

Upper Oligocene diatomaceous deposits in the northern North Sea – silica diagenesis and paleogeographic implications

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Relatively well-preserved diatoms, often cemented together as silica aggregates and mainly composed of opal-A, are present in Upper Oligocene sediments at burial depths down to about 1500 m in the northern North Sea. The taxon *Paralia thybergii* dominates, but *Stephanopyxis* spp., *Coscinodiscus* spp. and sponge spicules are also commonly present. The diatom flora indicates a nearshore environment and a shallow marine northern North Sea basin at that time. The silica facies interfinger with glauconitic facies to the west, as seen in well 34/7–1, and this also suggests shallow marine conditions and sediment starvation. A structural high located between 60 and 61°N restricts the extensive biogenic silica deposits to the northern part of the North Sea. Seismic mapping shows that a basin with water depths up to at least 800 m existed in the northernmost North Sea–Møre Basin area in mid-Oligocene time. The basin was bounded by shallow shelf areas in the east and southwest. The Late Oligocene basin configuration caused upwelling when the wind came from a southerly direction. Preservation of the siliceous sediments indicates highly productive surface waters, in a shallow basin with starved clastic sedimentation in the northern North Sea with wind-driven upwelling in a north–south direction.

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Introduction

Paleocene and Eocene diatom-rich sediments are well known both from the North Sea and onshore Denmark, but similar regional deposits have not been reported from the Oligocene sequence. We found a biosilica-rich Upper Oligocene sequence, distributed regionally in the northern North Sea. Oligocene biogenic silica is known from the northern North Sea (Gran 1989; Rundberg 1989; Weinelt & Thiede 1992; Holmsen 1994; Tyridal 1994; Singh 1994; Gradstein & Bäckström 1996) but has not previously been described in detail.

The best-studied Paleogene diatom deposits in the area in and around the North Sea are from the Fur Formation (earlier known as Moler) in Jutland, Denmark. The Fur Formation is of latest Paleocene or earliest Eocene age and comprises alternate layers of diatomite and ash equivalent to the Balder Formation in the North Sea. Detailed descriptions of the siliceous microfossils in the Fur Formation diatomite have been published (e.g. Benda 1972; Hohmann 1991; Fenner 1994; Mitlehner 1996). A description of some diatoms from the uppermost Paleocene–lowermost Eocene volcanic sediments (Balder Formation) of the North Sea have been presented by Jacqué & Thouvenin (1975), Malm et al. (1984) and Mitlehner (1994). A rich assemblage of diatoms and silicoflagellates from two samples within calcareous bands or concretions in the Balder Formation in well 30/2–1 has been reported by Malm et al. (1984). This flora was similar to that reported from the Mo-Clay (Fur Formation) diatomite in

Denmark (Benda 1972). Recently, Mitlehner (1996) has also worked on Paleocene/Eocene siliceous microfossils in calcareous concretions within the Fur Formation correlated with offshore sections in the North Sea Basin.

DSDP and ODP studies in the Norwegian–Greenland Sea have also used diatoms as biostratigraphic tools, and two distinct Tertiary biosilica-enriched intervals occurring during the Eocene and the Miocene have been documented. The diatom investigation from DSDP Leg 38 is the most extensive and is also a pioneering study on Norwegian Sea diatom biostratigraphy (Schrader & Fenner 1976).

Owing to their scarcity at most stratigraphic levels, diatoms have not been extensively used for biostratigraphic correlation in Tertiary deposits in the North Sea. Diatoms, with other microfossils, have been used for a basic zonation of the Tertiary to Quaternary North Sea, but only on a generic level or open nomenclature level, e.g. as Diatom sp. 3–5 (Jacqué & Thouvenin 1975; Hughes 1981; King 1983; Malm et al. 1984). Mitlehner (1994) sought to improve the diatom taxonomy mainly using pyritized casts.

The principal reason for the scarcity of taxonomic and biostratigraphic studies on Tertiary diatoms from the North Sea basin is their poor preservation below the depth where opal-A dissolves and opal-CT precipitates. Below this level only pyritized diatoms will remain but they show little of the detail of the skeletal structure which is necessary for identification. However, in this study siliceous microfossils have been identified at varying

depths in eight wells, between approximately 500 and 1550 m. One reason why diatoms are not recognized in biostratigraphic studies of North Sea Tertiary sediments may be that the standard preparation techniques for biostratigraphic investigations often either fail to collect or else destroy any diatoms present. Most biostratigraphic studies from the North Sea are based on either ubiquitous foraminifer or dinoflagellate cysts. When using foraminifer the sediments are sieved with a lower limit of 63 μm or larger, and only the large diatoms, pyritized diatoms and radiolarians are retained. For dinoflagellate preparation the strong acids used will remove any silica skeletons from the material. Biostratigraphic data are not included in this paper, but the most common or important diatom species are presented and used to constrain the Oligocene sequences in well 36/1-2.

Previous studies on silica diagenesis have concentrated on diatomites deposited as deep sea sediments (e.g. Calvert 1974; Oehler 1975; Hein et al. 1978; Hein & Scholl 1978; Riech & von Rad 1979; Isaac 1982a) or are experimental studies (Mizutani 1970; Kastner et al. 1977; Williams et al. 1985; Williams & Crerar 1985; Roaldset & Wei 1998b). Changes in silica phase from opal-A to opal-CT to diagenetic quartz can be observed with increasing burial depth and temperature (e.g. Murata & Larson 1975; Mitsui & Taguchi 1977; Isaacs 1982b; Williams et al. 1985; Williams & Crerar 1985; Roaldset & Wei 1998b). Temperature and time are generally thought to be the main factors controlling the rates of transformation, but water composition and sediment composition are important secondary factors (Kastner et al. 1977; Isaacs 1982a). The proportion of detrital minerals, particularly clay minerals in the sediment, influences the transformation. Hence, in sediments with a high detrital mineral content the opal-A to opal-CT transition occurs at greater depths but variations in carbonate volume do not significantly affect the rates of silica diagenesis (e.g. Monterey Formation – Isaac 1982b). Kastner et al. (1977) showed experimentally that the transformation rate of opal-A to opal-CT is much higher in calcareous sediments than in clay-rich sediments. The conversion of biogenic opal to authigenic opal-CT is slightly accelerated in calcareous sediments, whereas the presence of detrital clay facies retards the opal-CT to quartz transformation considerably. However, other data do not always seem to be in agreement with this concept (Riech & von Rad 1979).

In this study we document a regionally distributed, biosilica-enriched Upper Oligocene sequence from the northern North Sea. Diatoms are most abundant, mainly *Paralia thybergii* (Stabell 1996), but sponge spicules, silicoflagellates and radiolarians are also present. The siliceous microfossils have been identified at varying depths in eight wells, between approximately 500 m and 1550 m. The characteristic diatom assemblage of the Upper Oligocene sediments is presented in this paper, and the time and space distribution of biogenic silica and silica diagenesis is discussed. The biogenic silica facies represented in the Upper Oligocene sediments will also be

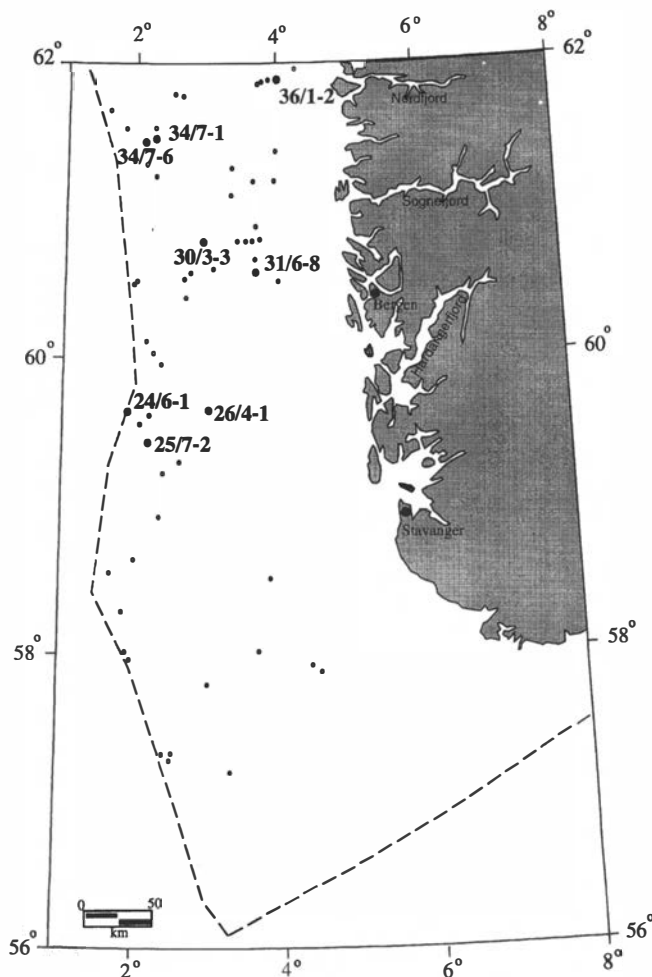


Fig. 1. Map of the study area showing the location of the wells investigated. Courtesy of H. Jordt.

discussed in a paleogeographic context in order to contribute to the understanding of the regional distribution of this biogenic facies and the basin development of the northern North Sea.

Database and methods

Wells located close to the coastline of present Western Norway and in a more central part of the Viking Graben in the northern North Sea have been investigated (Fig. 1). Cuttings samples from 8 wells (24/6-1, 25/7-2, 26/4-1, 30/3-3, 31/6-8, 34/7-1, 34/7-6, and 36/1-2) at depth intervals varying between 450 and 1850 m were studied. The Cenozoic Sequence Stratigraphy (CSS) of Jordt et al. (1995) was used.

The sampling interval for diatom analysis was mostly 10–50 m and a total of 187 samples was prepared. All samples were treated with 37% HCl and 10% hydrogen peroxide and washed with distilled water until a pH of 7 was achieved. A drop of the suspension was pipetted onto a cover slide; slides were then mounted in Naphrax. The

slides were examined under the microscope at 400 \times and 1000 \times magnification. Diatom abundances were recorded at $\times 400$; as barren (0) if no specimens were observed in one horizontal traverse; rare (1) if one to ten specimens occurred per horizontal traverse; few (2) if one to four specimens occurred in five fields of view; common (3) if one to five specimens occurred in one field of view and abundant (4) if six or more specimens were present in one field of view. Of 187 samples, 55 samples contain common to abundant diatoms. Scanning electron microscopy (SEM) was undertaken on selected samples. Identification of species, and biostratigraphic ranges are based mainly on Schrader & Fenner (1976) and Fenner (1985).

