# Prediction of Archie's cementation factor from porosity and permeability through specific surface

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## ABSTRACT

Based on Archie's cementation factor as measured on North Sea chalk and on published data, we explore how the cementation factor depends on other physical properties of the chalk. A relationship between cementation factor and specific surface with respect to bulk volume is obtained for chalk. This leads to how Archie's cementation factor may be predicted from porosity and permeability for chalk as well as for sandstone. A common relationship between cementation factor and specific surface with respect to bulk volume calculated from porosity and permeability is obtained. As an alternative, the $a$-factor in Archie's equation is related to specific surface with respect to bulk volume, but the relationship is less clear than the simple relationship between cementation factor and specific surface.

## INTRODUCTION

The cementation factor in Archie's equation (Archie, 1942) is a central factor in determining water saturation in oil reservoirs. This factor is often assumed to be constant $m = 2$ for carbonate rocks, but applying a constant cementation factor in Archie's equation can lead to a wrong estimate of fluid saturations in an oil reservoir (Borai, 1987). In Archie's equation, the cementation factor describes the power to which porosity must be raised, so small changes in $m$ can alter the estimated saturation. Therefore, further knowledge of how cementation factor varies is of interest for estimating hydrocarbon reserves.

## Archie's equation

Archie (1942) shows experimentally a simple relationship between the formation factor of a completely water-saturated sedimentary rock and the porosity of the rock, and introduces the equation

$$F = \frac{1}{\varphi^m},\qquad(1)$$

where $F$ is formation factor, $\varphi$ is porosity, and $m$ is the cementation factor. Archie (1942) postulated that $m$ depends on cementation. The formation factor $F$ is the resistivity of a fully water-saturated rock $R_o$, divided by the resistivity of the water $R_w$:

$$F = \frac{R_o}{R_w}.\qquad(2)$$

Archie's equation was based on measurements of formation factors and porosities for clean sandstones. He obtained cementation factors of 1.8–2.0. The equation applies only for sediments where the electric current is carried by an electrolytic pore fluid and the grains are insulators. Winsauer et al. (1952) modified Archie's equation to

$$F = \frac{a}{\varphi^m},\qquad(3)$$

where the $a$-factor corrects for clay and other conducting minerals.

If a sedimentary rock is partly water saturated, a relationship between degree of water saturation, porosity, resistivity of the pore water, and resistivity of the partly saturated rock is given as

$$S_w^n = \frac{a}{\varphi^m}\frac{R_w}{R_t},\qquad(4)$$

where $n$ is the saturation exponent and $R_t$ is the resistivity of the partly water-saturated rock.

## Cementation factor

The cementation factor would equal one if the pores in a rock were straight, parallel cylindrical tubes in the direction of the current. However, a sedimentary rock contains irregularly shaped grains, and that reduces the effective cross-sectional area of the conductor (satu-

rated pore space). Therefore, the electric resistance of the rock will be higher and the cementation factor will be larger than one.

Several workers have reported variation in cementation factor with porosity, e.g., Borai (1987), Focke and Munn (1987), and Saha et al. (1993). Borai (1987) presents a relationship between cementation factor and porosity for carbonates based on laboratory data. He finds that the cementation factor is above 2 for porosities above 15% and decreases to 1.5 for lower porosities of 3%. Similar results are obtained by Focke and Munn (1987). Saha et al. (1993) find the cementation factor for dolomites to be 1.48–2.45 for porosities ranging from 3% to 29%. The cementation factor tends to decrease with decreasing porosity.

Other workers have found a variation in the cementation factor for sediments with interparticle porosity related to the shape of the grains. Wyllie and Gregory (1953) find that for the same porosity, the formation factor is lowest for spheres; shapes such as discs, cubes, and triangular prisms result in higher formation factors. The difference in formation factors between spheres and nonspheres is up to 20%. Wyllie and Gregory (1953) conclude that grain shape is important for the formation factor and is influenced by degree of cementation. Similarly, Jackson et al. (1978) find that the cementation factor depends on the shape of particles. The cementation factor varies from 1.2 for spheres to 1.9 for platy shell fragments for unconsolidated sediments. Variation in grain size and sorting has less influence on cementation factor. Finally, Raiga-Clemenceau (1977) finds a relationship between cementation factor and permeability for sandstones.

