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Clay mineral assemblages as a tool in source-to-sink studies: an example from the Lower Cretaceous of the North Sea Basin

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The alternating marlstone and chalk of the Lower Cretaceous succession in the Danish Central Graben (DCG) are important for the understanding of the evolution of the larger North Sea Basin. This study focusses on the clay mineral assemblages of the upper Hauterivian – lower Aptian in the DCG and Danish Basin (DB) and their implications. Clay mineral assemblages are predominantly used to assess palaeoclimate. In this study, however, they were additionally used in a source-to-sink context. Kaolinite was found to form a dominant component of the clay mineral assemblage in the sampled wells of the DCG and in the DB, suggesting that a feldspar- or kaolinite-rich source was present and actively eroded in the region during the Early Cretaceous. Moreover, a decreasing gradient west to east of average kaolinite content is observed in the three studied wells for the early Hauterivian to late Barremian (BC9-BC17), with the highest content observed in the North Jens-1 well (av. 74%), followed by the Boje-2C well (av. 49%) and lastly in the Vinding-1 well (av. 39%). Due to the relatively rapid settling of kaolinite in marine environments compared to other clay minerals, this gradient suggests that the main clay mineral source was located in the south-western part of the DCG. Isochore maps, a new palaeogeographic map of the DCG and the western part of the German sector of the North Sea illustrates where Lower Cretaceous rocks are absent in this region, due to either erosion or non-deposition. Potential subaerially exposed highs included the distant Baltic Shield to the north, the Ringkøbing–Fyn High to the east and the Heno Plateau within the DCG, with the latter being located closest to the North Jens-1 well and containing feldspar-rich sandstones of the Heno Formation (upper Kimmeridgian – lowermost Volgian/Tithonian). During the Early Cretaceous, part of the Heno Formation was potentially subaerially exposed or subject to wave reworking/erosion in parts of the Danish and German sectors. The sandstones could weather into kaolinite and this structural high is therefore suggested to have been the main source area for this part of the DCG, with minor sediment influxes from the Ringkøbing–Fyn High and Baltic Shield. In addition, the overall decrease in kaolinite in the DCG from the late Hauterivian to the late Barremian indicates a climatic change towards drier conditions, with some minor, slightly more humid periods.

Keywords: Barremian, Danish Central Graben, Heno Plateau, kaolinite, source-to-sink, Tuxen Formation.

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The Lower Cretaceous succession in the Danish Central Graben (DCG) has been studied to better understand the tectonic (Vejbæk 1986; Japsen *et al.* 2003; van Buchem *et al.* 2017), palaeoecological (Jeremiah 2001; Mutterlose & Bottini 2013), palaeoceanographic (Mutterlose & Böckel 1998) and palaeoclimatic (Chenot *et al.* 2018; Blok *et al.* 2022) basin evolution. The succession is characterised by alternating marlstone and chalk, composed of pelagic calcareous nannofossils, micritic grains and hemipelagic detrital material (Ineson 1993). A systematic study of the carbonate facies has recently been conducted (Jelby *et al.* 2022). However, the exact geographic origin of the detrital material, specifically of the clay minerals that were transported into the DCG, remains largely unknown.

New high-resolution clay mineral data are presented here from the offshore Boje-2C well (DCG) and the onshore Vinding-1 well (Danish Basin; DB). Generally, clay mineral assemblages are used to interpret palaeoclimate, as the type of clay minerals formed in soils is influenced by climate. Illite, for example, is prone to form in dry conditions, whereas kaolinite normally forms in humid conditions (Singer 1984; Chamley 1989; Ruffell *et al.* 2002). In this study, however, the notably large amount of kaolinite permits these data to, in addition, be utilised as a tool in a source-to-sink analysis. An Early Cretaceous palaeogeographic map is presented, showing Lower Cretaceous successions in the basins and absent intervals in surrounding areas (Figs 1, 7). In several areas, Lower Cretaceous strata were very thin or absent and those areas were likely subject to erosion and/or non-deposition (Jensen *et al.* 1986; Vejbæk 1986; Vejbæk & Andersen 2002; Japsen *et al.* 2003). These areas are evaluated on their location and lithological properties, as they could qualify as source areas for the basins. If these structural highs contain sandstones with diagenetic kaolinite or are rich in feldspars, kaolinite would potentially have washed out into the basin (Exley 1976; Chamley 1989; Lanson *et al.* 2002). The gradual differences between amounts of kaolinite in the two newly studied wells and the North Jens-1 well (Blok *et al.* 2022) are used to determine the main source area.

The aim of this study is to evaluate potential source areas for detrital material and the transport directions into the DCG. Structural highs that have previously been proposed as potential source areas for the DCG are the Baltic Shield (Olivarius *et al.* 2015), the Ringkøbing–Fyn High High (Mørk *et al.* 2003; Olivarius *et al.* 2015) and the Heno Plateau (Weibel *et al.* 2020). The presented study provides a better spatial constraint on the Early Cretaceous palaeogeographic evolution of the DCG and DB.