X-ray diffraction (XRD) analyses, of about 60 samples, of washed drill bit cuttings samples (with a sample interval of approximately 50 m) were also integrated into this study in order to detect opal-CT. Unoriented powder samples were analyzed on a Phillips 1700/1710 with CuK α -radiation. Semi-quantitative estimates for the most abundant minerals are presented in Thyberg et al. (1998a). Material from well 36/1-2 was treated with 37% HCl and 10% hydrogen peroxide in order to run XRD on the silica content, to avoid interference from other minerals such as carbonates and to minimize the clay mineral content when the material was examined for opal-A and opal-CT.

Time and space distribution of biogenic silica

Three wells in the southernmost part of the study area (24/6-1, 25/7-2 and 26/4-1) located at approximately 60°N, indicate no or very little biogenic silica in the Oligocene sequences (Fig. 2a). Diatoms were rare in wells 26/4-1 and 25/7-2 in Upper Eocene and Lower to Upper Oligocene intervals. Biosiliceous fragments and sponge spicules are common in the Oligocene intervals, but rare in Upper Eocene samples (Table 1). Biosiliceous fragments and opal-CT are also recorded in the Lower Oligocene and close to the Eocene–Oligocene boundary in wells located at approximately 60°40'N (Gran 1989).

The five northern wells (30/3-3, 31/6-8, 34/7-1, 34/7-6 and 36/1-2) are characterized by common to abundant diatoms occurring between depths of approximately 600 and 1360 m (Fig. 2b). The samples investigated are characterized by rare diatom fragments and sponge spicules when diatom abundance is low and common fragments and sponge spicules when diatom abundance is high. Silicoflagellates are infrequently observed, and radiolarians are always rare in these samples (Table 1). Relatively well-preserved diatoms were observed in rare and common abundance down to 1550 m in well 30/3-3.

In a Cenozoic sequence stratigraphic context (Jordt et al. 1995), high diatom abundances in the northernmost part of the study area correlate with the upper part of the Lower Oligocene sequence (CSS-3) but are mainly confined to the Upper Oligocene sequence (CSS-4). An upward decrease in diatom content occurs near the top of CSS-4 (Fig. 2b). Unfortunately, well 31/6-8 has been sparsely sampled,

but the relative diatom abundance indicates the same trend.

Diatom assemblage

The Upper Oligocene (CSS-4) has a high relative abundance and a rich diatom flora dominated by *Paralia thybergii* as illustrated by well 30/3-3 (Fig. 3). A detailed description of *Paralia thybergii* can be found in Stabell (1996). The relative proportion of *P. thybergii* increases from 40% at 1150 m to approximately 80% at the top of this interval. *Stephanopyxis* spp. show the same trend, increasing upwards from 3% to 20%. Resting spores of *Chaetoceros* inversely correlate, decreasing upwards from about 30% at 1150 m to about 5%. *Coscinodiscus* spp. and *Rhizosolenia* spp. also decrease upwards from a maximum for each group of about 7%. The diatom flora thus changes from a *P. thybergii* and *Chaetoceros* resting spore assemblage in early CSS-4 to a *P. thybergii* and *Stephanopyxis* spp. assemblage in late CSS-4. In an Upper Oligocene diatomite at Silstrup in Denmark (Heilmann-Clausen 1982) we have found a similar flora with a dominance of *P. thybergii*.

Also characteristic of the siliceous sediments in the northern North Sea are *Coscinodiscus* spp. fragments, which are often cemented together with better-preserved diatoms of different species as aggregates. Silica aggregates appear in the light microscope as dark clusters of debris (Fig. 4a). Unfortunately, owing to size differences, it was not possible to quantify the aggregates, but there is a clear general trend to increasing abundance and size downwards. In well 30/3-3 there are few aggregates at 1000 m, whereas they are common at 1050 m. The aggregates were also more loosely packed in the upper part of the sediment record than in the lower part. It is rarely possible to recognize the diatoms included in the aggregates in light microscope, but in SEM they are more easily observed (Figs. 5a, b). Fragments of *Coscinodiscus* spp. are almost always an important biogenic constituent, usually with a low degree of dissolution. *Coscinodiscus* species are found intact and sometimes not fragmented, but examples of silica overgrowth have also been observed (Fig. 4b). The larger fragments of *Coscinodiscus* spp. seemed to act as a trap for the other diatom fragments incorporated in the aggregates (Fig. 4c).

Species of biostratigraphical importance are also common in the Upper Oligocene sequence, they include the species *Asteromphalus oligocenicus* Schrader and Fenner (Late Oligocene), *Coscinodiscus rhombicus* Castracane (Late Oligocene–Miocene), *Cymatosira compacta* Schrader and Fenner (Late Oligocene), *C. praecompecta* Fenner and Schrader (Late Eocene–Late Oligocene), *Goniothecium odontella* Ehrenberg (Oligocene–Miocene), *Lisitzina ornata* Jousé (Late Oligocene), *Melosira architecturalis* Brun (Middle Eocene–Late Oligocene), *Rhizosolenia prebarboi* Schrader (Late Oligocene–Middle Miocene), *Rocella praeinitida* (Fenner) Fenner (Late Oligocene),

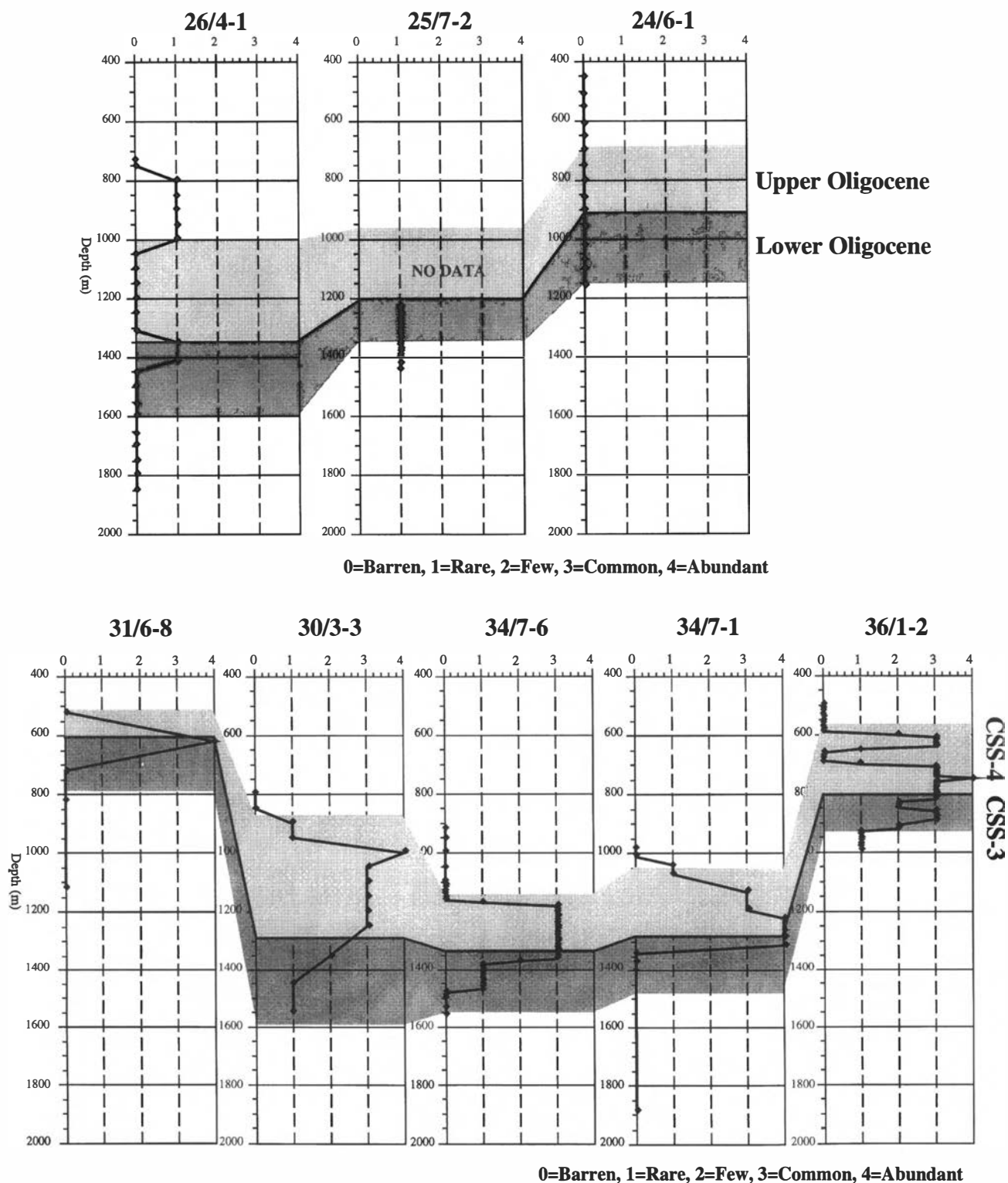


Fig. 2. (Above) Time and space distribution of abundance of diatoms in CSS-3 and CSS-4 sediments vs. depth in the different wells in the southernmost area. (Below) Time and space distribution of abundance of diatoms in CSS-3 and CSS-4 sediments vs. depth in the different wells in the northernmost area.

Rocella vigilans (Kolbe) Fenner (Late Oligocene), *Sceptroneis propinqua* Schrader and Fenner (Oligocene) (Fig. 6). The interval of high diatom abundance can also be dated as Late Oligocene from the biostratigraphic information.

The two intervals with a high diatom content in well 36/

1–2 (Fig. 2) are separated by a sandy interval corresponding to ~660 m–690 m, which does not contain diatoms. At the bottom of the high abundance sequence *Cymatosira compacta* Schrader and Fenner and *C. praecompacta* Fenner and Schrader were observed indicating an Oligocene age. *Pseudorocella barbadensis* Deflandre (Late

Table 1. Relative content of Oligocene biosiliceous organisms in investigated northern North Sea wells.