## Cementation

One measure of particle shape and degree of cementation is the specific surface. The specific surface is measured as the surface area of a material normalized to the weight or the volume of the material. For newly deposited sediments, the specific surface is high; when cement is precipitated on the surface of the grains, they become smoother and the specific surface decreases (Borre and Fabricius, 1998). This increases the effective pore radius of the chalk; consequently, the cementation factor is expected to decrease. A relationship between cementation factor and specific surface may therefore exist, and the specific surface potentially may be used to predict cementation factor.

## Kozeny's equation

Kozeny (1927) presents a relationship between porosity, permeability, and specific surface for a homogeneous material:

$$k = c\frac{\varphi^3}{S^2},$$

(5)

where $k$ is liquid permeability, $S$ is specific surface per bulk volume, and $c$ is close to 0.25 but depends on porosity. Mortensen et al. (1998) use Kozeny's equation for North Sea chalk. They show that, contrary to what is frequently assumed, $c$ is not an empirical factor and permeability can be predicted from Kozeny's equation if porosity and specific surface are known. According to Mortensen et al. (1998), $c$ in equation 5 can be estimated from

$$c = \left(4\cos\left(\frac{1}{3}\arccos\left(\varphi\frac{8^2}{\pi^3} - 1\right) + \frac{4}{3}\pi\right) + 4\right)^{-1}.$$

(6)

Røgen and Fabricius (2002) also show applicability of Kozeny's equation for chalk on a larger data set.

## Scope of the study

In this study of North Sea chalk, we use specific surface to predict cementation factor. We also discuss whether the $a$-factor in equation 4 is more closely related to specific surface than cementation factor.

## METHODS

This study is based on data from 21 chalk samples from different wells in the Danish and Norwegian sectors of the North Sea and from a chalk outcrop in Denmark. Besides the North Sea chalk samples, two chalk samples from the Ocean Drilling Program (ODP) leg 165, site 999A, in the Caribbean Sea were included. The samples were chosen to have as much variety in reservoir properties as possible. A geologic description of the samples was done to ensure homogeneity. No samples with visible fractures were included. The porosity of the North Sea chalk samples was obtained from a helium porosimeter, and the dry density of the regularly shaped samples was obtained from dry weight and the volume of the samples as measured by caliper. The content of carbonate of the solid phase was obtained from titration.

The specific surface for each sample was obtained with the nitrogen adsorption method (BET method, for Brunauer, Emmett, and Teller) (Brunauer et al., 1938). The specific surface was measured in a test tube where the sample was first dried by a helium flux then nitrogen gas was added and finally cooled. Part of the gas then adsorbed on the surface of the crushed sample, and the pressure in the test tube decreased. Based on the pressure measurements and the weight of the sample, the specific surface with respect to the weight of the sample was obtained (Brunauer et al., 1938). The measured specific surface was recalculated to specific surface with respect to bulk volume of the sample by multiplying the measured specific surface with respect to weight by density of the dry sample. Specific surface area with respect to weight multiplied by the grain density corresponds to specific surface with respect to grain volume, which in turn is multiplied by one minus porosity to obtain specific surface with respect to bulk volume. Klinkenberg permeability was also obtained for part of the samples (Table 1).

The samples were saturated with a 100 g sodium chloride per liter brine solution in a vacuum chamber before measuring resistance. A high salinity was chosen to minimize possible influence from conducting clay in the samples. The samples were further saturated in a pressure chamber under 11 MPa pressure for two days to increase their saturation. The degree of saturation was then calculated based on the volume of the sample and the dry and saturated weights. The degree of saturation is given in Table 2.

The measurements of resistance for the samples were done in a triaxial Hoek cell and under an axial stress level of 5 MPa and a confining stress of 0.5 MPa. The pore pressure was kept constant at atmospheric pressure. The stress level was chosen so the weakest sample would stay intact during measurements. The saturated sample was placed between the two pistons in the Hoek cell; a thin film of water was added between the end surface of the sample and the piston to

minimize the resistance between the sample and the piston. The pistons were insulated electrically from the loading frame to avoid the frames influencing the measurements.

