Diagenetic Variations between Upper Cretaceous Outcrop and Deeply Buried Reservoir Chalks of the North Sea Area*

By

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Abstract

In the central North Sea Basin hydrocarbon-bearing chalks are deeply buried (2-3 km) whereas chalks in the rim areas are cropping out in the surrounding countries. The differing diagenetic histories between buried and outcrop chalk result in different rock properties, which are of great importance when simulating reservoir conditions using outcrop chalks as models.

In general, deeply buried reservoir chalks show significant overgrowth as witnessed by reshaping of particles together with strengthening of particle contacts. Most outcrop chalks are moderately affected with looser interparticle connections and less altered particle shapes. The non-carbonate mineralogy of outcrop chalks is dominated by quartz, occasionally opal-CT and clinoptilolite, and the clay mineral smectite. In offshore chalks quartz still dominates; opal-CT has recrystallized into submicron-size quartz crystals, and smectite has been replaced by kaolinite. These diagenetic variations are explained by higher temperatures and pressures in the deeply buried reservoir chalks.

Introduction

Chalk deposition of north-western Europe was controlled by the Late Cretaceous sea-level highstand (Figure 1) together with the regional subsidence of the entire North Sea area basin. Subsidence of the central North Sea continued during the Cenozoic whereas rim area inversions caused removal of Cenozoic overburden as well as chalk layers (Hillis, 1995; Japsen, 1998). As a consequence the North Sea chalk constitutes a coherent, saucer-shaped body with the rim cropping out in several countries surrounding the North Sea Basin while the central part is buried beneath more than three km of Cenozoic sediments (Japsen, 1998).

Chalk is a porous, very fine-grained pelagic sediment (particle size ~ 1 µm) composed primarily of skeletal debris from calcareous nannofossils, mainly coccoliths, with minor contributions from microfossils and macrofossil fragments. During burial diagenesis the contact points between calcite particles are strengthened due to porosity-preserving recrystallization and, at greater burial (higher stress), porosity-reducing cementation due to pressure dissolution at calcite-silicate contacts (stylolitization) (Fabricius, 2003; Fabricius and Borre, 2007).

Deeply buried chalks in the Central Graben are overpressured. Pore fluids support part of the overburden load thus relaxing the effective stress at calcite particle contacts and delaying mechanical compaction. As a result porosities are generally high and often comparable with porosities of outcrop chalks. However, offshore chalks are deeply buried (~3 km) and maximum burial depths of outcrop chalks are estimated to 1-1.5 km in

Yorkshire (Hillis, 1995) and 0.5-1 km in eastern and northern Denmark (Japsen, 1998). This difference in burial depth impacts stress and temperature conditions, for example, and most likely type and degree of diagenetic alterations.

To reveal how different diagenetic histories are reflected in petrographical, petrophysical and mineralogical properties of chalk a number of offshore samples and outcrop samples encircling the present-day North Sea were investigated.