Biogenic content – southern transect			Biogenic content – northern transect					
Well	Sample depth	Biosilica	Well	Sample depth	Biosilica	Well	Sample depth	Biosilica
24/6–1	450	0	30/3–3	800	ssf	34/7–6	980	f
	510	0		850	ssf		1010	f
	550	0		900	dSSF r		1040	dSSF
	610	0		950	dSSF		1070	dSSF
	650	0		1000	DSSFs r		1130	DSSFs r
	700	ss		1050	DSSFs		1190	DSSFs
	750	0		1100	dSSFs r		1220	DSSF
	800	0		1150	dSSF r		1260	DSSF
	860	0		1200	dSSF r		1280	ssf
	900	0		1250	DSSF		1310	0
	960	0		1350	dSSF		1340	f
	1020	ss		1450	dssf		1370	ssf
	1070	0		1550	dssf		1400	
	1110	0					1890	
	1160	0						
25/7–2	1230	dSSF	31/6–8	520	f	36/1–2	500	0
	1240	dSSF		620	DSSFs		510	0
	1250	dSSF		720	0		520	0
	1260	dSSF		820	0		530	0
	1270	dSSFs		1120	0		540	0
	1280	dSSF	34/7–1				550	0
	1290	dSSF		920	0		560	0
	1300	dSSF		950	0		570	0
	1310	dSSF		1000	0		580	0
	1320	dSSF		1050	0		590	0
	1330	dssf		1100	0		600	dSSFs
	1350	dssf		1110	0		610	dSSFs
	1360	dssf		1120	0		620	DSSF
	1370	dssf		1130	0		630	DSSF
	1380	dssf		1140	0		640	dSSF
	1390	dssf		1150	0		650	dSSf r
	1400	dssf		1160	0		660	ssf
	1420	dssf		1170	dssf		670	ssf
	1440	dssf		1180	DSSF r		680	ss
				1190	DSSF		690	ssf
				1200	DSSF		700	dSSF
26/4–1	730	0		1210	DSSF r		710	DSSF
	750	0		1220	DSSF		720	DSSF
	800	dSSf r		1230	DSSF		730	DSSFs r
	850	dSSF r		1240	DSSFs		740	DSSFs
	900	dSSFs		1250	DSSF		750	DSSF
	950	dSSF r		1260	DSSFs		760	DSSF
	1000	0		1270	DSSF		770	DSSFs r
	1050	0		1280	DSSF		780	DSSFs
	1100	0		1290	DSSF		790	DSSFs
	1150	0		1300	DSSFs		800	DSSF
	1200	0		1310	DSSF		810	DSSF
	1250	0		1320	DSSF		820	DSSF
	1310	dssf		1330	DSSFs		830	dSSF
	1350	dssf		1340	DSSFs		840	dSSF
	1410	0		1350	DSSF		850	dSSF
	1450	ss		1360	DSSFs		860	DSSF r
	1500	ss		1370	dSSF		870	DSSF
	1560	0		1380	dSSF		880	DSSF
	1600	0		1390	dSSF		890	DSSFs r
	1660	0		1400	dSSF		910	dSSF
	1700	0		1410	d f		920	dSSFs
	1750	0		1420	d f		930	dssf
	1800	0		1430	d		940	dssf
	1850			1440	d F		950	d f
				1450	d f		960	dssf
				1460	d f		970	dssf
				1470	f		980	dssf
				1480	f		990	d f
				1490	f			
				1500	f			
				1530	f			
				1560				

0 = Barren biosilica, d = Diatoms (rare-few), D = Diatoms (common-abundant), ss = Sponge spicules (rare-few), SS = Sponge spicules (common-abundant), f = Fragments (rare-few), F = Fragments (common-abundant), s = Silicoflagellates (rare-few), S = Silicoflagellates (common-abundant), r = Radiolarians (rare-few), R = Radiolarians (common-abundant).

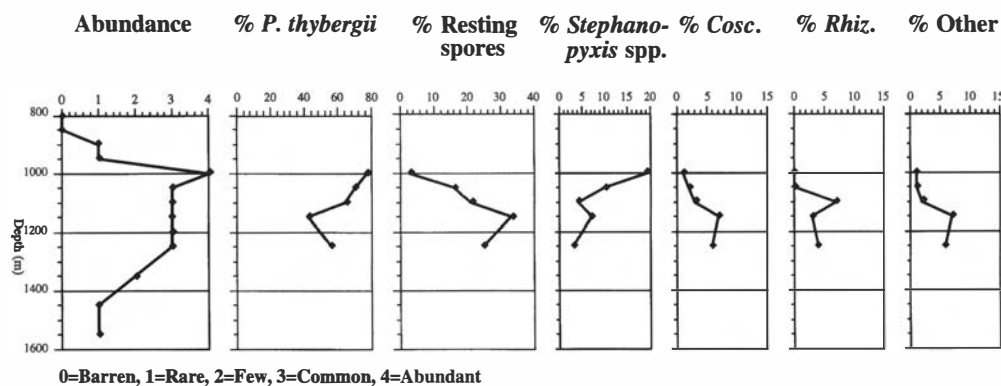


Fig. 3. Diatom abundance and percentage distribution of the most common diatoms in well 30/3-3. *P. thybergii* = *Paralia thybergii*, *Cosc.* = *Coscinodiscus* spp., *Rhiz.* = *Rhizosolenia* spp.

Eocene–Early Oligocene) was observed at 840 m. This gives a slightly younger age than indicated by the seismic interpretation of Jordt (1996). Of course, the possibility of caving cannot be excluded, since the material is drill bit cuttings, but typical Eocene diatoms were not found. We have therefore indicated the boundary CSS-4/CSS-3 at 800 m until further biostratigraphic studies give a more detailed dating.

Definition of Opal-A, Opal-A' and Opal-CT

Based on X-ray diffraction, a nomenclature of natural hydrous silicas can be subdivided into three well-defined structural groups, opal-A (highly disordered, near amorphous), opal-CT (disordered, a-cristobalite, a-tridymite) and opal-C (well-ordered, a-cristobalite) (Jones & Segnit 1971). The term opal-A includes naturally occurring varieties of hydrous silica; hence siliceous fossils are present as this phase. Opal-A is also characterized by an X-ray diffraction pattern of a very diffuse band at about 4.1 Å (Jones & Segnit 1971). An inorganic silica phase termed opal-A', morphologically distinct from opal-A, is identified by Hein et al. (1978), who suggest that biogenic opal-A dissolves and reprecipitates as an inorganic opal-A'. In this study we have used this nomenclature when discussing silica diagenesis.

Opal-CT recrystallized from opal-A is identified as lephospheres or dense masses of cement (e.g. Riech & von Rad 1979). Where opal-CT exists, within a limited temperature interval, its $d(101)$ spacing shows a progressive decrease from 4.10 Å (poorly ordered) to 4.04 Å (well ordered) with increasing temperatures, which reflects the structural ordering of opal-CT (e.g. Roaldset & Wei 1998a) in a sedimentary column. The idealized diagenetic sequence will be opal-A sediments overlying opal-CT sediments, which in turn overlie quartz sediments, where the opal-A–opal-CT–quartz transformation follows a dissolution–reprecipitation pathway (Williams et al. 1985). However, transformation does not occur instantaneously throughout a sedimentary sequence, and, as reported by many authors (Mizutani 1970; Hein et al. 1978; Riech & von Rad 1979; Kruege & Williams 1982), this is reflected

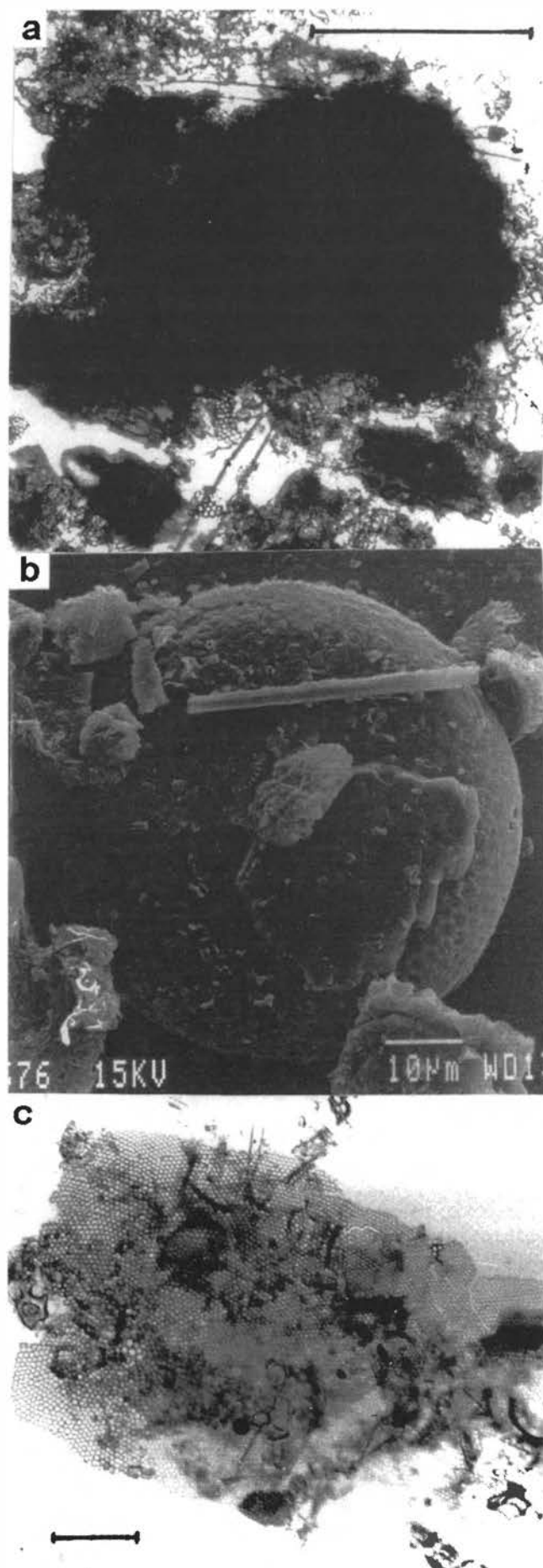
by the coexistence of different silica phases throughout much of the sedimentary column.