The Hoek cell was then installed in an AC circuit with variable resistance in series. The supplied voltage was 5 V, and the frequency was 20 kHz. The variable resistance was adjusted so the voltage over the variable resistance was half of the supplied voltage; then the resistance of the variable resistance equaled the resistance of the sample. The supplied voltage signal and the voltage signal over the variable resistance were recorded on an oscilloscope; the phase angle between the two different voltage signals was also recorded. The phase angle was in measurements between 0° and 1° and was assumed to be insignificant. Based on the measured resistance, length, and diameter of the sample, the sample's resistivity was calculated. The resistivity is given as an interval (Table 2), reflecting the uncertainty in obtaining the resistance of the sample.

The conductivity of the pore water was measured with a conductivity meter before each of the resistance measurements on the core. The resistivity of the pore water is the inverse of the conductivity and was near 0.075 ohm-m for all samples at 21°C, corresponding to the room temperature in the laboratory. The resistivity of the pore water is given for each sample (Table 2). For the two ODP samples, the pore water resistivity is different from the other samples because re-

sistivity for these two samples was measured in the natural state (Sigurdsson et al., 1997).

The pore space in a low-permeable sedimentary rock such as North Sea chalk is difficult to water saturate completely because air bubbles remain trapped in the pore network after saturation. Equation 1 only applies when the sample is completely water saturated, so the cementation factor must be calculated in a different way. One way is to count the air bubbles as a part of the solid phase. The air bubbles as well as the solid part of the chalk are insulated electrically. In this case, the chalk samples were not completely water saturated and the formation factor was calculated as the formation factor of the saturated pore space. We assume $m$ and $n$ in equation 4 are equal and obtain $m$ from

$$F = \frac{1}{(S_w \varphi)^m}. \tag{7}$$

Another way of obtaining $m$ is to assume a constant value for $n$ in equation 4 when $S_w$ is different from unity and then calculate $m$ based on the assumed value of $n$. Normally, $n = 2$ for carbonates (Schlumberger, 1989); to be on the safe side, we assume $n$ is 1.8–2.6. This is because the sample saturation is the result of imbibition; in this case, $n$ for chalk may be at least as high as 2.4 (Van De Verg et al.,

**Table 1. Porosity, Klinkenberg permeability, density of dry rock, and carbonate content of the solid phase of the North Sea chalk samples. Permeability data from wells Q-1, Otto-1, West-Lulu-1, Baron-2, I-1, Cecile-1B, and Gert-1 represent water-zone samples (Fabricius et al., 2007).**

| Well | Depth (ft) | Depth (m) | Porosity (%) | Klinkenberg permeability (mD) | Density dry (g/cm³) | Carbonate content (%) |
|------|-----------|-----------|-------------|-------------------------------|---------------------|-----------------------|
| Valhall | 10,831.4 | 3301 | 27.8 | – | 1.97 | 65.7 |
| Valhall | 10,758.9 | 3279 | 38.1 | – | 1.71 | 63.1 |
| Nana | 6948.2 | 2118 | 26.2 | 0.225 | 1.99 | 93.3 |
| Nana | 7083.2 | 2159 | 26.2 | 0.756 | 2.01 | 97.9 |
| Nana | 7138.1 | 2176 | 26.9 | 0.681 | 1.98 | 97.5 |
| Nana | 7183.2 | 2189 | 20.9 | 0.335 | 2.14 | 97.9 |
| Outcrop | N/A | N/A | 44.4 | – | 1.52 | 99.2 |
| ODP999A | 34.5 | 11 | 67.8 | – | 0.87 | 56.2 |
| ODP999A | 372.5 | 114 | 64.3 | – | 0.96 | 62.2 |
| Q-1 | 10,125.3 | 3086 | 14.5 | 0.0009 | 2.32 | 84.5 |
| Q-1 | 10,138.1 | 3090 | 15.7 | 0.007 | 2.32 | 70.2 |
| Q-1 | 10,147.3 | 3093 | 9.7 | 0.003 | 2.44 | 78.2 |
| Otto-1 | 8495 | 2589 | 19.0 | 0.157 | 2.20 | 95.0 |
| Gert-1 | 12,838.9 | 3913 | 11.0 | 0.003 | 2.38 | 69.2 |
| Gert-1 | 12,846.4 | 3916 | 6.7 | 0.012 | 2.52 | 74.3 |
| W-Lulu-1 | 11,159.5 | 3401 | 6.3 | 0.0006 | 2.56 | 93.3 |
| W-Lulu-1 | 11,213.3 | 3418 | 7.9 | 0.0013 | 2.53 | 92.7 |
| Baron-2 | 9368.6 | 2856 | 26.6 | 0.076 | 1.98 | 83 |
| Baron-2 | 9378.4 | 2859 | 24.6 | 0.025 | 2.04 | 78.3 |
| Baron-2 | 9406.3 | 2867 | 21.9 | 0.029 | 2.12 | 79.2 |
| I-1 | 9508.5 | 2898 | 26.8 | 0.034 | 1.98 | 84.7 |
| Cecilie-1B | 7942.1 | 2421 | 7.3 | 0.006 | 2.52 | 79.1 |
| Gert-1 | 12,854.5 | 3918 | 3.9 | 0.002 | 2.6 | – |