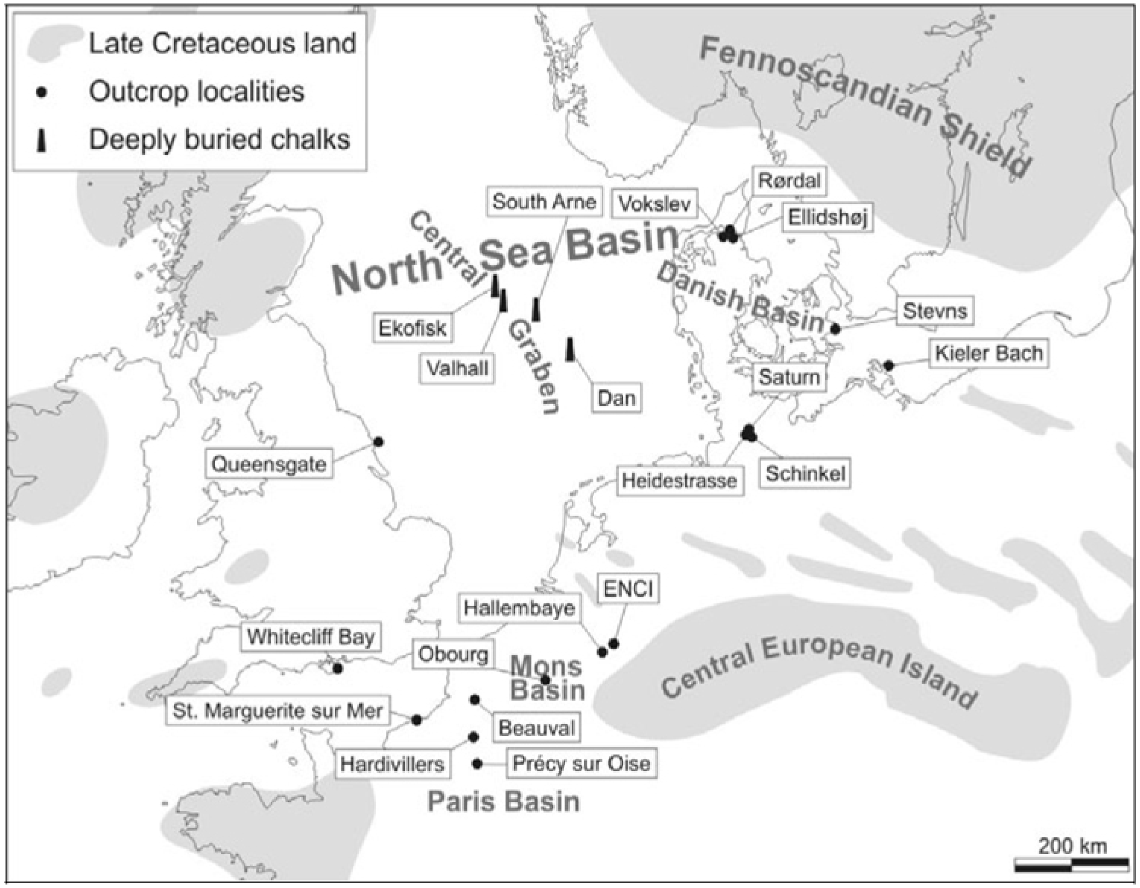


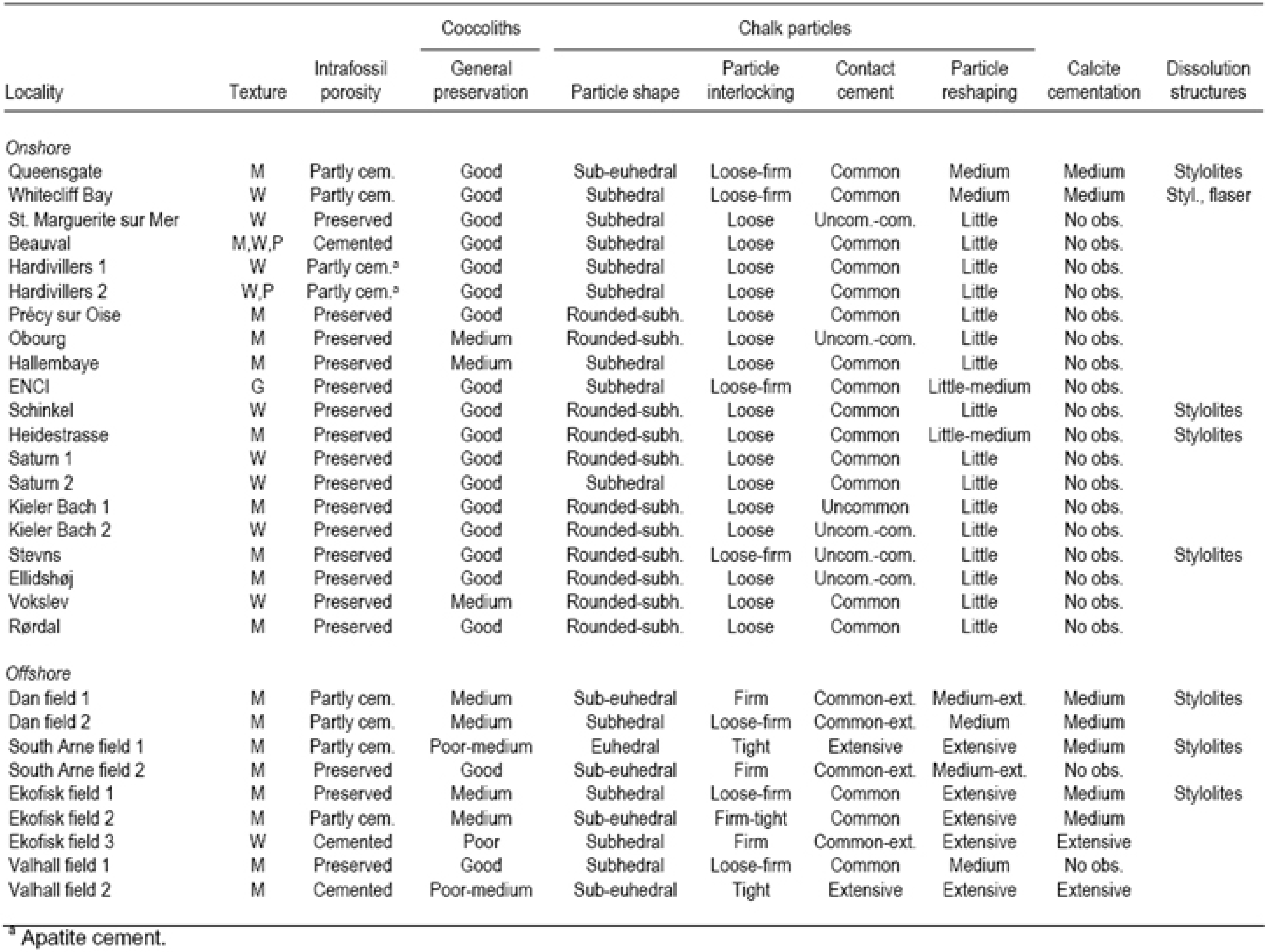
Figure 1. Palaeogeography of the Late Cretaceous North Sea area (modified after Ziegler, 1990). Indicated highs represent nondeposition areas that may be land or shoals. Investigated localities are indicated.

Methods

The investigated chalk samples span the stages Santonian, Campanian, and Maastrichtian and were selected from 17 outcrop localities covering 6 countries and from 4 offshore localities within the Central Graben (Figure 1). Apart from offshore chalks all samples were cored and crushed, respectively. Cores were used to determine porosity and permeability. Crushed samples were used for measurements of carbonate content, oxygen isotope values ($\delta^{18}O$), specific surface area, loss on ignition (LOI), and for mineral identification by X-ray diffraction (XRD). In addition crushed chalk powder was dissolved with HCl and chemical analysis performed on the insoluble residue to establish quantitative relations between silica, silicates, and other non-carbonate phases. Scanning electron microscopy (SEM) investigations were carried out on a Zeiss Supra 35VP field emission microscope equipped with a SE detector, and Backscatter electron microscopy (BSE) investigations were carried out using a Jeol JSM-5900 instrument equipped with EDS detector.

Results and Discussion

Based on petrographical, petrophysical, and mineralogical data (Tables 1, 2 and 3, respectively), a number of diagenetic trends within chalks can be described.