Diatom preservation and silica diagenesis

Diatoms dominated the biosiliceous assemblage in the Oligocene sediments even though sponge spicules and radiolarians are generally more resistant to dissolution. The occurrences of diatom fragments, sponge spicules, silicoflagellates and radiolarians were noted separately and are presented in Table 1. All the samples analyzed in the Upper Oligocene (CSS-4) section contain diatom frustules (opal-A), and as deep as approximately 1550 m, in Lower Oligocene sediments, diatom fragments of opal-A and sponge spicules were observed. Relatively well-preserved frustules of *P. thybergii* are illustrated in Fig. 7a and a generally good preservation of the silica assemblage is shown in Fig. 7b from well 30/3-3 at 1000 m depth. The silica-rich sediment was, however, mainly composed of diatom fragments (Figs. 7c, d).

Coincident with early dissolution, reprecipitated silica occurs as overgrowths as seen on *P. thybergii* (Figs. 5c, d), also often observed as mildly deformed frustules in the same samples (e.g. Figs. 5a, b). Surface irregularities (i.e. ornamentation) and the more porous tests are preferential sites of dissolution (Hurd 1973, 1983; Kastner et al. 1977; Hurd & Birdwhistell 1983; Iler 1979), resulting in local precipitation of a slightly less soluble phase (opal-A' phase?). There seems to be a tendency for reprecipitation (deformation) to start at the mantle edge as illustrated in Fig. 5c. Mildly deformed *P. thybergii* were found as deep as 1430 m in well 34/7-1 (Fig. 5c), where some dissolution and reprecipitation of the diatom has occurred. Correspondingly, extensive overgrowth of a *P. thybergii* was, for example, observed in well 30/3-3 at 1350 m depth.

An even higher degree of deformation and dissolution of biogenic silica was observed particularly in well 36/1-2 at present-day depths of approximately 600–780 m, as illustrated in Figs. 8a, b. In general, well 36/1-2, which is the northernmost well studied, close to western Norway (Fig. 1), and in a part of the basin that was uplifted (Rundberg 1989; Jordt et al. 1995), shows the highest degree of



cementation (Figs. 8a, b). At the stage of deformation and reprecipitation shown in Fig. 8b, the frustules are almost unrecognizable due to the overgrowth of silica. However, diverse and relatively well-preserved diatoms (opal-A) have also been observed in well 36/1-2 (Fig. 6). It is possible that the precipitate in this case was an opal-A' phase, since the opal-CT content is below the XRD detection limit (Fig. 9a). Well 36/1-2 was therefore probably not buried deep enough or long enough for opal-CT to form.

X-ray diffraction analysis of wells located in the deeper part of the basin, well 34/7-1 detects no opal-CT (Fig. 9b), but petrographic studies indicate silica cementation (e.g. Figs. 8a, b). Thus, in general the silica-'cement' we observe probably represents an opal-A' phase.

Our observations also indicate that the biogenic silica (opal-A) dissolves and reprecipitates locally, probably within micrometers to millimeters. However, the overgrowth layer is so thin that we can still observe details in diatom frustules. Hein et al. (1978) have defined a phase (opal-A') which occurs at lower temperatures than the opal-CT phase and which represents a transitional step towards the formation of opal-CT. They identified this early diagenetic phase when the sediments had no obvious diatom frustule fragments but had an XRD pattern like opal-A, and therefore opal-A' is interpreted to be morphologically distinct from opal-A. The low abundance of opal-A' suggests rapid growth of the newly formed crystallites with subsequent formation of opal-CT (Hein et al. 1978).

Opal-CT forms cement (massive), or lepispheres and blades if suitable open spaces are available (e.g. Hein et al. 1978; Riech & von Rad 1979). In this study we have mainly observed silica overgrowths (Figs. 5c, d) or 'massive' cement (Figs. 8a, b), and only rarely small lepispheres. The reason lepispheres have not been observed may be that the transformation from opal-A to opal-CT has not reached the stage of lepisphere formation. Lepispheres are observed at the interface between massive opal-CT and open pore space, and have been observed to grow with time (Compton 1990). We have therefore interpreted the silica overgrowth observed in the Oligocene sediments in the northern North Sea as mainly opal-A'. This is because although silica cementation has been identified in SEM, opal-CT has not been detected on XRD and lepispheres have seldom been identified petrographically. Another reason for the lack of lepispheres could be that *Coscinodiscus* spp., demonstrated by Hein et al. (1978) to act as a nucleation point for lepispheres, is not transformed to opal-CT in the northern North Sea. A dominance of diatom fragments at the beginning of opal-

Fig. 4. Examples of observed development. (a) Light microscope photograph showing silica aggregates and debris (well 30/3-3, 1200 m). Scale bar = 100 µm. (b) SEM photograph of *Coscinodiscus* sp., commonly observed in the diatom assemblages (well 36/1-2, 760 m). The specimen is partly covered by a thin overgrowth of silica, particularly in the central part, but fine and detailed structure of the skeleton is also observed. (c) Light microscope photograph showing *Coscinodiscus* spp. fragment and silica debris (well 31/6-8, 620 m). Scale bar = 100 µm.

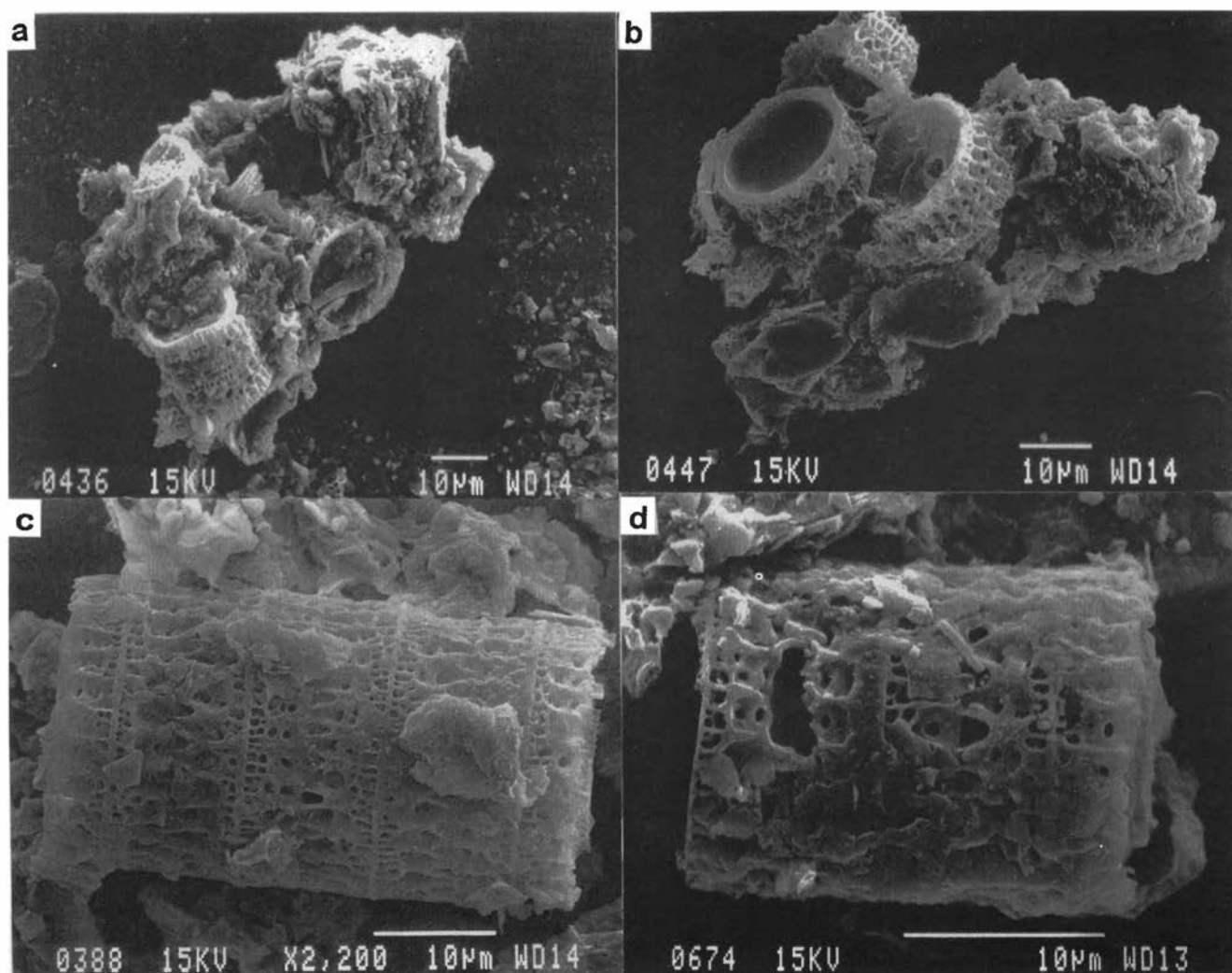


Fig. 5. Aggregates and deformation/dissolution stages of diatoms (*P. thybergii*) in SEM. (a) Silica aggregate and mildly deformed *P. thybergii*, well 30/3-3, 1250 m. (b) Silica aggregate and *P. thybergii*, well 30/3-3, 1000 m. (c) Early dissolution stage of *P. thybergii*. Cell walls and areolae are beginning to dissolve, well 34/7-1, 1430 m. (d) A relatively high degree of dissolved *P. thybergii* with silica overgrowth, well 36/1-2, 760 m.