1999). We calculate *m* as an interval based on the highest and the lowest value of *m*, with *n* equal to 1.8 and 2.6.

Finally, we obtain the *a*-factor from equation 4 based on resistivity for the sample and the pore water. The value of the *a*-factor is determined with equal values of *m* and *n*. If the *a*-factor is to account for clay in the sediments, a value of *m* equal to the value of *m* for clean samples should be used and the *a*-factor then calculated as the residual. For the clean chalk samples in this study, $m = 2$, so $m = 2$ and $n = 2$ were used to calculate the *a*-factor.

Both *m* and the *a*-factor were calculated for the upper and lower values for resistivity of the samples. In the following figures, *m* and the *a*-factor are therefore given as intervals with error bars.

## RESULTS

The cementation factor for the samples calculated under different assumptions is given in Figure 1. The two methods yield equal cementation factors for all samples within the uncertainty for the two methods. The uncertainty where *n* is assumed to vary in the interval 1.8–2.6 is largest. Therefore, cementation factor from this method is used in the discussion of the cementation factor.

## DISCUSSION

### Influence on cementation factor from porosity, permeability, and specific surface

The cementation factor may depend on pore structure for a sedimentary rock, and in this study we measured three basic parameters describing the pore structure's porosity, permeability, and specific surface. These three properties are related to each other by Kozeny's equation (equation 5). A positive relationship between porosity and cementation factor was found (Figure 2a), as also noted in studies of other carbonates (Borai, 1987; Focke and Munn, 1987; Saha et al., 1993). However, the porosity does not directly control the cementation factor. If the data are divided into two groups, more clear relationships between cementation factor and porosity are obtained.

Samples from the Stevns outcrop and Nana have relatively low specific surface with respect to bulk volume for a given porosity; they also have a low cementation factor. The cementation factor is not related to permeability for the samples (Figure 2b), but the cementation factor is correlated to the specific surface with respect to bulk volume. The correlation is significant at the 1% test level (Figure 2c).

The specific surface is given with reference to bulk volume because the electrical resistivity of the samples is also given with refer-

**Table 2. Specific surface (BET) of the samples, saturation during resistance measurement, pore-water resistivity $R_w$ and resistivity of the samples $R_t$. The resistivity of the samples is given as intervals that reflect the uncertainty in the measurements.**

