorting classes obtained from core plugs may be somewhat less precise than when specified from thin sections, as the evaluated of sorting classes in thin sections is based on sorting comparators (Longiaru 1987). However, it may still not be as accurate as if obtained from sieve analyses, which on the other hand can not be performed on cemented sandstones. The degree of sorting may be expected to have an even larger influence on the porosity−permeability trends based on the literature (e.g. Ethier and King 1991; McKinley et al. 2011). However, it is possible that the effect of sorting is difficult to document on the basis of this relatively limited dataset, which may be biased by abundant samples from the deeply buried and diagenetically influenced parts of the formation.

The grain size distribution and degree of sorting are controlled by the transport media and the energy of the depositional environment (e.g. Block and Helmold 1995; Dutton and Willis 1998; McKinley et al. 2011). Consequently, a marked variation between the different facies is expected. The fluvial facies are strongly associated with coarse grain sizes, and the lagoonal and offshore facies are fine-grained, whereas the shoreface and estuarine facies are varied in terms of grain size (Fig. 5A).

Burial depth and burial diagenesis

Porosity and permeability decrease with increasing burial depth both present-day and maximum burial depth (Fig. 5A). Mechanical compaction and diagenetic changes are the likely reasons for the porosity and permeability reduction with burial. For the Gassum Formation, the relationship between burial depth and diagenetic changes is best illustrated by authigenic quartz (Fig. 5A). Porosity reduction of quartz arenites with increased burial depth can be described by a mechanical compaction at shallow burial depth and quartz cementation at deeper burial (e.g. Ehrenberg 1990; Bjørlykke and Egeberg 1992; Giles et al. 1992; Ramm et al. 1997; Robinson and Gluyas 1992; Marcussen et al 2010). Sandstones of the Gassum Formation are mainly subarkoses, but nevertheless quartz diagenesis plays a major role in the burial diagenesis. The subarkosic composition leads to additional diagenetic changes such as feldspar alteration, kaolinite and illite precipitation, which also give rise to porosity reduction. Detrital K-feldspar abundance has a strong affinity to high porosity and permeability (Fig. 5A). This is indirectly related to a low diagenetic intensity, as K-feldspar is dissolved (forming secondary porosity) and altered to kaolinite and illite in the deepest buried parts of the formation. Though secondary porosity increases with burial it seems to have a negative effect on the total porosity, as secondary porosity commonly consists of very small pores (Bouch et al. 2006) and since secondary porosity becomes more abundant as the primary porosity of large pores is reduced. The relationship between porosity reduction and carbonate cementation is more difficult to establish than for authigenic quartz, as carbonate cement formed both early and later during burial of the formation and occasionally occurs in specific intervals.

Most reactions that reduce porosity will also gradually reduce permeability. However, when diagenesis takes over, the permeability decreases relatively more than the porosity, as can be observed in all porosity−permeability plots (Figs 2 and 3). In the deepest buried parts of the formation (the Aars-1 and Farsø-1 wells) progressive diagenesis results in increasingly smaller pores and narrower pore throats. Authigenic quartz overgrowths and quartz pressure solution reduce the average pore throat size and quartz stylolites create impermeable layers, which in all cases reduces the permeability more than the porosity. Authigenic clays (kaolinite and illite) reduce the porosity to some degree and depending on the clay mineral morphology the permeability may be more or less affected. Alteration of unstable minerals (e.g. feldspar grains and heavy minerals) leads to clay mineral precipitation and generation of the permeability reducing secondary porosity.