CT formation has also been reported by Roaldset & Wei (1998a), and this is in agreement with our observations. Correspondingly, at the stages of maximum yield of opal-CT, they have not observed biogenic fragments. Both XRD data, which in most of the studied samples often shows very little evidence of opal-CT, and SEM studies, which show the occurrence of diatom frustules, therefore indicate an early stage of opal-CT formation. If the formation of lepispheres occurs late in the opal-CT stage, their very rare occurrence in the Upper Oligocene sediments also supports the interpretation of a generally low degree of opal-CT formation. Roaldset & Wei (1998a) have also reported signs of dissolution of diatoms and precipitation of a phase of non-biogenic amorphous silica (opal-A'). The silica phases present in the Upper Oligocene sediments in the northern North Sea are probably therefore opal-A, opal-A' and in some wells, e.g. well 30/3-3 (which will be discussed in more detail later), also opal-CT. We have so far only one high abundance biogenic sample from well 31/6-8, (620 m), where opal-A', and opal-CT, may act as cement-forming silica aggregates (Figs. 5a, b). Sample

1250 m in well 30/3-3 is characterized by the presence of silica aggregates, but still, relatively well-preserved diatoms are present. *P. thybergii* as opal-A is commonly observed as shown in Fig. 5a, where small lepispheres may also be seen. Well 30/3-3, 1350 m also shows a relatively high degree of massive cementation but fine structures and biogenic silica are still seen.

Our observations therefore indicate the coexistence of opal-A/opal-A' and opal-CT, particularly in the deeper part of well 30/3-3. In depths above the opal-A/opal-CT boundary, and in the other wells presented from the northern part of the study area, opal-A and opal-A' occur together. In well 34/7-6, in which no detectable amounts of opal-CT have been recorded on XRD, opal-A and opal-A' are also interpreted to co-exist.

Silica diagenesis and seismic velocity

The presence of opal-CT in well 30/3-3 is indicated by the XRD pattern (Fig. 9a), although limited to the Upper

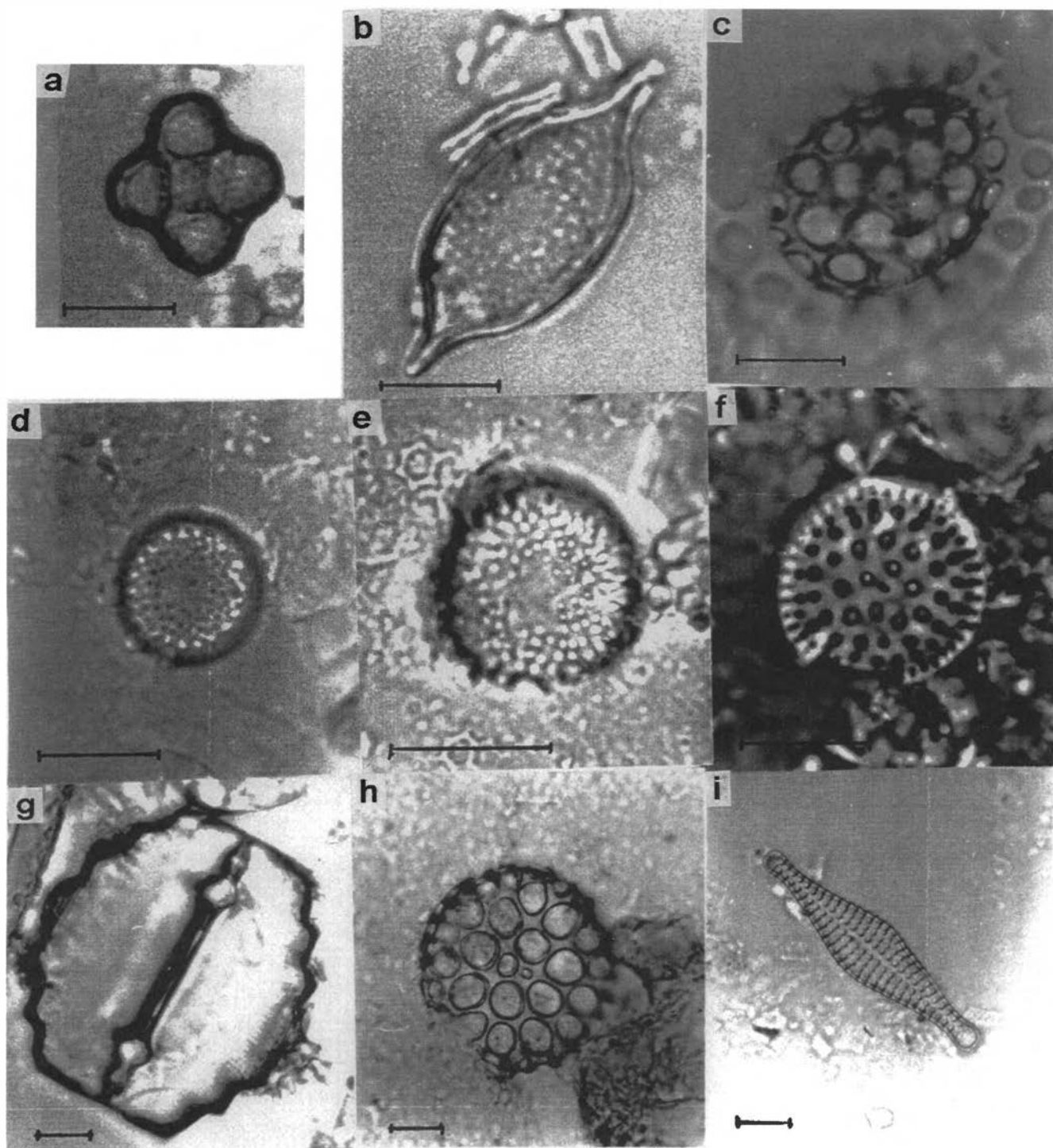


Fig. 6. Commonly observed diatom species used biostratigraphically. Scale bar always = 10 µm. (a) *Lisitzina ornata* (well 36/1-2, 720-730 m). (b) *Cymatosira praecompacta* (well 36/1-2, 720-730 m). (c) *Pseudorocella barbadensis* (well 36/1-2, 840-850 m). (d) *Melosira architecturalis* (well 36/1-2, 620-630 m). (e) *Melosira architecturalis* (well 36/1-2, 640-650 m). (f) *Rocella praeinitida* (well 36/1-2, 910-920 m). (g) *Goniothecium odontella* (well 36/1-2, 720-730 m). (h) *Rocella vigilans* (well 36/1-2, 610-620 m). (i) *Sceptrotroneis propinqua* (well 36/1-2, 880-890 m).

Oligocene interval (Fig. 10). Investigations in SEM show that opal-A is still present over the same depth interval. In well 30/3-3 (Fig. 10) a rather good correlation is seen between an increase in seismic velocity, a slight reduction in relative abundance of diatoms, the first occurrence of opal-CT and a marked seismic reflector. This seismic reflector is interpreted as an increase in seismic velocity

(Fig. 10) caused by the diagenetic transformation of opal-A to opal-CT, which may give rise to a sharp acoustic impedance contrast. Experimental studies show that the opal-A to opal-CT transformation is accompanied by marked changes in volume density, porosity, grain density, mechanical strength, and sonic velocity (Roaldset & Wei 1998a). Our investigations indicate that we are observing

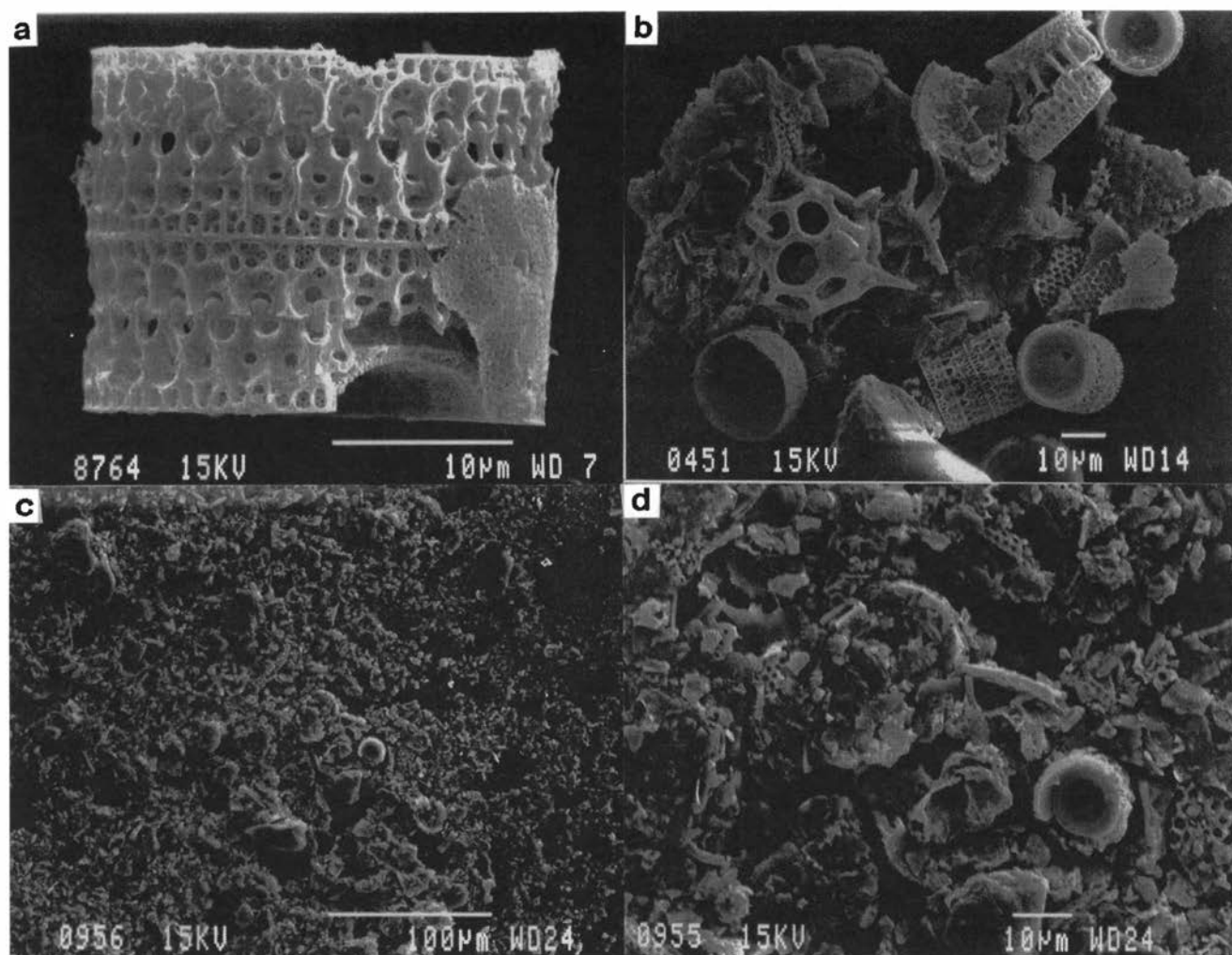


Fig. 7. Examples of biogenic silica content in studied sediments. (a) SEM photograph of a well preserved *P. thybergii* (well 30/3–3, 1000 m), the most characteristic and dominant diatom species observed in Oligocene sediments in the northern North Sea. (b) Common siliceous constituents in Oligocene sediments in the northern North Sea, showing *P. thybergii*, *Stephanopyxis* sp., silicoflagellate, and other silica fragments (well 30/3–3, 1000 m). Note: sieved sample. (c) Silica debris (well 30/3–3, 1200 m). (d) Detail of (c) (enlarged).

an early stage in the opal-CT formation, as also indicated in the XRD diagram (Fig. 10), which, according to Roaldset & Wei (1998a), is the stage where most physical changes occur. Correspondingly, according to Williams et al. (1985), the changes in rock properties are not abrupt boundaries, but happen very gradually through the rock column owing to the fact that opal-A to opal-CT transformations do not occur instantaneously throughout a sedimentary sequence.