| Well | Depth (ft) | Depth (m) | Specific surface (m²/g) | Saturation | $R_w$ (ohm-m) | $R_t$ (ohm-m) |
|---|---|---|---|---|---|---|
| Valhall | 10,831.4 | 3301 | 6.87 | 0.95 | 0.073 | 1.70–1.77 |
| Valhall | 10,758.9 | 3279 | 6.76 | 0.94 | 0.073 | 0.86–0.89 |
| Nana | 6948.2 | 2118 | 1.98 | 0.98 | 0.075 | 1.08–1.12 |
| Nana | 7083.2 | 2159 | 1.19 | 0.99 | 0.073 | 0.96–0.98 |
| Nana | 7138.1 | 2176 | 1.14 | 0.99 | 0.072 | 0.94–0.97 |
| Nana | 7183.2 | 2189 | 1.33 | 0.99 | 0.075 | 1.42–1.45 |
| Outcrop | N/A | N/A | 1.88 | 0.99 | 0.074 | 0.36–0.38 |
| ODP 999A | 34.5 | 11 | 23.9 | 1.00 | 0.206 | 0.59–0.61 |
| ODP 999A | 372.5 | 114 | 25.6 | 1.00 | 0.206 | 0.69–0.71 |
| Q-1 | 10,125.3 | 3086 | 3.33 | 0.94 | 0.073 | 5.88–6.11 |
| Q-1 | 10,138.1 | 3090 | 3.82 | 0.85 | 0.074 | 5.31–5.42 |
| Q-1 | 10,147.3 | 3093 | 2.42 | 0.95 | 0.073 | 12.5–12.7 |
| Otto-1 | 8495 | 2589 | 1.69 | 0.99 | 0.073 | 1.99–2.05 |
| Gert-1 | 12,838.9 | 3913 | 2.65 | 0.96 | 0.073 | 15.6–15.8 |
| Gert-1 | 12,846.4 | 3916 | 3.05 | 0.91 | 0.072 | 26.9–27.7 |
| West Lulu-1 | 11,159.5 | 3401 | 2.08 | 0.87 | 0.072 | 32.3–36.9 |
| West Lulu-1 | 11,213.3 | 3418 | 2.72 | 0.92 | 0.072 | 16.2–16.4 |
| Baron-2 | 9368.6 | 2856 | 3.32 | 0.98 | 0.07 | 1.87–2.12 |
| Baron-2 | 9378.4 | 2859 | 4.18 | 0.97 | 0.073 | 1.73–1.75 |
| Baron-2 | 9406.3 | 2867 | 3.05 | 0.97 | 0.072 | 2.32–2.34 |
| I-1 | 9508.5 | 2898 | 4.68 | 0.98 | 0.073 | 1.99–2.06 |
| Cecilie-1B | 7942.1 | 2421 | 2.79 | 0.85 | 0.078 | 14.8–15.3 |
| Gert-1 | 12,854.5 | 3918 | – | 0.85 | 0.074 | 29.9–30.4 |

ence to bulk volume of the chalk. The specific surface of the chalk depends on degree of cementation, and the fine-grained noncarbonate fraction has a significant influence (Røgen and Fabricius, 2002). The fine-grained noncarbonate fraction does not have a significant influence on resistivity because of the high salinity of the pore fluid. The apparent linear relationship between cementation factor and specific surface with respect to bulk volume is in accordance with the observation that cementation factor depends on grain shape (Wyllie and Gregory, 1953; Jackson et al., 1978) because grain shape is related to the specific surface.

The specific surface with respect to bulk volume can be predicted from Kozeny's equation (equation 5) based on porosity and permeability. The specific surface predicted from Kozeny's equation is correlated to the measured specific surface with respect to bulk volume (Figure 3). This result will be used to discuss the predictability of the cementation factor based on porosity and permeability.

### The *a*-factor versus specific surface for chalk

As an alternative, the *a*-factor can also vary in equation 4 instead of varying the cementation factor and keeping the *a*-factor equal to unity. The *a*-factor was introduced to account for conducting clays. Apparently, it is related positively to the specific surface with respect to bulk volume (Figure 4a), but a significant linear relationship cannot be defined. For clean samples from the Stevns outcrop and Nana, the *a*-factor is close to unity as expected for a sediment with small clay content and a low BET value (Figure 4b). Because the cementation factor shows a more clear correlation with the specific surface, it may be better to use Archie's equation in the simple form (equation 1) and avoid the complication of equation 3.