			Coccoliths	Chalk particles					
Locality	Texture	Intrafossil porosity	General preservation	Particle shape	Particle interlocking	Contact cement	Particle reshaping	Calcite cementation	Dissolution structures
Onshore									
Queensgate	M	Partly cem.	Good	Sub-euhedral	Loose-firm	Common	Medium	Medium	Stylolites
Whitecliff Bay	W	Partly cem.	Good	Subhedral	Loose-firm	Common	Medium	Medium	Styl., flaser
St. Marguerite sur Mer	W	Preserved	Good	Subhedral	Loose	Uncom.-com.	Little	No obs.	
Beauval	M,W,P	Cemented	Good	Subhedral	Loose	Common	Little	No obs.	
Hardivillers 1	W	Partly cem.[a]	Good	Subhedral	Loose	Common	Little	No obs.	
Hardivillers 2	W,P	Partly cem.[a]	Good	Subhedral	Loose	Common	Little	No obs.	
Précy sur Oise	M	Preserved	Good	Rounded-subh.	Loose	Common	Little	No obs.	
Obourg	M	Preserved	Medium	Rounded-subh.	Loose	Uncom.-com.	Little	No obs.	
Hallembaye	M	Preserved	Medium	Subhedral	Loose	Common	Little	No obs.	
ENCI	G	Preserved	Good	Subhedral	Loose-firm	Common	Little-medium	No obs.	
Schinkel	W	Preserved	Good	Rounded-subh.	Loose	Common	Little	No obs.	Stylolites
Heidestrasse	M	Preserved	Good	Rounded-subh.	Loose	Common	Little-medium	No obs.	Stylolites
Saturn 1	W	Preserved	Good	Rounded-subh.	Loose	Common	Little	No obs.	
Saturn 2	W	Preserved	Good	Subhedral	Loose	Common	Little	No obs.	
Kieler Bach 1	M	Preserved	Good	Rounded-subh.	Loose	Uncommon	Little	No obs.	
Kieler Bach 2	W	Preserved	Good	Rounded-subh.	Loose	Uncom.-com.	Little	No obs.	
Stevns	M	Preserved	Good	Rounded-subh.	Loose-firm	Uncom.-com.	Little	No obs.	Stylolites
Ellidshøj	M	Preserved	Good	Rounded-subh.	Loose	Uncom.-com.	Little	No obs.	
Vokslev	W	Preserved	Medium	Rounded-subh.	Loose	Common	Little	No obs.	
Rørdal	M	Preserved	Good	Rounded-subh.	Loose	Common	Little	No obs.	
Offshore									
Dan field 1	M	Partly cem.	Medium	Sub-euhedral	Firm	Common-ext.	Medium-ext.	Medium	Stylolites
Dan field 2	M	Partly cem.	Medium	Subhedral	Loose-firm	Common-ext.	Medium	Medium	
South Arne field 1	M	Partly cem.	Poor-medium	Euhedral	Tight	Extensive	Extensive	Medium	Stylolites
South Arne field 2	M	Preserved	Good	Sub-euhedral	Firm	Common-ext.	Medium-ext.	No obs.	
Ekofisk field 1	M	Preserved	Medium	Subhedral	Loose-firm	Common	Extensive	Medium	Stylolites
Ekofisk field 2	M	Partly cem.	Medium	Sub-euhedral	Firm-tight	Common	Extensive	Medium	
Ekofisk field 3	W	Cemented	Poor	Subhedral	Firm	Common-ext.	Extensive	Extensive	
Valhall field 1	M	Preserved	Good	Subhedral	Loose-firm	Common	Medium	No obs.	
Valhall field 2	M	Cemented	Poor-medium	Sub-euhedral	Tight	Extensive	Extensive	Extensive	

[a] Apatite cement.

Table 1. Petrographical data for onshore and offshore chalk samples. Abbreviations: M=mudstone, W=wackestone, G=Grainstone, Cem.=Cemented, Subh.=Subhedral, Uncom.=Uncommon, Com.=Common, Ext.=Extensive, Obs.=Observation, Styl.=Stylolites.