In well 30/3–3 a strong horizontal reflection crosscuts the CSS-3/CSS-4 sequence boundary (Fig. 10). Reflectors crosscutting stratigraphic horizons have been documented in the Barents Sea (Riis & Fjeldskaar 1992) and in the Vøring Basin (Blystad et al. 1995) and also in the northern North Sea in wells 30/3–3 and 31/2–5 (Rundberg 1989). This is explained as an increase in seismic velocity due to the transformation of opal-A to opal-CT at a relatively constrained depth. Rundberg (1989) has reported a marked vertical increase in opal-CT in well 31/2–5 and well 30/3–3 at the stratigraphic level corresponding approximately to the CSS-3/CSS-4 boundary in our study. In

blocks 30 and 31 in the northern North Sea opal-A and opal-CT transitions have mainly been identified in the Lower Oligocene and close to the Oligocene–Eocene boundary (Gran 1989). Also in well 25/7–2, opal-A and opal-CT have been reported in Lower Oligocene and Upper Eocene sediments (Tyridal 1994).

Discussion

The diatom assemblage in the studied wells is distinctly different from that reported from the Balder Formation (Malm et al. 1984) and from the Fur Formation in Jutland (Hohmann 1991, Fenner 1994). The diatom flora in the Fur and Balder Formations is believed to have been deposited in a deeper marine environment than the Oligocene diatoms in the northern North Sea. The distinct differences in diatom floras between the Paleocene–Eocene and Upper Oligocene strata demonstrate that reworking of Paleocene–Eocene siliceous sediments could not have occurred. Studies from onshore Denmark also demonstrate this

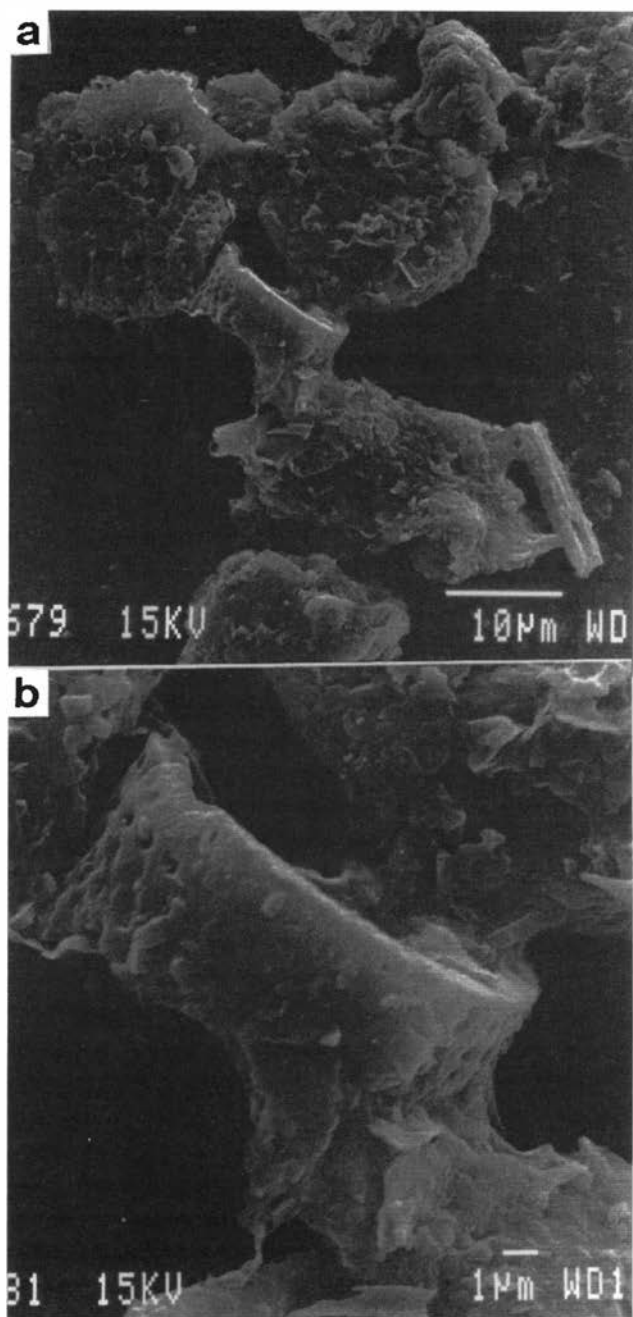


Fig. 8. Deformation and reprecipitation of biogenic silica (well 36/1–2, 760 m). (a) Overview. (b) Detail of (a) (with *Paralia* sp.).

(Heilmann-Clausen 1994). It is interesting to note that the main differences between the Fur (Balder) Formation diatomites and these Oligocene deposits are the composition of the diatom floras and the fact that the diatoms in the investigated northern North Sea Oligocene deposits are more diagenetically altered than those in the onshore Fur Formation.

Paralia thybergii probably indicates a nearshore setting if extinct *Paralia* species, such as *Paralia thybergii*, reflect the same environment as the presently living *Paralia sulcata*. *Paralia sulcata* is a marine, tycho planktonic, coastal species, commonly found in the North Sea today

(Stabell 1985; Stabell & Lange 1990). The Oligocene deposits also commonly contain *Chaetoceros* resting spores and *Stephanopyxis* spp., which also indicate a nearshore environment. The extensive glauconite-rich sands of the Skade Formation (Fig. 11) which prograde into the western part of the northern North Sea (Isaksen & Tonstad 1989; Knox & Halloway 1992) indicate clastic sediment starvation and shallow marine conditions in Late Oligocene to Miocene times. This glauconitic sandy facies interfingers with a mud-rich diatomaceous facies as demonstrated in well 34/7–1 (Thyberg et al. 1998a). Poorly sorted, immature and angular clastic grains in certain beds in well 34/7–1 (Thyberg et al. 1998a) also indicate periodic local clastic sediment supply from basement rocks or Mesozoic sediments into a shallow marine basin (Thyberg et al. 1998a). Seismic evidence supports the mineralogical and sedimentological evidence; that reduced clastic supply and low onshore topographic relief existed in the northern North Sea in the Late Oligocene (Jordt et al. 1995; Jordt 1996), and confirms a sediment-starved basin.

The highest abundance, most diverse flora and best-preserved siliceous microfossils have been found in calcareous concretions within the Fur Formation (Mitlehner 1996) and the Balder Formation (Malm et al. 1984), where the early formation of calcite cement may prevent the effect of burial and diagenesis. However, in this study, biosilica-rich sediments are commonly observed in the Upper Oligocene and fragments of diatom frustules (opal-A) have been observed as deep as approximately 1550 m, in most cases these sediments are not carbonate cemented, although carbonate cemented layers containing high concentrations of biogenic silica have been found, as exemplified at 1000 m and 1100 m in well 30/3–3 (Thyberg et al. 1998a). The abundance of biogenic silica irrespective of carbonate cementation indicates that the preservation potential for the Upper Oligocene siliceous sediments was high due to high productivity or deposition of heavily silicified diatom frustules, since sea water is mostly undersaturated with respect to silica (Lisitzin 1972; Heath 1974). The intervals of high content of carbonate also indicate high production of calcareous organisms together with high production of siliceous organisms.

Upper Paleocene and Eocene siliceous sediments contain ample evidence of volcanic ash falls, but volcanic activity in Oligocene time has not been reported in earlier published literature. Thus, smectitic mudstones probably representing reworked volcanic sediments with a basaltic composition are an important component of the clastic sediment supplied to the northern North Sea in Late Oligocene time (Thyberg et al. 1998a, b). There is also an enrichment of trace elements such as Ni, Cu, Co and Zn and Ti and Fe, although the general trend is that the Upper Oligocene sediments have lower concentrations of these elements than the underlying Tertiary sediments, indicating a mixed clastic source. The good preservation of siliceous microfossils could therefore reflect both a dominance of robust diatom frustules, which are rather