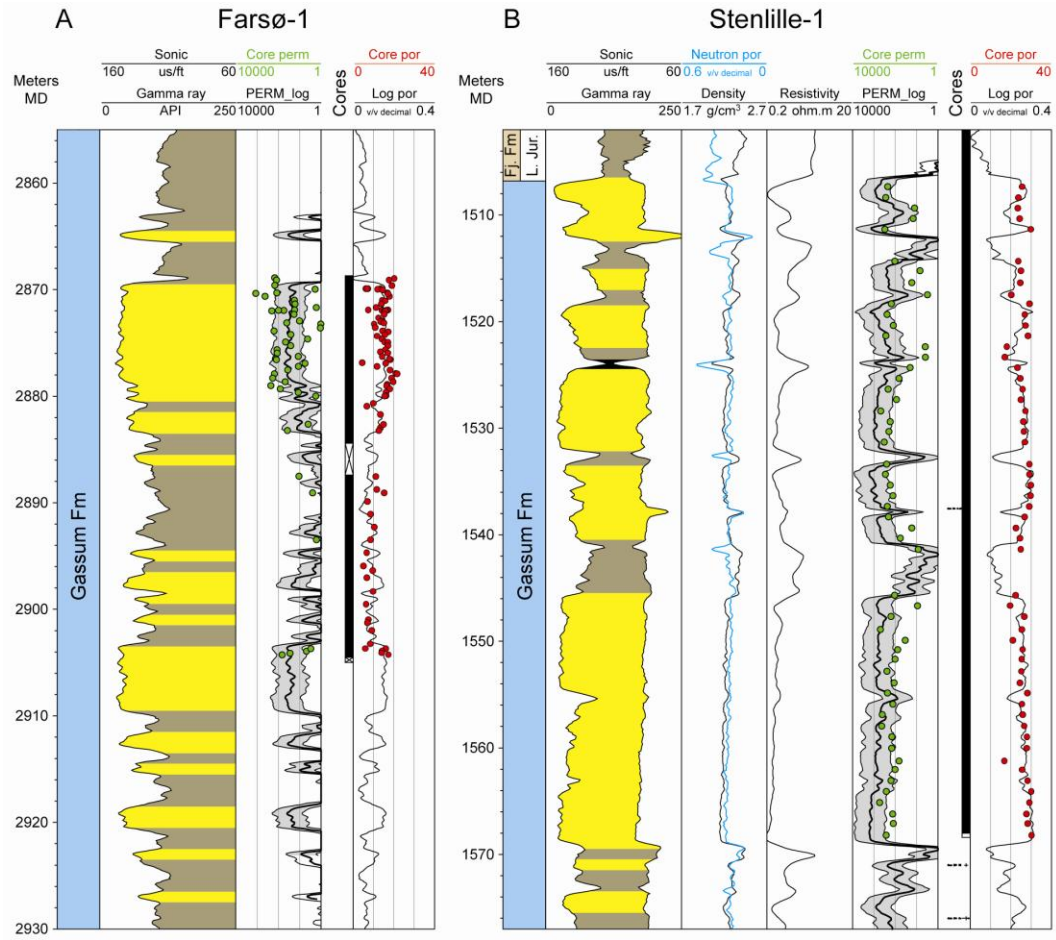

Fig. 6: *Log interpretation of porosity (PHIE) based on the available raw log curves of gamma-ray (GR), density (RHOB) and neutron porosity (NPHI) if available. The estimated permeability envelope is based on high and low cases of the porosity−permeability trend for the Gassum Formation. Conventional core analyses are presented as dots, green for permeability and red for porosity.* ***A.*** *The log interpretation results in porosities in the 20–30% range in shallow buried parts of the Gassum formation such as the Stenlille-1 well with a present-day burial depth of 1600 m and an estimated maximum burial of 2150 m.* ***B.*** *Porosities of only 10–20% are found in the more deeply buried parts of the Gassum Formation such as the Farsø-1 well with a present-day burial depth of 2800 m and an estimated maximum burial of 3400 m. The log interpreted porosities and the here from estimated permeabilities show reasonable good match with porosities and permeabilities obtained from conventional core analysis. Some outliers cannot be described by log variation nor with the permeability envelope, which can be due to scale-differences between plugs (2.5 cm) and logs (average of 30-50 cm) or due to geological variations, such as grain size variations or degree of diagenesis.*

Grain density

High grain density is correlated with low porosity and permeability. Fine-grained sediments with abundant heavy minerals, allogenic clays and carbonate cement are characterised by higher grain density, as these minerals have relatively higher densities than framework grains such as quartz and feldspar (Fig. 5A). Carbonate cement closes the open porosity and alteration of heavy minerals may result in secondary porosity and authigenic clay minerals, anatase, pyrite etc.

Facies

Shoreface and estuarine facies seem to have the highest porosities and permeabilities (Fig. 4). Estuarine channel/mouth-bar and foreshore sandstones of Jurassic age in the northern North Sea also have high porosities and permeabilities, although the shoreface sandstones have mostly poor to moderate reservoir quality (Ramm 2000). The amounts of mica and clay matrix strongly affect the porosity and permeability.

The fluvial facies is strongly associated with coarse grain size and therefore the abundance of rock fragments and polycrystalline quartz, which have a higher survival potential in the coarse fraction. Lowstand slope fan deposits were also found to contain more rock fragments than the deposits from highstand and transgressive systems tracts (Dutton and Loucks 2010; Morad et al. 2010). The coarse grain size of the fluvial facies may have promoted more fluid circulation, which may have led to more intensive alteration of detrital grains and precipitation of illite, kaolinite and authigenic feldspar (Figs 4 and 5B). Consequently, the diagenetically altered fluvial sediments have relatively low porosity and permeability. The lagoonal and offshore sediments are also characterised by relatively low porosity and permeability, which in this case is due to a fine grain size, abundant allogenic clays and carbonate cement. Carbonate cement also seems to be associated with these facies, and is likely to originate from the dissolution of carbonate fossils (e.g. Bjørlykke et al. 1992; Burns et al. 2005).