### Predicting cementation factor from porosity and permeability

The specific surface is usually unknown for a reservoir rock when saturation calculations are done; thus, the relationship between
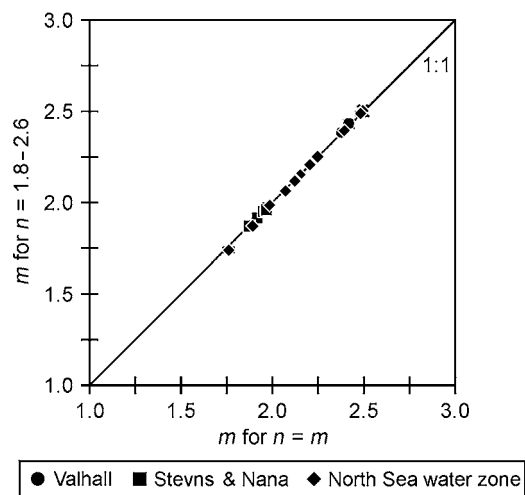
cementation factor and specific surface with respect to bulk volume is mainly an academic result (Figure 2c). However, the result may be used practically by applying Kozeny's equation (equation 5).

Porosity and permeability are usually measured in the laboratory on core material. Assuming a homogeneous sediment, the effective specific surface can be calculated from porosity and permeability
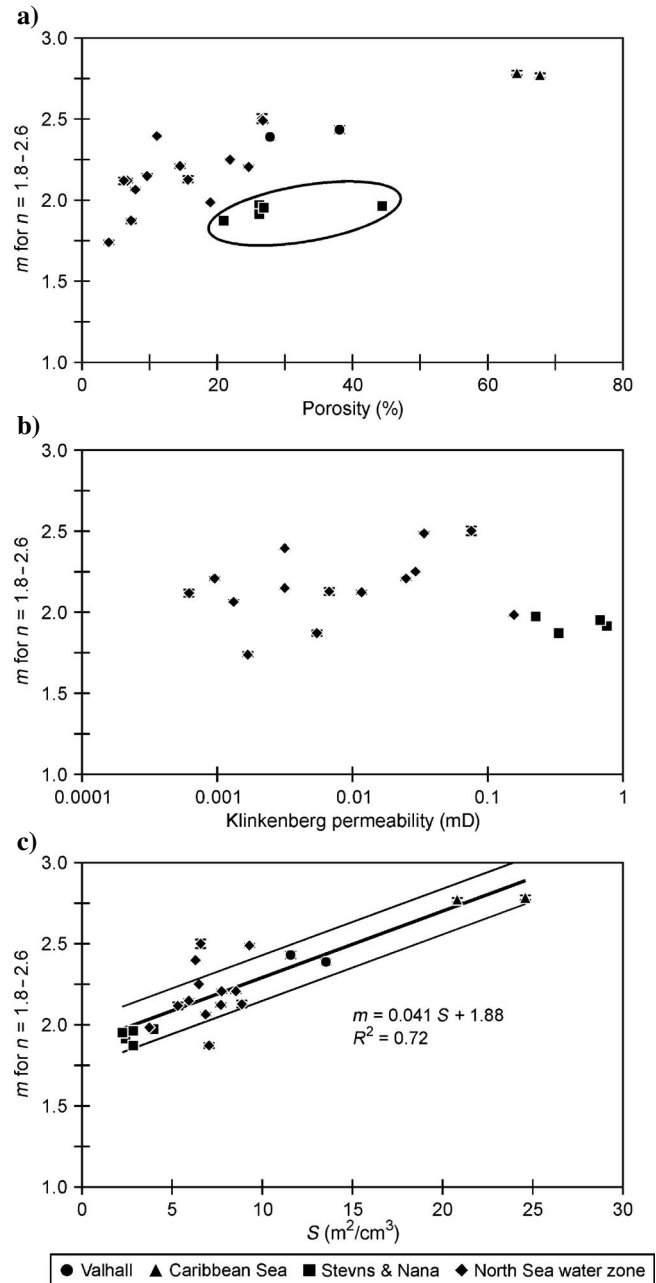
Figure 2. (a) Cementation factor *m* versus porosity. Stevns outcrop and the Nana samples are marked on the figure with an ellipse; these samples have a lower specific surface than the other samples. (b) Cementation factor versus Klinkenberg permeability. Samples with unknown permeability are not included. (c) Cementation factor versus specific surface *S* with respect to bulk volume. A sample with unknown specific surface is not included. The linear regression line is shown with two thin lines, which represent the confidence interval corresponding to one standard deviation.