Basin configuration and lithostratigraphy

The Danish Central Graben (DCG)

The Boje-2C and North Jens-1 wells are located in the DCG, in the western part of the Danish North Sea, which is part of the North Sea rift system that extends from offshore Norway and UK, southwards towards the Dutch offshore area (Fig. 1). Intense Jurassic rifting, with NNW–SSE-orientated faulting, was initiated during the Bajocian and continued into the Volgian (Tithonian) creating a system of half-grabens (Vejbæk 1986; Johannessen & Andsbjerg 1993; Johannessen 2003; Michelsen *et al.* 2003). Syn-rift subsidence first resulted in the deposition of middle Jurassic fluvio-deltaic sediments (Andsbjerg & Dybkjær 2003). As the subsidence rates increased during the late Kimmeridgian, and more accommodation space was created, the DCG was filled with the organic-rich marine mudstones of the Lola and Farsund Formations (Ponsaing *et al.* 2020). However, subsidence was less pronounced on the complexly faulted Heno Plateau, especially in the north shallow-marine sandstones might indicate that the water depths were shallower than in the rest

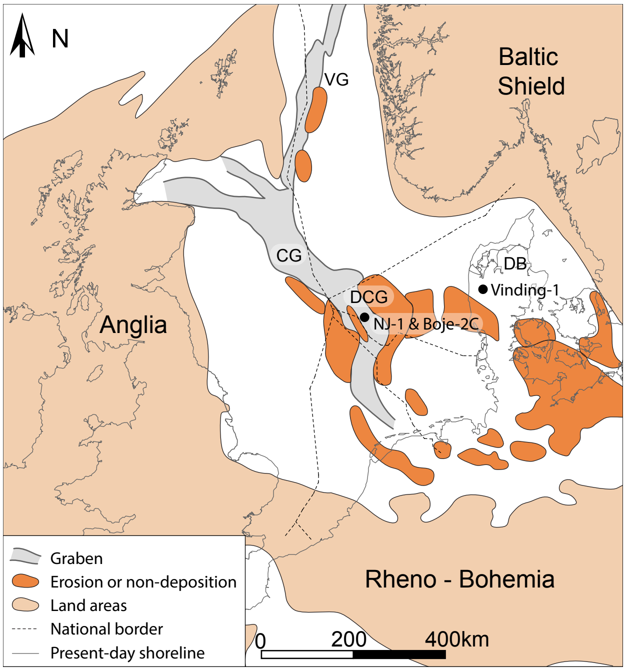

Fig. 1. Early Cretaceous palaeogeographic map based on Copestake *et al.* (2003), Mutterlose and Böckel (1998) and Lauridsen *et al.* (2022). The studied wells marked are areas of erosion or non-deposition during the Early Cretaceous are marked with a dark orange colour. NJ-1 = North Jens-1, VG = Viking Graben, CG = Central Graben, DCG = Danish Central Graben, DB = Danish Basin.

of the basin (Johannessen & Andsbjerg 1993; Johannessen 2003). In the late Volgian – early Ryazanian (late Tithonian – early Berriasian), turbidites of the Poul Formation and organic-rich mudstone of the Bo Member in the Farsund Formation were deposited (Jensen *et al.* 1986; Ineson *et al.* 2003; Ponsaing *et al.* 2020).

Cessation of rifting in the Ryazanian (Berriasian) led to the onset of thermal subsidence and the inherited Jurassic rift topography was filled with the Lower Cretaceous Cromer Knoll Group (Jensen *et al.* 1986; van Buchem *et al.* 2017). It consists of the Vyl, Valhall (including the Leek Member), Tuxen, Sola and Rødby Formations, with its lower boundary commonly referred to as the Base Cretaceous Unconformity (BCU; Fig. 2; Jensen *et al.* 1986; Kyrkjebø *et al.* 2004; van Buchem *et al.* 2017). The argillaceous Valhall Formation of Valanginian – Hauterivian age locally has a base of sands referred to as the Vyl Formation (Jensen *et al.* 1986; Ineson 1993; Vidalie *et al.* 2014). The Valhall Formation is overlain by alternating chalks and marlstones of the Tuxen, Sola and Rødby Formations (Ineson 1993). Deposition was influenced by phases of basin inversion beginning in the Hauterivian and peaking in the Late Cretaceous (Vejbæk 1986; Vejbæk & Andersen 1987, 2002; van Buchem *et al.* 2017). A period of reduced water circulation during the Barremian created anoxic conditions at the sea floor, resulting in preservation of organic matter and deposition of the Munk Marl Bed (Tuxen Formation; Thomsen 1989; Rudra *et al.* 2021). The Sola Formation includes the organic-rich Fischschiefer Member, which was deposited during the well-documented early Aptian Oceanic Anoxic Event 1a (OAE-1a; Arthur *et al.* 1990; Jenkyns 2010; Kuhnt *et al.* 2011; Föllmi 2012). A detailed study of late Hauterivian – early Aptian palaeoclimatic changes in the Boreal Realm, shows a long-term change from humid to more arid conditions for the late Hauterivian – late Barremian interval (Blok *et al.* 2022).