	Chalk							Insoluble residue	
Locality	Porosity (%)	Klinkenberg permeability (mD)	Carbonate content (wt. %)	Particle density (g/cm^3)	Specific surface area (m^2/g)	Average particle diameter (µm)	δ^{18}O Craig corrected (per mil.)	Specific surface area (m^2/g)	LOI (%)
Onshore									
Queensgate	24.6	0.3	96.2	2.72	1.5	1.5	-3.834	47.0	4
Whitecliff Bay	31.1	2.9	97.2	2.72	1.5	1.5	-2.856	46.0	10
St. Marguerite sur Mer	46.0	4.2	95.3	2.73	2.1	1.1	-1.793	41.4	5
Beauval	45.7	17.7	56.0	2.91	6.9	0.3	-2.541	15.6	3
Hardivillers 1	47.8	6.3	76.5	2.84	3.2	0.7	-2.094	13.6	3
Hardivillers 2	44.1	7.9	77.4	2.81	3.1	0.7	-1.988	19.2	4
Précy sur Oise	43.0	4.4	100.1	2.69	1.5	1.5	-1.716		
Obourg	39.1	1.0	94.3	2.72	3.4	0.7	-1.897	58.7	4
Hallembaye	41.9	3.5	98.6	2.72	1.7	1.3	-1.890	31.9	7
ENCI	50.4	2021.9	98.5	2.73	1.0	2.3	-0.660	45.2	8
Schinkel	45.2	9.2	98.7	2.74	1.2	1.8	-1.273	27.4	7
Heidestrasse	43.6	4.6	97.1	2.75	1.4	1.6	-2.599	47.1	3
Saturn 1	45.6	4.3	95.1	2.73	2.3	1.0	-2.563	41.8	5
Saturn 2	45.1	3.9	95.6	2.73	2.3	1.0	-1.488	52.5	3
Kieler Bach 1	46.1	4.5	98.2	2.72	1.9	1.2	-1.611	22.4	11
Kieler Bach 2	43.2	7.4	97.3	2.67	0.9	2.4	-1.275	0.2	46
Stevns	53.4	8.1	99.8	2.76	1.7	1.3	-1.640	23.9	
Ellidshøj	50.5	6.0	92.6	2.70	6.0	0.4	-1.085	79.5	2
Vokslev	42.5	4.8	92.6	2.73	2.4	0.9	-1.126	51.0	5
Rørdal	47.2	4.6	93.8	2.72	3.6	0.6	-0.794	59.1	3
Offshore									
Dan field 1	30.0	1.1	97.1	2.7[a)]	1.3	1.7	-4.120		
Dan field 2	40.8	4.1	98.6	2.71[a)]	1.5	1.5	-3.353		
Syd Arne field 1	30.4	0.8	98.6	2.72[a)]	1.7	1.3	-4.628		
Syd Arne field 2	42.5	5.2	96.6	2.71[a)]	1.8	1.2	-2.908		
Ekofisk field 1	32.2	1.4	97.5	2.71[b)]	1.5	1.5	-3.912		
Ekofisk field 2	45.0		96.8	2.71[b)]	1.3	1.7	-4.230		
Ekofisk field 3	20.8	0.4	94.3	2.71[b)]	1.4	1.6	-4.248		
Valhall field 1	48.0		97.5	2.74[a)]	1.6	1.4	-0.831		
Valhall field 2	11.0	0.008[a)]	98.9	2.70[a)]	0.9	2.5	-0.047		

[a)] Field operator's data.
[b)] Assumed particle density.

Table 2. Petrophysical data for investigated chalk samples. LOI = loss on ignition. Offshore data cited from Røgen et al. (1999) or calculated from data therein, except particle density and δ^{18}O.