Figure 1. Value of *m* calculated when assuming *a*-factor $= 1$ and *n* is 1.8–2.6 versus *m* calculated assuming $m = n$ and *a*-factor $= 1$. Samples from the Caribbean Sea are not included because the saturation equals one and the two different methods for obtaining *m* yield the same result.
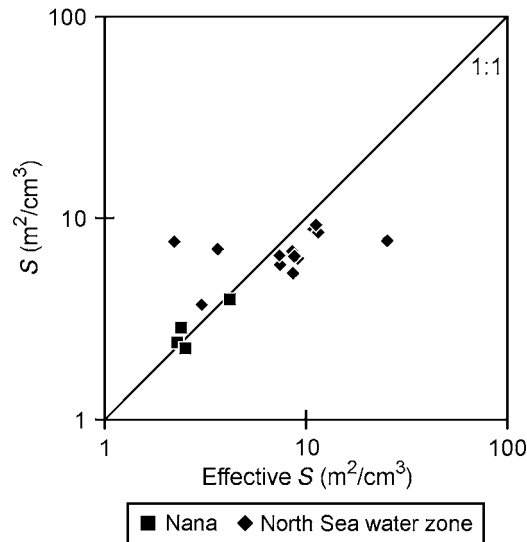
Figure 3. Specific surface $S$ with respect to bulk volume versus effective $S$ with respect to bulk volume calculated from Kozeny's equation (equation 5). A sample with unknown specific surface is not included.
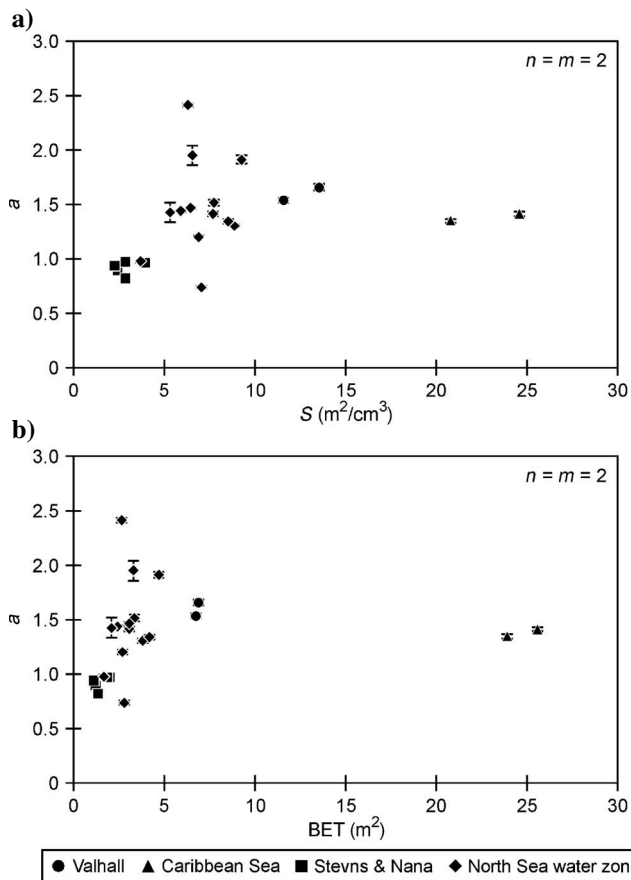


Figure 4. (a) The $a$-factor versus specific surface with respect to bulk volume. (b) The $a$-factor versus BET. A sample with an unknown specific surface is not included.

and used to predict cementation factor. Interestingly, Raiga-Clemenceau (1977) finds a relationship between cementation factor and permeability for sandstones with up to 9% clay and up to 22% carbonate content.

To test if the effective specific surface can be predicted for sandstones, we used porosity and permeability data for the sandstone samples published by Raiga-Clemenceau (1977) to calculate the corresponding effective specific surface with respect to bulk volume. For sandstone, the specific surface measured in the laboratory as the area of the surface normalized to weight or volume is larger than the effective specific surface in Kozeny's equation that controls permeability. This is because sandstone has small fractures on the surface of the grains that contribute to the specific surface of the sandstone but that do not influence the effective specific surface that controls the permeability in Kozeny's equation (Donaldson et al., 1975; Solymar, 2002).