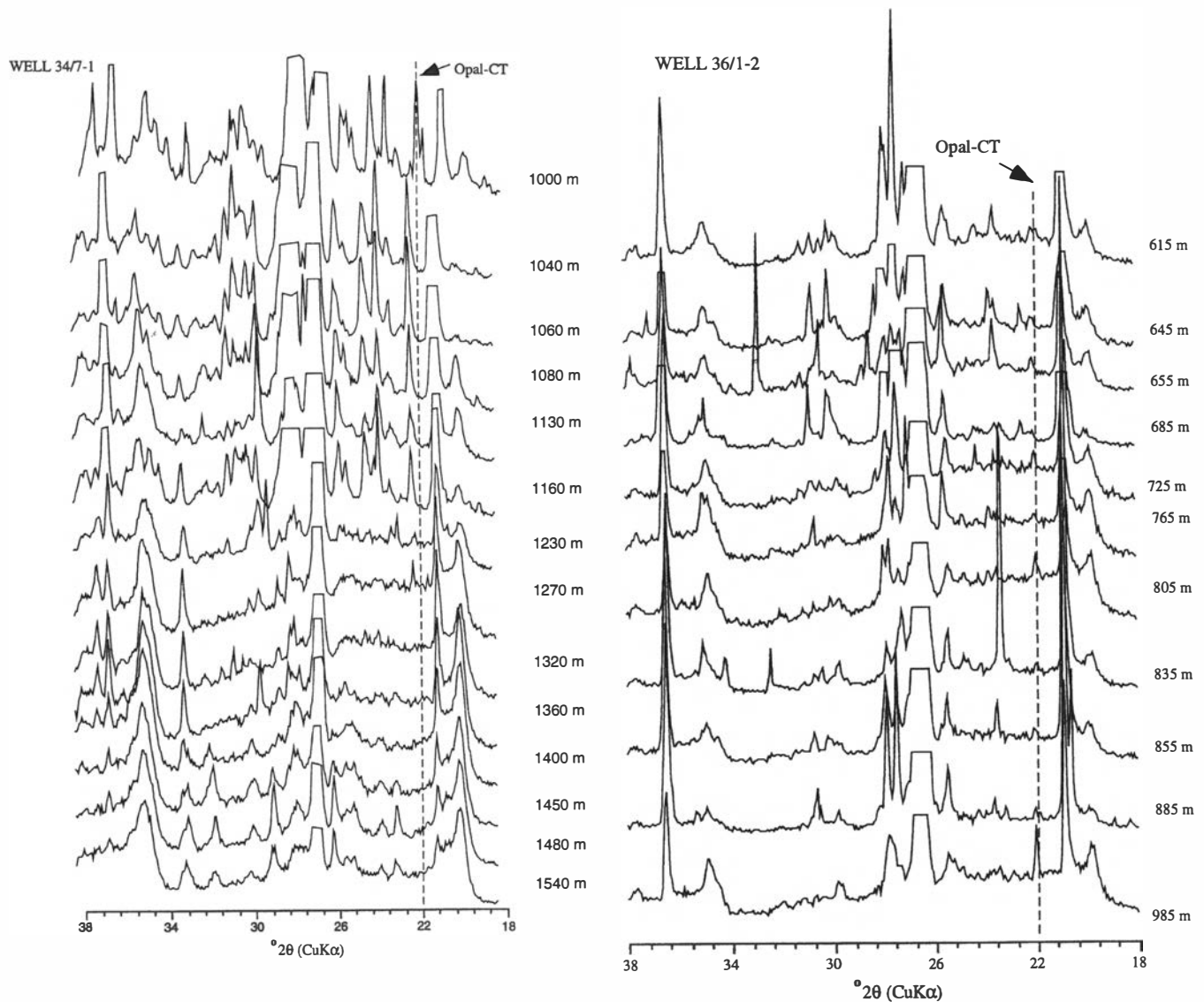


Fig. 9. XRD bulk analysis indicating that opal-CT is below detection limit in sediments of Oligocene age. (a) Well 34/7-1. (b) Well 36/1-2.

resistant to dissolution, and porewaters saturated with respect to silica due to reworked volcanic material, such that dissolution of siliceous microfossils was inhibited. Preservation of these biosiliceous sediments is also interpreted to indicate the presence of highly productive surface waters, as surface water productivity, by controlling the supply rate of siliceous valves to the seafloor and the silica saturation level of the pore waters, exerts a primary control on the abundance of siliceous microfossils in the sediments (Schink et al. 1974; Broecker & Peng 1982; Pokras & Molino 1986).

The occurrence of abundant diatoms is, however, generally related to upwelling. In modern coastal areas high diatom production corresponds to areas of upwelling with a high concentration of nutrients (Lisitzin 1972; Heath 1974). The Upper Oligocene diatom-rich beds may therefore mainly be associated with periodic upwelling as indicated by the interlayering of diatomaceous facies and glauconite beds in well 34/7-1 (Thyberg et al. 1998a).

However, wells 25/7-2 and 26/4-1, located approximately at 60°N (Fig. 1) contain much smaller amounts of biogenic silica than are documented in the northernmost part of the study area, and in well 24/6-1 no biogenic silica was observed. During the Late Oligocene the area of widespread and abundant biogenic silica deposition may therefore have been confined to the northern part of the North Sea which contained a relatively shallow, clastic sediment-starved basin with upwelling. A regional N-S section in the North Sea (Fig. 12, Line C, Jordt et al. 1998) shows that a structural high was formed between 60 and 61°N in approximately mid-Oligocene time. The lower part of the Upper Oligocene sequence (CSS-4) onlaps the high on both sides, while the upper part of the sequence covers it. In mid-late Oligocene times this high probably represented a shallow water threshold between deeper, but still shallow, basins to the north and south; i.e. separating the northern North Sea basin from a basin further south. Gradstein & Bäckström (1996) discussed a pronounced

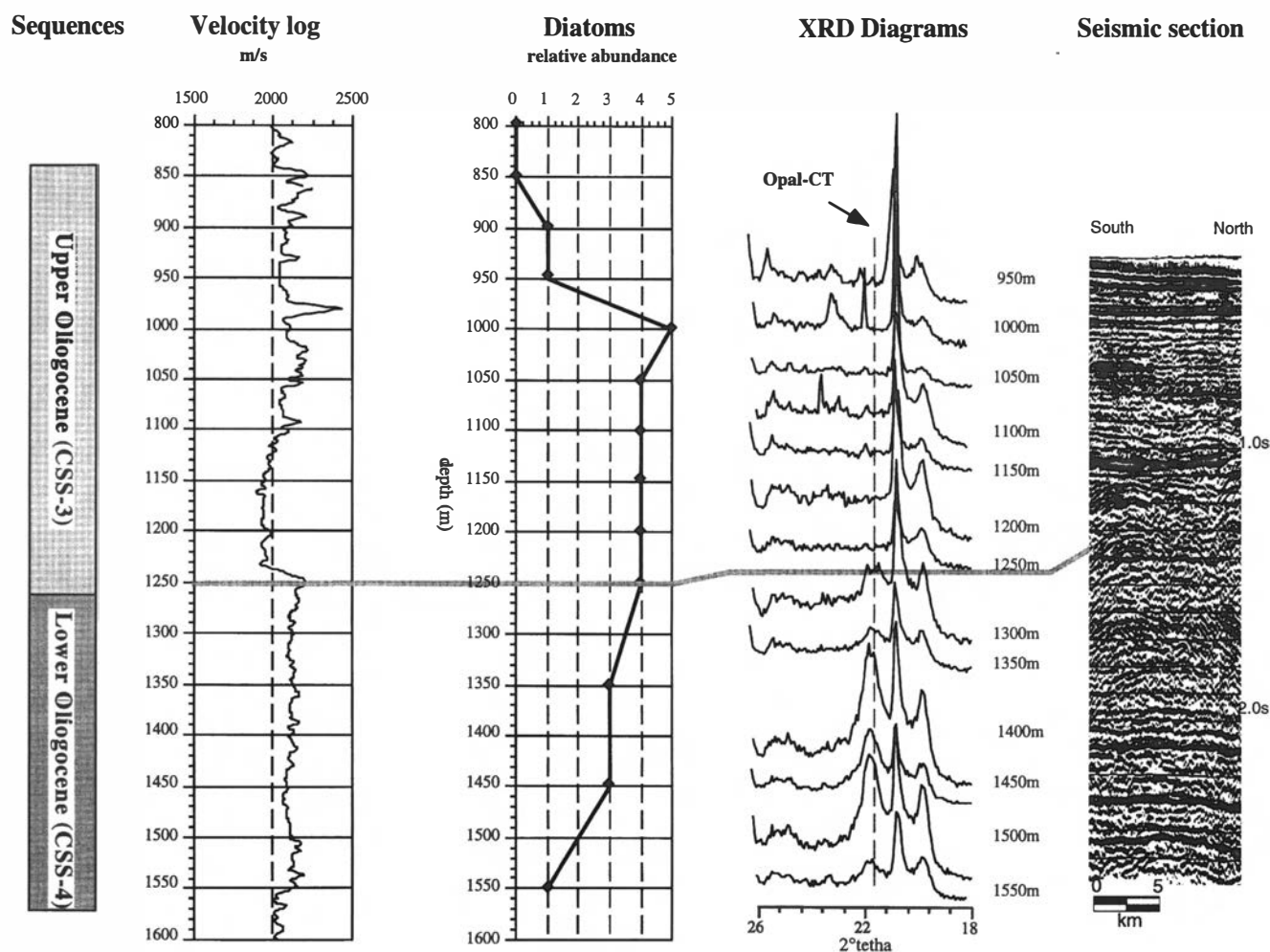


Fig. 10. Opal-A – opal-CT and diatom abundance correlated with velocity log and seismic section versus depth in well 30/3-3, CSS-3 & -4.

mid-Oligocene shallowing in the same area (Tampen Spur), which they attributed to eustatic shallowing, combined with uplift. They assume that the occurrence of a highly siliceous interval of Late Oligocene age reflects this local high between the North Sea and the Norwegian Sea, which probably inducing upwelling. We are uncertain about how far this high continues westward (Fig. 11). The southerly regional limit of biosiliceous sediments close to 60°N in Late Oligocene time is consistent with the paleogeographic development outlined by Rundberg et al. (1995), who suggested that a northern embayment of the North Sea probably existed at approximately 61°N in Late Miocene time. Seismic mapping also shows that a basin with a water depth of up to at least 800 m existed in the northernmost North Sea-Møre Basin area in mid-Oligocene time (Fig. 13a; Rossavik, 1993). Seismic data show an intra Oligocene shelf edge located 50–70 km off the present coastline north of 62°N (Line A, Fig. 13a; Rossavik, 1993). Sediments onlap a distinct paleo-slope and fill in a basin relief of at least 800 m. Miocene sediments cover the Oligocene sequence on both sides of the shelf edge. The Oligocene shelf-edge is difficult to trace southwards into the northern North Sea because glacial erosion during Quaternary times removed the Oligocene

upper slope and shelf sediments, (Line B, Fig. 13b). The Late Oligocene setting, a shallow marine northern North Sea, bounded by shallow shelf areas to the east and southwest, with a structural high located between 60 and 61°N and relatively deep waters in the northernmost North Sea-Møre Basin area, induced upwelling when the winds came from the south (Fig. 11). A pronounced biogenic silica facies of Late Oligocene to Early Miocene age offshore mid-Norway is interpreted (Gradstein pers. comm.) to reflect freshening surface waters and a paleobathymetry assigned as bathyal (at least several hundreds of meters deep), indicating that the mid-Cenozoic silica biofacies of offshore Norway is not solely of shallow marine origin. Weinelt & Thiede (1992), based their results on a previous study (Steurbaud et al. 1991), which reported the entry of very rich diatom associations in the Middle Rupelian interpreted to be due to the incursion of colder Arctic waters, resulting from important paleo-oceanographic changes in the Arctic area. As also indicated by Rundberg (1989), the combination of high organic productivity, low dissolution rate and reduced clastic sediment supply resulted in the concentration of biogenic silica. The area of silica concentration is constrained to the northern North Sea by the basin configura-