	Measured element content (wt. %)					Calculated mineral content, normalized (wt. %)						
Locality	Si	Al	Mg	K	Fe	Silica	Smectite	Mica	Kaolinite	Clinoptilolite	Silica	
											Quartz	Opal-CT
Onshore												
Queensgate	33	4	1	1	2	55	40	5			55	
Whitecliff Bay	23	7	1	1	3	30	55	15			30	
St. Marguerite sur Mer	27	6	1	1	2	30	30	10		30	30	
Beauval	1	0	0	0	0	100% apatite						
Hardivillers 1	1	0	0	0	0	100% apatite						
Hardivillers 2	1	0	0	0	0	100% apatite						
Précy sur Oise												
Obourg	25	7	0	2	3	35	50	10	5		35	
Hallembaye	27	5	1	1	2	50	10	10		30	50	
ENCI	29	4	1	1	4	45	45	10			45	
Schinkel	28	4	1	1	3	50	40	10			50	
Heidestrasse	32	4	1	1	2	60	30	10			60	
Saturn 1	28	5	1	1	2	40	10	10		40	30	10
Saturn 2	29	5	1	1	3	40	40	10		10	30	10
Kieler Bach 1	24	5	1	1	2	30	30	10		30	20	10
Kieler Bach 2	11	3	1	1	1	45	10	10		35	45	
Stevns	6	2	1	0	1	25	60	15			25	
Ellidshøj	36	2	0	0	1	70	10	5		15	20	50
Vokslev	27	5	2	1	3	20	60	10		10	20	
Rørdal	35	3	1	1	2	70	20	5		5	30	40
Offshore												
Dan field 1												
Dan field 2												
South Arne field 1[a)]	13	4		1		50		15	35		50	
South Arne field 2[a)]	14	3		0		60		5	35		60	
Ekofisk field 1												
Ekofisk field 2												
Ekofisk field 3[a)]	17	2		0		75		5	20		75	
Valhall field 1[a)]	30	4	0	0	2	65		5	30		65	
Valhall field 2[a)]	26	6	0	0	4	55		5	40		55	

[a)] The offshore silica and clay mineralogy are based on chemical data used in Røgen & Fabricius (2002).

Table 3. Chemical analysis of insoluble residue. Measured amounts of elements are shown to the left and calculated quantities of silica, clay, and zeolite minerals to the right.

Characterization of Outcrop and Offshore Chalk

As outcrop chalks have been subjected to limited maximum burial (e.g., Hillis, 1995; Japsen, 1998) and pressures and temperatures accordingly remained low, incipient stylolites and porosity-reducing cementation are only observed at few relatively deeply buried or tectonically affected localities. High porosities are preserved, and $\delta^{18}O$ values remain relatively high. Due to recrystallization chalk particles have formed loose-firm contacts (Figure 2A, B), as witnessed by varying degrees of contact cementation. In general original particle shapes are preserved, although overgrowth is always present and some reshaping into rhombs occurs. Non-calcite mineralogy is mainly dominated by quartz and smectite, but occasionally opal-CT, clinoptilolite, and apatite occur in vast quantities. Where smectite and especially opal-CT dominates, the specific surface area of the non-carbonate phase is at maximum; in combination with low carbonate content the specific surface area of chalk increases.

Some pronounced diagenetic variations occur within outcrop chalks:

- English chalks have characteristics similar to offshore chalks. Porosity, permeability, and $\delta^{18}O$ values are reduced compared to other outcrop samples (Table 2). Recrystallization and cementation have reshaped particles, and in cemented areas contact cements are very well developed (Table 1). In the case of Queensgate these diagenetic alterations may have been caused by a maximum burial of possibly 1500 m (e.g., Hillis, 1995), and in the case of Whitecliff Bay by stresses induced by the inversion of the Sandown pericline.
- The French phosphatic chalks at Beauval and Hardivillers are characterized by low carbonate content and a non-carbonate fraction completely dominated by apatite (Table 3). Texture variations from mudstones over wackestones to packstones within few mm probably reflect the sharp transition from phosphatic chalk to coccolith chalk (Jarvis, 1992). The significantly lower carbonate content relative to other investigated samples increases the specific surface area of chalk (Table 2).
- As a grainstone the ENCI chalk has considerably higher permeability compared to the mud- and wackestones from other localities (Table 2). The grains (microfossils) are heavily overgrown due to meteoric diagenesis facilitated by the high permeability.
- Danish and German chalks often contain opal-CT and clinoptilolite (Table 3), both of which form from dissolved opal-A; their coexistence is thus not surprising. Quantitatively opal-CT dominates in Danish samples and clinoptilolite dominates in German samples. Minor occurrences of clinoptilolite were observed in French, Belgian, and Danish samples.
- Extraordinarily high organic carbon content was found in the Kieler Bach samples (LOI, Table 2), causing a dramatic drop in specific surface area of chalk (Table 2). The origin of organic carbon was not identified, but most likely an external source polluted the chalk.