For chalk, the measured specific surface corresponds to the effective specific surface in Kozeny's equation (Mortensen et al., 1998; Røgen and Fabricius, 2002). Only part of the North Sea chalk samples were included in this analysis because permeability data exist for only part of the samples (Table 1).

A common relationship between cementation factor and the logarithm of the effective specific surface was obtained for the chalk and the sandstone samples (Figure 5). In this case, a logarithmic scale is used for specific surface because the specific surface data cover three orders of magnitude. The samples with a specific surface higher than $1 \ m^2/cm^3$ are chalk samples; those with a specific surface lower than $1 \ m^2/cm^3$ are sandstone. The permeability of the sandstones in Raiga-Clemenceau (1977) is orders of magnitude larger than the permeability of North Sea chalk; therefore, the effective specific surface is much lower for sandstones than for North Sea chalk (Figure 5).

The sandstone and the chalk samples follow the same trend, which indicates that for both sandstone and chalk, the effective spe-
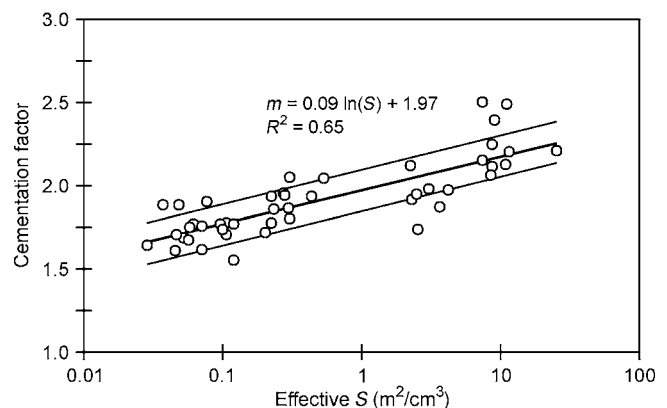


Figure 5. Cementation factor $m$ versus effective specific surface with respect to bulk volume as calculated by using Kozeny's equation and porosity and permeability data. The samples with a specific surface area higher than $1 \ m^2/cm^3$ are chalk, and the samples with a specific surface area lower than $1 \ m^2/cm^3$ are sandstone (from Raiga-Clemenceau, 1977). The log-linear regression line is shown together with two thin lines, which represent the confidence interval corresponding to one standard deviation.

cific surface is a main parameter controlling cementation factor. Sandstone and chalk can be treated equally when cementation factor is predicted with the equation from Figure 5:

$$m = 0.09 \ln\left( \sqrt{\frac{c\varphi^3}{k}} \right) + 1.98, \qquad (8)$$

where $k$ is measured in square micrometers ($10^{-12}$ m²) (equation 5). The log-linear relationship is significant on a 1% confidence level. For sandstone and chalk with an effective specific surface around 1 m²/cm³, the cementation factor is approximately two, which is the normal value to assume for carbonates. When the specific surface is significantly different from 1 m²/cm³, the cementation factor will deviate from two.

An advantage of predicting $m$ from effective specific surface is that it allows the definition of an anisotropic $m$-factor because the effective specific surface is calculated from porosity and the anisotropic permeability. This is of special interest because the electric conductivity in sedimentary rocks may be anisotropic (Kennedy, 2003).

## CONCLUSIONS

The cementation factor for chalk is variable and depends on porosity and specific surface of the chalk. The primary property that influences cementation factor is the specific surface of the chalk. For chalk, a local, apparently linear relationship between cementation factor and the specific surface with respect to bulk volume exists. The $a$-factor apparently is related positively to the specific surface, but a significant linear relationship cannot be defined. When the effective specific surface is calculated from porosity and permeability data, a common log-linear relationship between effective specific surface and the cementation factor is found for chalk and for published data on sandstone. This opens the perspective of defining an anisotropic cementation exponent.

## ACKNOWLEDGMENTS

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