The Cromer Knoll Group has a maximum thickness of approximately 750 m in the DCG, but is absent in other parts of the basin (Vejbæk 1986; van Buchem *et al.* 2017). Compared to the homogeneous chalks of the Upper Cretaceous Chalk Group (Hardman 1982; Surlyk *et al.* 2003), the Lower Cretaceous is more argillaceous and organic-rich (Jensen & Buchardt 1987; Copestake *et al.* 2003). This paper is focussed on the uppermost Valhall Formation, the Tuxen Formation, including the Munk Marl Bed and the lower Sola Formation including the Fischschiefer Member (Fig. 2).

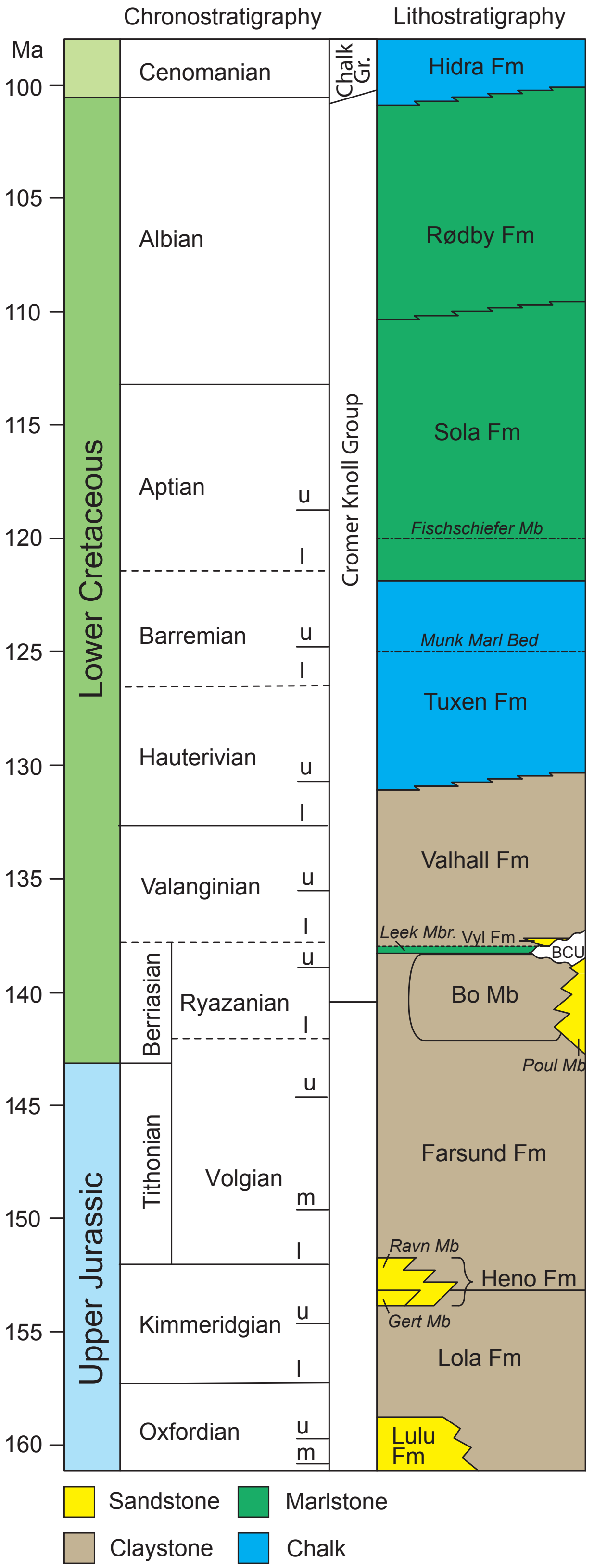

Fig. 2. Upper Jurassic – Lower Cretaceous chronostratigraphy and lithostratigraphy of the Danish Central Graben (modified after Jelby *et al.* (2022). Cretaceous chronostratigraphy is based on Gale *et al.* (2020). BCU = Base Cretaceous Unconformity.