Deeper burial (2400-3600 m) and thus increased pressure and temperature of offshore chalks have generally reduced porosities, and stylolites, cementation features, and lower $\delta^{18}O$ values occur commonly. However, overpressuring of the chalks has created a special diagenetic environment where porosities are much higher (up to 48%) than dictated by burial depth. Even in high-porosity samples where little or no cementation has taken place, recrystallization has mostly reshaped chalk particles into rhombs (Figure 2C, D) and strengthened the cohesion between particles as seen from conspicuous contact cements. In low-porosity samples cementation has reshaped nearly all particles, and even microfossils may be hard to recognize. Only coccoliths show remarkable resistance against alterations, although their numbers diminish. In contrast to outcrop chalks non-calcite mineralogy is unvaried and consists mostly of quartz, kaolinite, and mica (Table 3). Opal-CT and clinoptilolite were not observed in the studied samples, and smectite in just one sample. Quartz is the dominant mineral and occurs in larger amounts offshore than onshore, indicating that opal-CT and clinoptilolite have been transformed into quartz. Possibly submicron-size quartz crystallites arranged in aggregates have recrystallized from opal-CT lepispheres. The specific surface area of chalk is very unvaried despite variations in carbonate content. This is probably an effect of equalization of particle sizes during recrystallization and due to the absence of smectite and opal- CT, minerals with large specific surface areas.