Factors with less or indirect influence on the porosity−permeability trend

Microporosity

When primary porosity is changed into microporosity, the permeability no longer follows the trends of the porosity. Microporosity is, according to Dutton and Loucks (2010) defined as the difference between porosity from conventional core analysis and point-counted porosity from modal analysis of thin sections. Microporosity, as defined, has little effect on the porosity and permeability (Fig. 4), though the general reduction following burial diagenesis is likely to be associated with a change from larger to minor pores and pore throats. The calculation of microporosity may be subject to some uncertainties, as point-counted porosity commonly underestimates the porosity when compared with porosity measured in laboratory. This can be due to microporosity within some mineral phases (as suggested by Storvoll et al. 2002; Dutton and Loucks 2010), but is probably also due to a systematic error when point counting clays and other minerals of minute crystal sizes (when the crystal size is less than the thin section thickness). Abundant authigenic clay minerals forming during burial may thus result in increased microporosity. During increased diagenesis, alteration of unstable minerals (in particular heavy minerals or feldspar) will commonly result in precipitation of clay minerals and increased porosity (secondary porosity). Secondary porosity derived from dissolution of feldspar increases the total porosity up to 10 % in fluvial subarkoses (Hammer et al. 2010), and 3-10 % in lithic arkoses and feldspathic litharenites (Dutton and Loucks 2010). Secondary porosity tends to increase microporosity more than effective porosity and thus exerts a less positive influence on the permeability.

Clays

Clayey and heterolithic sandstones have lower porosities and permeabilities than fine-grained sandstones (Figs 2B and 2C), which is probably a result of a more intense mechanical compaction of argillaceous sandstones compared to quartz-dominated sandstones (e.g. Worden and Burley 2003; Hammer et al. 2010). Porosity and permeability reduction can be directly linked to clay content, when the total clay content is above 20 % (Ramm 2000). The clay content seem to have less direct influence on the porosity and permeability reduction in the Gassum Formation, possibly due to a generally low total clay content.

Other factors

In contrast to the North Sea Central Graben reservoirs, the Gassum Formation, onshore Denmark, is not affected by hydrocarbon introduction, nor is overpressure considered to have played a role during burial (Japsen et al. 2007; Petersen et al. 2008). Any deviation from the general porosity−permeability trend is consequently not associated with over-pressured reservoirs (Ramm and Bjørlykke 1994; Gluyas and Cade 1997) nor can it be related to inhibited or retarded diagenesis due to hydrocarbon introduction (e.g. Marchand et al. 2001).

In quartz dominated sandstones, porosity reduction with burial depth can be described by mechanical compaction and quartz cementation (e.g. Robinson and Gluyas 1992; Giles et al. 1992; Dutton and Loucks 2010; Marcussen et al. 2010). Even in the mainly subarkosic Gassum Formation, quartz cementation is one of the major porosity-reducing parameters. Any process or factor that can retard or inhibit quartz cementation will potentially improve the reservoir porosity and permeability. Grain coatings of opal, microquartz, illite or chlorite on detrital quartz grains can retard or inhibit quartz cementation (Ehrenberg 1993; Ramm et al. 1997; Storvoll et al. 2002; Stokkendal et al. 2009; Weibel et al. 2010). Deviations from the porosity-depth trends in the Gassum Formation however are not considered to be related to over-pressuring, hydrocarbon-introduction, nor to grain coatings.

Outliers and outlying values in the porosity−permeability trends

Outliers and outlying values in the porosity−permeability trends are caused by grain-size variation, diagenesis and occasionally fractures. Within each grain-size group, the upper and lower values in the uncertainty band are representing relatively coarser and finer grain sizes within the group. Comparison of the data from the Stenlille-15

and Stenlille-19 wells shows that sediments can have different porosities and permeabilities due to grain size variations (very fine- to fine-grained versus fine- to medium- grained), given that other factors (position in the basin, burial depth, degree of sorting, detrital composition, almost no diagenetic alterations) are almost similar. The explanation for the grain-size variation is probably local variation in the depositional environment.

Investigations of some of the outliers show that the morphology and mineralogy of clay is of major importance. Authigenic kaolinite seems to have relatively little influence on the permeability and porosity measured by conventional core analysis (Figs 5A and 5B). Whether kaolinite will behave differently when exposed to fluid flow of longer duration is not known. The presence of illitised mica in the pore spaces reduces the permeability substantially, albeit without affecting the porosity significantly. In the Brent Group, central North Sea, a major porosity reduction occurs at 3100 m burial depth, at which level illite precipitation becomes increasingly more important (Giles et al. 1992). In the Gassum Formation, the illitisation of mica is found in some samples even at a maximum burial depth of 2000 m, which is significantly shallower than in the Brent Group.