The Danish Basin (DB)

The present-day position of the Vinding-1 well, onshore Denmark, corresponded to a shallow shelf area of the DB during the Early Cretaceous (Fig. 1;

Lauridsen *et al*. 2022). In the Early Cretaceous, the DB was bound to the northeast by the Fennoscandian Border Zone and to the south by the Ringkøbing–Fyn High (Nielsen 2003). Formation of the DB was initiated by crustal extension during the Late Carboniferous – Early Permian, followed by thermal cooling and subsidence that continued into the Late Jurassic, with a short regional uplift-event and associated erosion during the Early – Middle Jurassic (Vejbæk 1989; Nielsen 2003; Petersen *et al.* 2008). The basin continued to expand during the Early Cretaceous and as sea level rose, the upper Hauterivian – upper Barremian interval was dominated by siliciclastic material and became generally more enriched in pelagic carbonates. The Aptian succession varies between marlstone and chalk controlled by sea-level fluctuations (e.g. Ruffell 1991; Copestake *et al.* 2003). In the DB this stratigraphic interval is referred to the Vedsted Formation (Larsen 1966).

Methods and material

Sampling

Ten samples from core 25 of Vinding-1 (approx. 5 m) and 108 samples from cores 1–4 from the *c.* 80 m long Boje-2C core were selected for whole-rock and clay mineral analysis. The biostratigraphy of the Boje-2C core was based on calcareous nannofossils using the Boreal (BC) zonation scheme (Bown *et al.* 1998). A detailed sedimentological description of facies in the Boje-2C core is presented by Jelby *et al.* (2022). The chronostratigraphy and a lithological description of the Vinding-1 well are described by Lauridsen *et al.* (2022).

X-ray Diffraction (XRD)

Two grams of each sample were crushed and homogenised in an agate mortar for whole-rock mineralogy analysis. Approximately one gram of each sample was placed in a steel holder, analysed on the Thermo Scientific ARL Thermo X'tra diffractometer (Institute of Earth Sciences, University of Lausanne, Lausanne) and the mineralogy was quantified with a standard error between 5 and 10 % (Klug & Alexander 1974; Kübler 1983; Adatte *et al.* 1996).

For the clay mineral analysis, two grams of each sample were crushed into 0.2 – 0.5 mm chips, using an agate mortar. The rock chips were treated with 3% H_2O_2, to remove the main part of the organic matter (Righi *et al.* 1995). Separation and analysis of the clay fraction (<2 μm) was based on Kübler (1987) and Adatte *et al.* (1996), including decarbonation with 1.25N HCl and clay settling based on Stoke's law. Quantification of the clay mineralogy was conducted on oriented, air-dried, ethylene-glycolated smear slides which were measured on the Thermo Scientific ARL Thermo X'tra diffractometer, based on the methods of Kübler (1987) and Moore and Reynolds (1989) (Fig. 3). The error is minimised to less than 5%. The kaolinite/(illite + chlorite) ratio is used to indicate the significance of the weathering and is referred to as the weathering index (WI).

Results

The Boje-2C core spans the lower Hauterivian – upper Barremian nannofossil Zones BC9 to BC17 (Figs 4, 5; Gale *et al.* 2020). The whole-rock mineralogy of the Boje-2C well is presented in figure 3, showing that the amount of clay minerals varies between 6–50%, with an average of 24% (supplement 1). The most abundant mineral is calcite (32–89%, average 67%), followed by quartz (2–15%, average 5%) and pyrite (0–5%, average 1%). In some samples, traces of dolomite, gypsum or hematite were observed. Clay mineral analysis of the core shows that the most abundant clay type is kaolinite, varying between 30–73% with an average of 49% (Fig. 5; supplement 1). It is followed by illite, with a range of 9.0–33.6%, averaging 23%. The two least abundant types are illite/smectite (I/S) mixed layers (6–34%) and chlorite (5–21%), averaging 17% and 12%, respectively. Pure smectite is completely absent in the core.

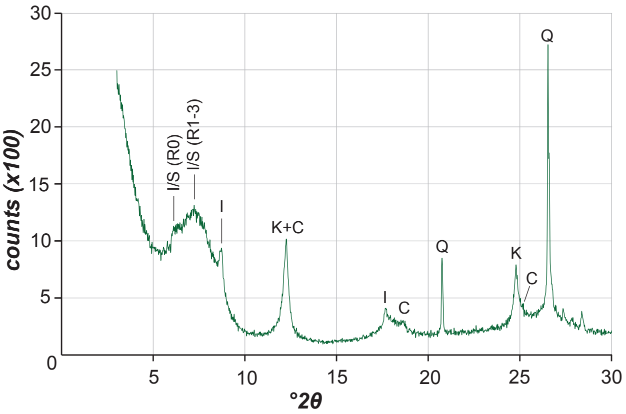

Fig. 3. Clay mineral X-ray Diffractogram (XRD) of sample Boje-2C #119. The diagram shows raw data of the intensity of the different clay mineral peaks. I/S = interstratified illite/smectite, I = illite, K = kaolinite, C = chlorite, Q = quartz. The peaks were quantified and this sample contains 34% kaolinite, 31% interstratified illite/smectite, 27% illite and 8% chlorite (supplement 1).