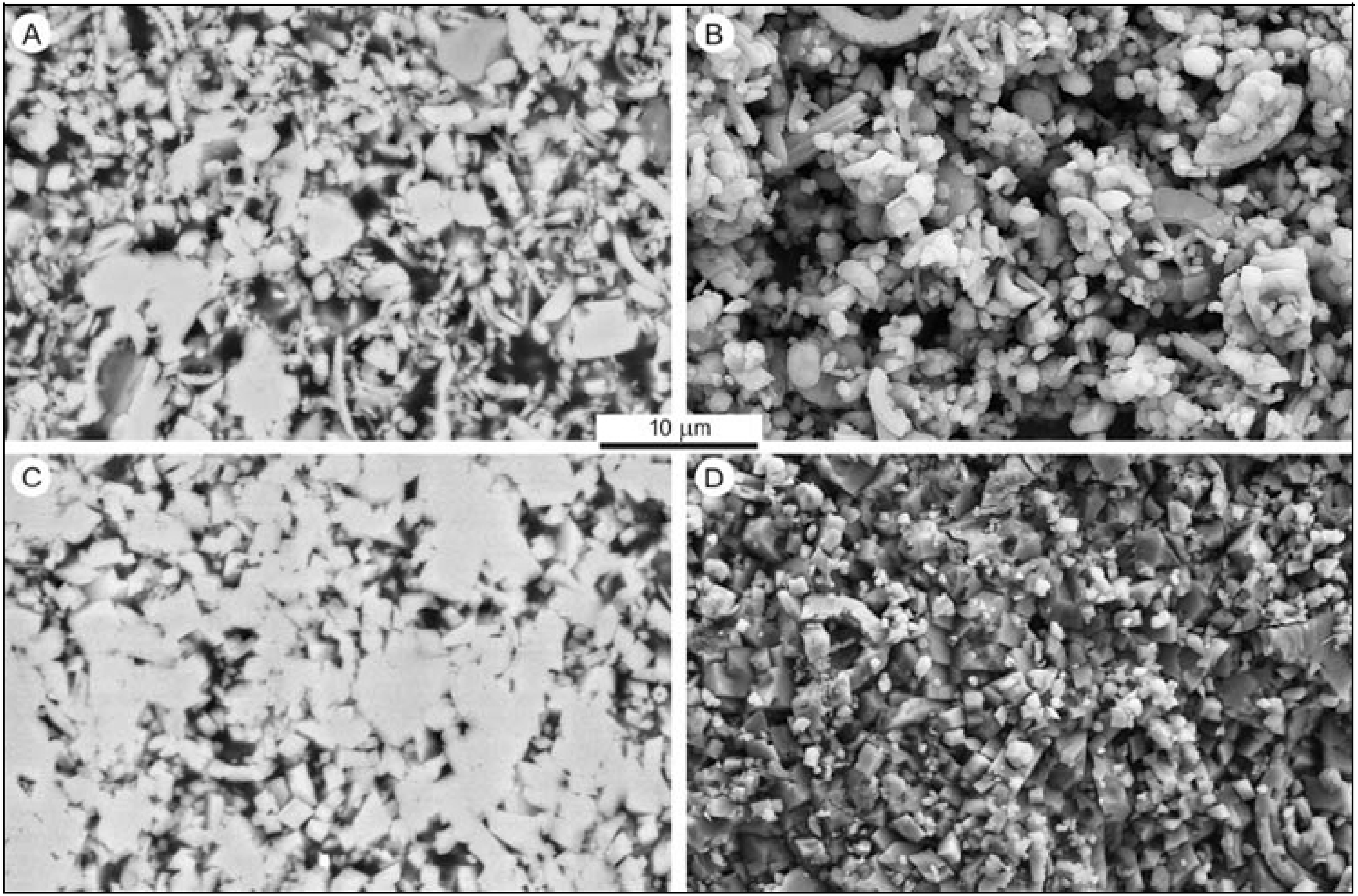


Figure 2. BSE (A+C) and SEM (B+D) images of chalk. (A+B) Typical high-porosity outcrop chalk, showing moderate reshaping of particles and loose particle contacts. (C+D) Typical offshore chalk. Extensive cementation has reshaped particles into rhombs, strengthened particle contacts, and reduced porosity.

Outcrop Chalks as Substitutes for Reservoir Chalks

Judged from petrographical and petrophysical evidence, English chalks resemble offshore chalks the most. Recrystallization and cementation features in Queensgate and Whitecliff Bay chalks are nearly as well-developed as observed in offshore chalks.

Chalks from Stevns, Rørdal, and Hallembaye are often used as substitutes for reservoir chalks. However, these outcrops chalks are less diagenetically altered than chalks from the Dan, South Arne, and Ekofisk fields. Recrystallization features are clearly visible, but severe reshaping, porosity-reducing cementation, and strengthened particle contacts are either absent or less developed; these expectedly, from a matrix point of view, would make them mechanically weaker than reservoir chalks. One exception is the Valhall field, where overpressure and hydrocarbon presence has preserved very high porosities in some sections and impeded cementation, as witnessed by loose chalk particle contacts, less pronounced particle reshaping, and high $\delta^{18}O$ values.

Some chalks differ significantly from reservoir chalks and will probably constitute poor substitutes for the latter. These chalks include:

- The phosphatic Hardivillers and Beauval chalks with low carbonate content and textures ranging from mudstone over wackestone to packstone.
- The highly permeable ENCI grainstone subjected to meteoric diagenesis.
- The Kieler Bach chalks assumingly subjected to organic carbon pollution.

Conclusions

Burial depth is a main diagenesis-controlling factor. Recrystallization and porosity-reducing cementation of chalk particles, coccoliths, and microfossils are clearly evident in onshore samples subjected to shallow maximum burial, but much more pronounced in deeply buried offshore samples. In addition, mineralogy changes and $\delta^{18}O$ values are lowered in response to burial.

The significant diagenetic alterations of English chalks make these rather similar to, and possibly acceptable substitutes for, offshore chalks from the Dan, South Arne, and Ekofisk fields. In contrast less diagenetically altered chalks from Stevns, Rørdal, and Hallembaye, for example, share characteristics with Valhall field chalks.

Acknowledgement

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