Micro-anisotropy is shown by multivariate analysis to be negatively correlated to grain size and more or less associated with mica, organic matter and carbonate cement (Figs 5C and 5D). This fits with the petrographical observations where the occurrence of micro-anisotropy was identified in fine-grained sediments as irregular laminae of organic matter, mica or carbonate cemented intervals. The reason that micro-anisotropy may have an effect on the permeability in horizontal plugs may be because the mica, organic matter or carbonate cemented areas form dipping flow baffles possibly due to primary cross-laminae. Micro-anisotropy consequently reduces the permeability more than the porosity.

Upscaling of reservoir conditions (porosity and permeability)

For each well the porosity distribution is calculated based on well-log interpretation and calibration against conventional core porosity data. Permeability is estimated by use of the porosity−permeability trends defined for one grain-size group within one formation. The average permeability estimated for the formation in each well can be interpolated between wells for similar burial depths. Corrections will have to be made for different burial depths, and ongoing work aim at quantifying how increased burial depth and intensified diagenesis reduce porosity and permeability.

The next step forward is to identify typical well-log motifs or other characteristic log responses that can dictate which porosity−permeability trends should be applied. For example, mica is likely to give highly reduced porosities and permeabilities if exposed to deep burial. In a similar way, illitisation can be problematic for the permeability, and thus high K response or the gamma–ray log may be an indication of a risk of pore-occluding illite. This illustrates that the more we understand the limitations of the porosity−permeability trends, the more precisely they can be defined, the more accurate the permeability estimates and thus the geological prognosis will be.

CONCLUSIONS

The sandstones of the Danish Upper Triassic–Lower Jurassic Gassum Formation have been examined in order to describe the relations between porosity and permeability locally and on a regional scale. The porosity−permeability trends, based on core analysis data, are best fitted to a power function. The trends can be used for estimating the permeability from log-calculated porosities. The uncertainty on the estimated permeability is, however, quite large and the most likely permeabilities are therefore given as averages with uncertainty bands.

Significant efforts have been initiated to improve the understanding of how these important reservoir properties, porosity and permeability, are influenced by parameters such as grain size, sorting, facies, burial depth and diagenesis. The conventional core analysis dataset has been subdivided according to grain size, sorting and plug orientation in order to improve the porosity−permeability trends. Multivariate analysis of the combined petrographical−porosity−permeability dataset has been used to evaluate the influence from a number of parameters, such as burial depth, facies, detrital mineralogy and diagenetic changes. Of these parameters, grain size, and burial depth and burial related diagenesis are particularly important in defining the porosity−permeability trend.

The original porosities and permeabilities are defined by the grain size and sorting at the time of deposition which again is controlled by the energy of the depositional environment. Improved porosity−permeability trends are obtained by subdividing the samples into three groups, medium- (and coarse-) grained sandstones, fine-grained sandstones and finally clayey and heterolithic bedded sandstones and siltstones. Very poor sorting, as observed in clayey or heterolithic sandstones, reduces both porosity and permeability. Subdivision into even finer grain-size groups may actually improve the definition of the porosity−permeability trend, as the outlying values

are commonly due to grain-size variation within the groups.

Mechanical compaction and diagenesis during burial gradually reduce the original porosity and permeability of the sandstones. Despite the Gassum Formation being of subarkosic composition, the diagenesis is primarily a consequence of increased amounts of quartz cement. Quartz cementation and pressure solution reduce the average pore and pore throat sizes and consequently reduce the permeability more than porosity. The variable detrital mineralogy, though, also gives rise to other diagenetic changes, such as carbonate cementation, kaolinite and illite precipitation along with formation of secondary porosity. Internal porosity in the clay minerals and the secondary porosity, consisting of numerous small pores, will reduce the permeability more than the porosity. The burial-related influence from the carbonate cement is less evident than for quartz diagenesis as carbonate cement forms during early as well as late diagenesis. The diagenetic changes that reduce porosity, are accompanied by a reduction in permeability, and as diagenesis becomes increasing more effective, the permeability is reduced more than the porosity.

Outliers and outlying values in the porosity−permeability plots tend to be caused by subtle grain-size variation within the grain size groups and diagenetic influence. Relatively high permeabilities (values in the upper part of the uncertainty band) are typically related to coarse-grained sediments and occasionally to fractures. Relatively low permeabilities (values in the lower part of the uncertainty band) typically represent diagenetically altered samples. In the coarse-grained sandstones, illitised mica reduces the permeability without affecting the porosity. In fine-grained sandstones, permeability-reduction is due to micro-anisotropy associated with deformed mica laminae with incipient pressure solution or siderite cement along mica laminae. The micro-anisotropic diagenetically formed barriers affect permeability more than porosity. As our understanding of the diagenetic reasons for outliers increases, the limitations of using the porosity−permeability trend will be better defined, leading to improved permeability assess-ments and geological prognoses of reservoir properties in undrilled sections.

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