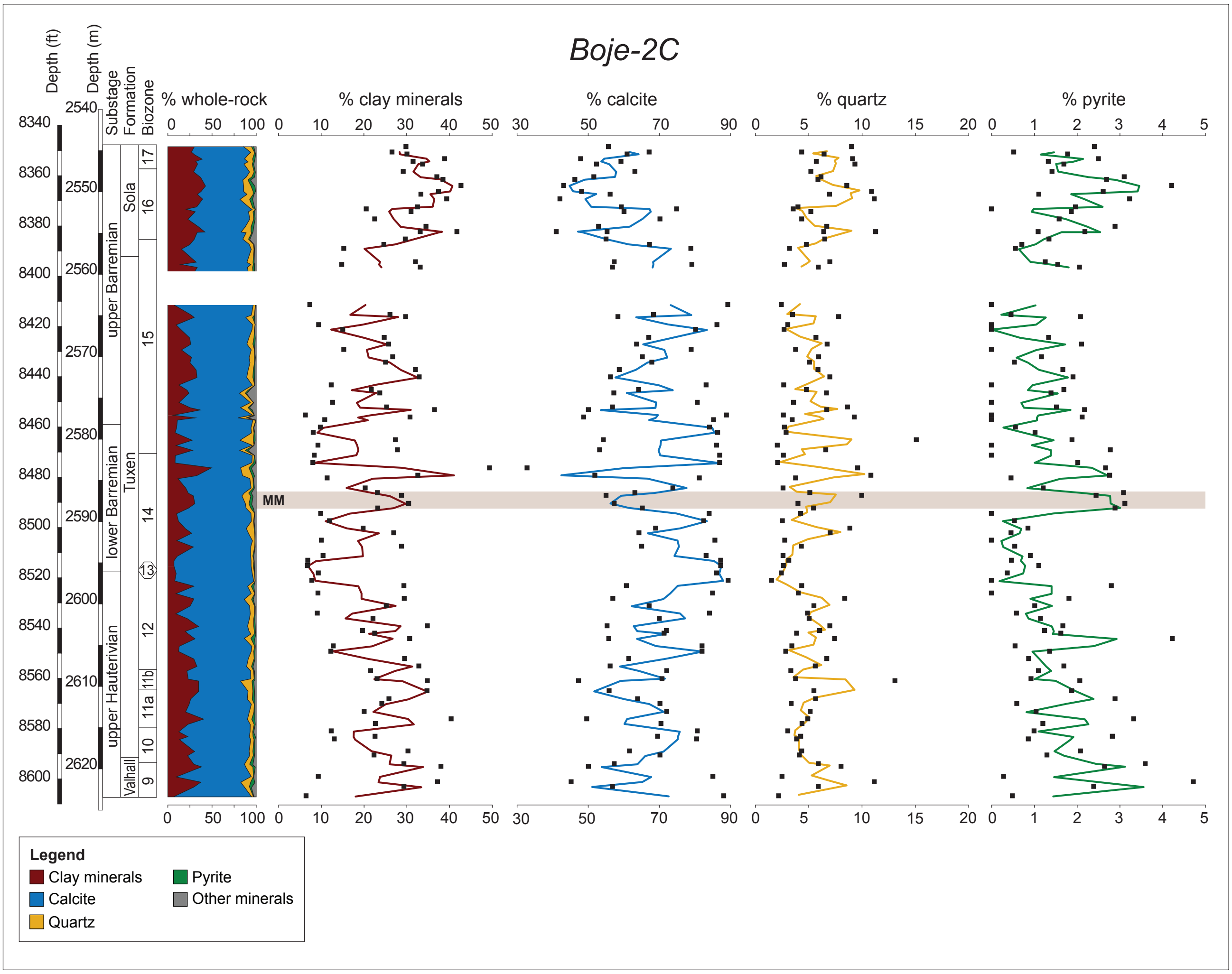

Fig. 4. Whole-rock mineral assemblages of the Boje-2C core, based on XRD analysis. 'Other minerals' include dolomite, gypsum, hematite and undefined minerals (supplement 1). The curves are based on a two-period moving average. MM = Munk Marl Bed.

The whole-rock mineralogy of the Vinding-1 well is dominated by calcite (35–90%), clay minerals (8–43%) and quartz (2–15%) (Fig. 6, supplement 2). In addition to small amounts of K-feldspar (0–4%) and Na-plagioclase (0–3%) traces of gypsum, pyrite, hematite and goethite are present in the core. The clay mineralogy of the upper Hauterivian – lower Aptian of the Vinding-1 well is dominated by kaolinite (20–53%), followed by I/S (9–44%) and illite (23–32%). Chlorite (5–14%) and smectite (0–4%) occur in small amounts in this core (Fig. 6, supplementary).