Upper Oligocene

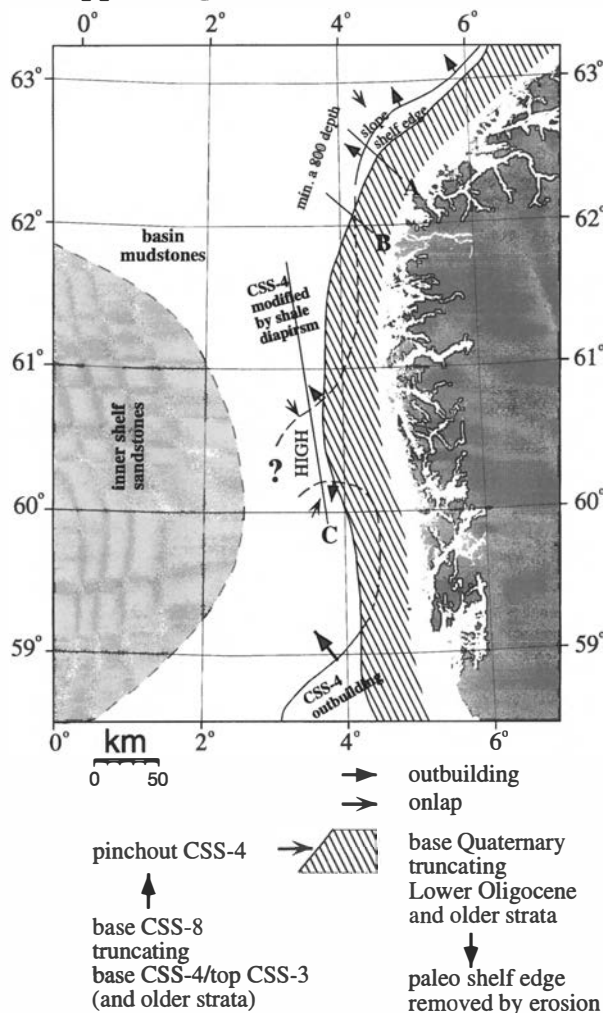


Fig. 11. Simplified Late Oligocene paleogeographic reconstruction of the study area indicating the shelf edge in the northernmost North Sea-Møre Basin, and a structural high close to 60–61°N (based on available published data).

tion and structural and depositional setting, which may also have promoted biogenic silica production by inducing upwelling.

Conclusions

Upper Oligocene (CSS-4) siliceous sediments in the northern North Sea are composed mostly of diatoms, with a dominance of the taxon *Paralia thybergii*, but also with sponge spicules and small amounts of silicoflagellates and radiolarians. Thus, by using standard methods for preparation of diatom samples an abundant diatom flora was found and this flora afforded useful information about both environment and stratigraphy.

This study demonstrates that opal-A and also probably opal-A' occur in sediments deposited in Late Oligocene time in the northern North Sea, indicating an early stage of silica diagenesis. Relatively well-preserved diatoms of opal-A were found down to burial depths of 1550 m. The phases also coexist with opal-CT over a limited stratigraphic interval, particularly in well 30/3–3.

The deepest occurrence of opal-A is an important indicator of the burial history. The fact that silica-rich layers occur at distinct stratigraphic horizons and the opal-A to opal-CT transformation varies laterally make it difficult to infer any post-Oligocene tectonic uplift based on the occurrence of opal-CT in the northern North Sea.

The siliceous sediments occur in a sequence of smectitic rocks but there is no direct evidence of volcanic ash. A clastic volcanic sediment source would probably produce laterally extensive smectitic deposits, enhancing the high degree of biogenic silica preservation in the siliceous deposits.

The sediments were probably deposited during a period of sediment starvation and upwelling in a north-south direction. The biogenic silica facies are present only in a limited number of wells. These wells are located in the northernmost part of the study area with the southerly extent constrained by a structural high located between 60 and 61°N, which can be used to indicate the lateral direction of upwelling.

The Late Oligocene basin configuration, which was characterized by relatively deep waters in the northernmost North Sea-Møre Basin area, shallowing towards east,

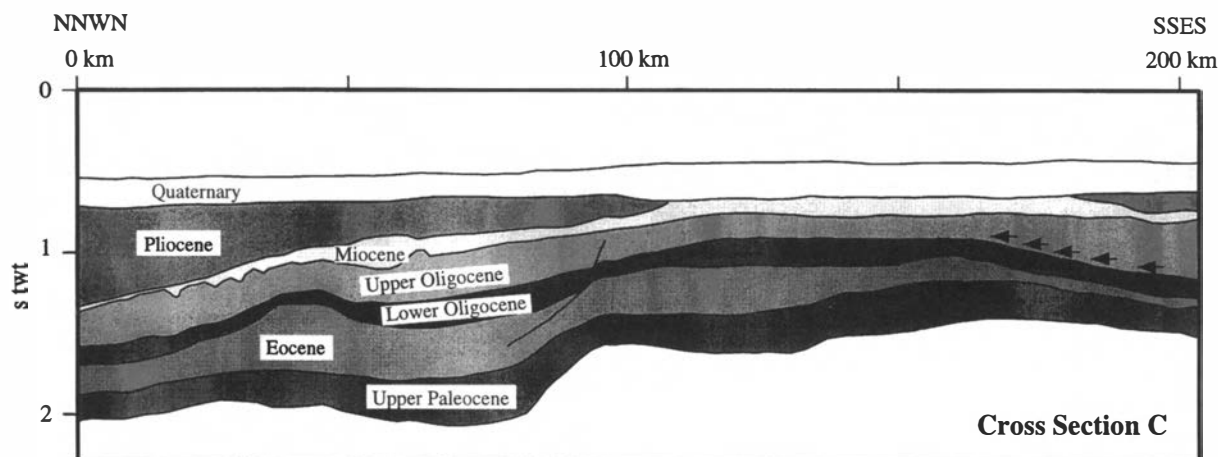


Fig. 12. A regional N-S line in the northern North Sea (Line C on Fig. 11) showing a high formed between 60–61°N at approximately mid-Oligocene time (Jordt et al. 1998).

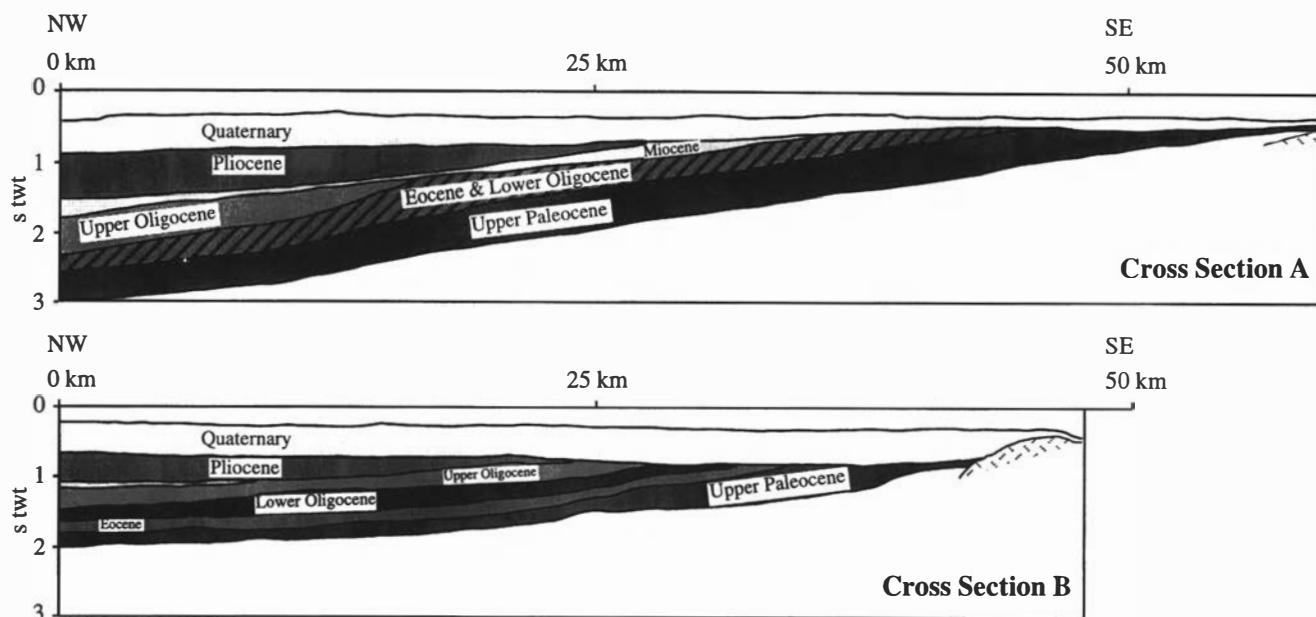


Fig. 13. (a) Seismic data showing an intra Oligocene shelf edge in the northernmost North Sea-Møre Basin. Sediments onlap a distinct paleo-slope and fill in a basin relief at least 800 m (Line A on Fig. 11, modified from Rossavik, 1993). (b) Line B on Fig. 11 (modified from Rossavik, 1993) showing that glacial erosion has removed the Oligocene upper slope and shelf sediments during Quaternary time and hence the Oligocene shelf-edge is difficult to trace southwards into the northern North Sea.

south and southwest, produced a setting for upwelling when the wind direction came from the south.

Preservation of the siliceous sediments reflects productive surface waters, a shallow basin and starved clastic sedimentation in the northern North Sea with an upwelling in a north-south direction.

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