The trend lines of the kaolinite and WI curves in the Boje-2C well show similar trends, with a slight increase in nannofossil Zones BC9–BC11 (upper Hauterivian), followed by a decrease towards the Munk Marl Bed (BC14; lower Barremian) (Fig. 7). Just above the Munk Marl Bed, an increase in kaolinite in the upper BC14 and BC15 (lower – upper Barremian) is observed. This trend continues into BC16 (upper Barremian) for the WI, but the kaolinite percentage drops slightly in this zone.

Discussion

Significance of clay mineral assemblages

Impact of diagenesis

Evaluation of clay mineral origin and transport is essential in order to use clay mineral assemblages for palaeoclimatic or palaeogeographic reconstruction in the DCG and DB. Clay mineral assemblages could have been influenced by factors of detrital or authigenic nature (Chamley 1989). Two processes contribute to *in situ* clay mineral formation: i) diagenetic precipitation in pore spaces, and ii) recrystallisation due to increased pressure and/or temperature during

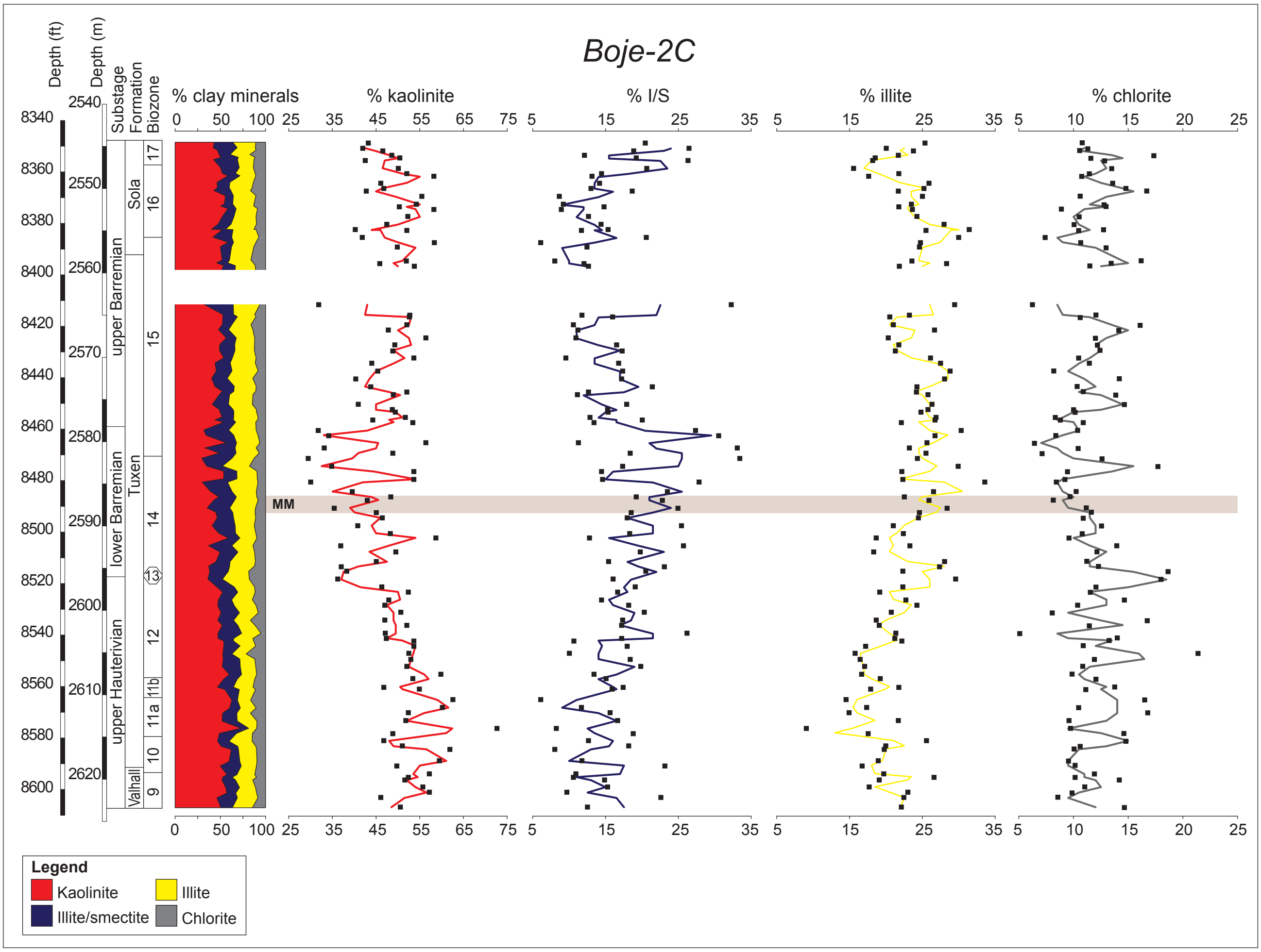

Fig. 5. Clay mineral assemblages of the Boje-2C core, based on XRD analysis. The curves are based on a two-period moving average. MM = Munk Marl Bed.

burial (Singer 1984). Authigenic clay mineral formation would clearly obscure the original detrital signal and therefore needs to be evaluated in the Boje-2C and Vinding-1 cores.

Illite, chlorite and kaolinite are known to form diagenetically in pore spaces due to fluid circulation, but this is more likely to happen in sandstones than in the low porosity and permeability marlstones and chalks of the Lower Cretaceous successions (Shelton 1964; Weaver 1990; Lanson *et al.* 2002; Jakobsen *et al.* 2004; Wilson *et al.* 2014). Scanning Electron Microscopy (SEM) images of selected North Jens-1 core samples have shown that the dominant kaolinite minerals have a detrital origin, based on their anhedral crystal shape (Blok *et al.* 2022). Due to the very similar lithologies in the Boje-2C well (Jelby *et al.* 2022), it is highly unlikely that diagenetic clay mineral precipitation took place in either well. Clay minerals in the Vinding-1 well also appear to have a detrital origin, as SEM images presented by Lauridsen *et al.* (2022) do not show any indication of authigenic clay mineral formation.

Burial diagenesis could result in recrystallisation of clay minerals during burial and pressure and/or temperatures increase (Curtis 1985). Illitisation of smectite could occur at depths greater than 2000 m (Burtner & Warner 1986). The Boje-2C samples were collected from depths of approximately 2540 to 2630 m and therefore subject to burial diagenesis (Fig. 4). At the present day, the Lower Cretaceous succession of the Vinding-1 well is found at a depth of *c.* 1300 m (Lauridsen *et al.* 2022), but burial history curves of nearby cores indicate that the succession has been exposed to a burial depth of approximately 2000 m (Weibel 1999). Smectite is completely absent in the Boje-2C core and only minor amounts were observed in the Vinding-1 core, and it is therefore highly likely that burial diagenesis has transformed smectite into mixed layers of illite/smectite type, similar to observations in the North Jens-1 core (Blok *et al.* 2022). Nevertheless, kaolinite is still present in large amounts, implying that burial diagenesis only had an overall limited effect (Fig. 5).

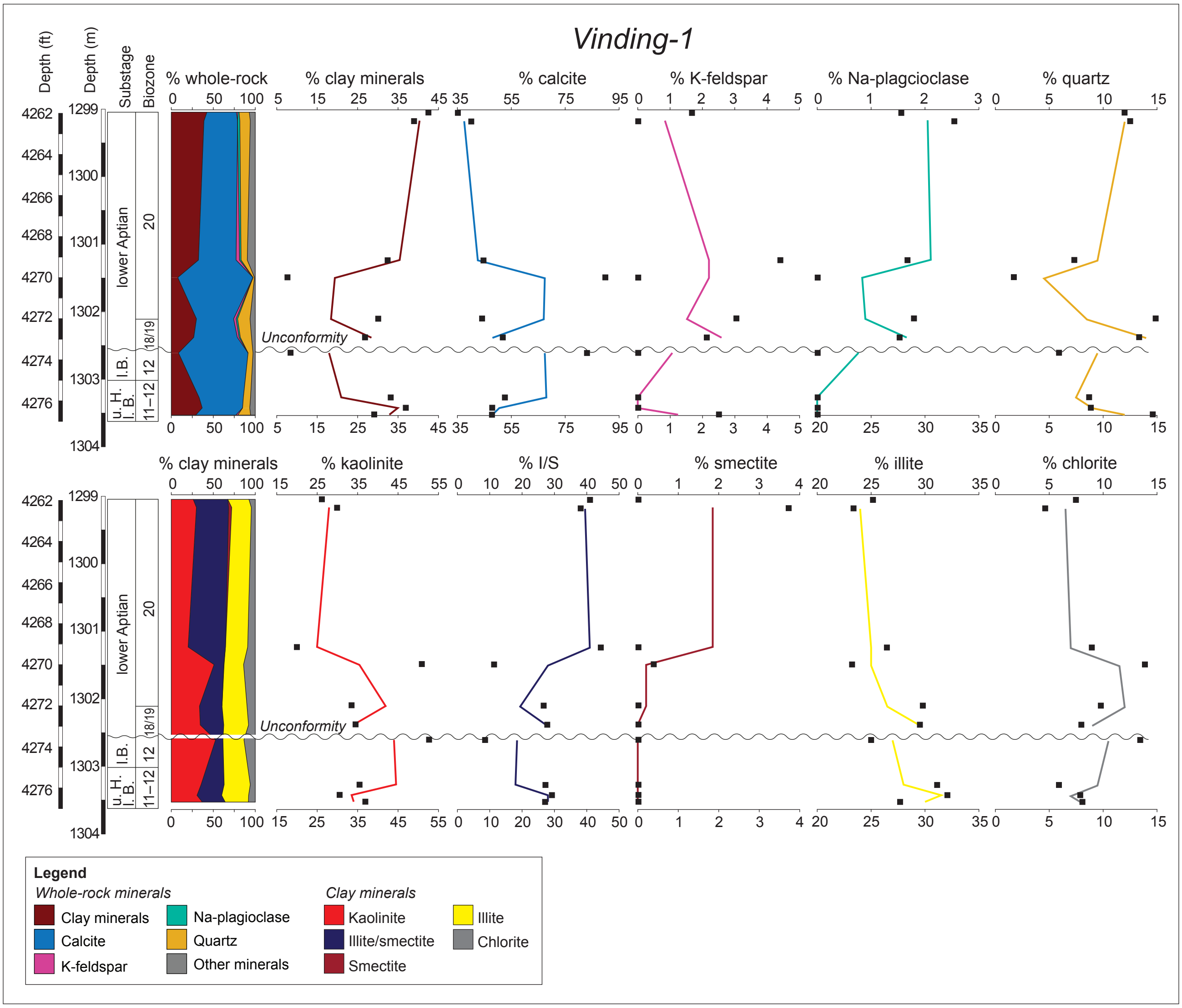

Fig. 6. Whole-rock and clay mineral assemblages of the Vinding-1 cores, based on XRD analysis. The curves are based on a two-period moving average. Chronostratigrahpy and biostratigraphy from Lauridsen *et al.* (2022). 'Other minerals' include gypsum, pyrite hematite, goethite and undefined minerals (supplement 2). u.H. = upper Hauterivian, l. B. = lower Barremian.

Detrital clay minerals

The clay mineral abundancies can be used to reconstruct palaeoclimate and palaeogeography, as authigenic clay mineral formation has been limited to transformation of smectite into I/S. Detrital clay minerals could have three different origins: i) they were formed in palaeosols under specific palaeoclimatic conditions (Chamley 1989; Ruffell *et al.* 2002), ii) they are the product of weathering feldspars in older sandstones, basement or volcanic rocks (Exley 1976; Keller 1978) or, iii) they were eroded from older diagenetically-derived clay minerals that were formed in porous sandstones (Deconinck *et al.* 2019). Detrital clay mineral assemblages can form a combination of the aforementioned formation processes, in which case the rate of erosion could be influenced by various factors. Relative sea-level fall can increase the area subject to erosion, resulting in enhanced erosion of detrital material. Changes in palaeoclimate to more humid conditions will intensify continental runoff and the amount of detrital material transported (Ketzer *et al.* 1999. A combination of these processes commonly affects transport of detrital material (e.g. Hallam *et al.* 1991; Adatte *et al.* 2002; Deconinck *et al.* 2019).

There are no indications of major eustatic sea-level fluctuations or tectonic uplift during the late Hauterivian – early Aptian in the DCG, that could have significantly influenced detrital transport to the basins (Haq 2014; van Buchem *et al.* 2017). Based on changes in clay minerals and nannofossil assemblages a long-term trend towards drier conditions in the late Hauterivian – late Barremian followed by a change towards more humid conditions in the early Aptian was observed in the Boreal Realm, which probably led to changes in the transport of detrital material (Mutterlose & Bottini 2013; Blok *et al.* 2022).

Distribution of kaolinite

The source area providing detrital material to the DCG during the Early Cretaceous has been proposed to be the Baltic Shield with weathered basement rocks located towards the north (e.g. Christensen *et al.* 2002; Jakobsen *et al.* 2004). The Ringkøbing–Fyn High has been proposed as an alternative source area during the Triassic – earliest Cretaceous, although it is unclear whether similar processes were active during the remaining part of the Early Cretaceous (Nielsen *et al.* 2015; Olivarius *et al.* 2017; Petersen & Jakobsen 2021). Clay mineral assemblages and more specifically, kaolinite abundance is here used to infer the potential source area(s) for the DCG. Kaolinite percentages for the upper Hauterivian – upper Barremian (BC9–BC17) in the North Jens-1 core are relatively high with an average of *c.* 74%, compared to the Vinding-1 (39%) and Boje-2C (49%) wells (Fig. 7; Blok *et al.* 2022). This significant difference of *c.* 25–40%, and the fact that the distance between the Boje-2C and North Jens-1 wells is only *c.* 10 km suggests that there must be an additional influx of kaolinite for the North Jens-1 well, compared to the suggested kaolinite source to the north (Fig. 7). Thus, given that kaolinite minerals settle relatively rapidly due to their large size (Ruffell *et al.* 2002), it appears that the North Jens-1 well was located close to a source providing substantial amounts of kaolinite, whereas the Vinding-1 and Boje-2C wells were located further away or had a different source.

Subaerial exposure or shallow-marine settings are

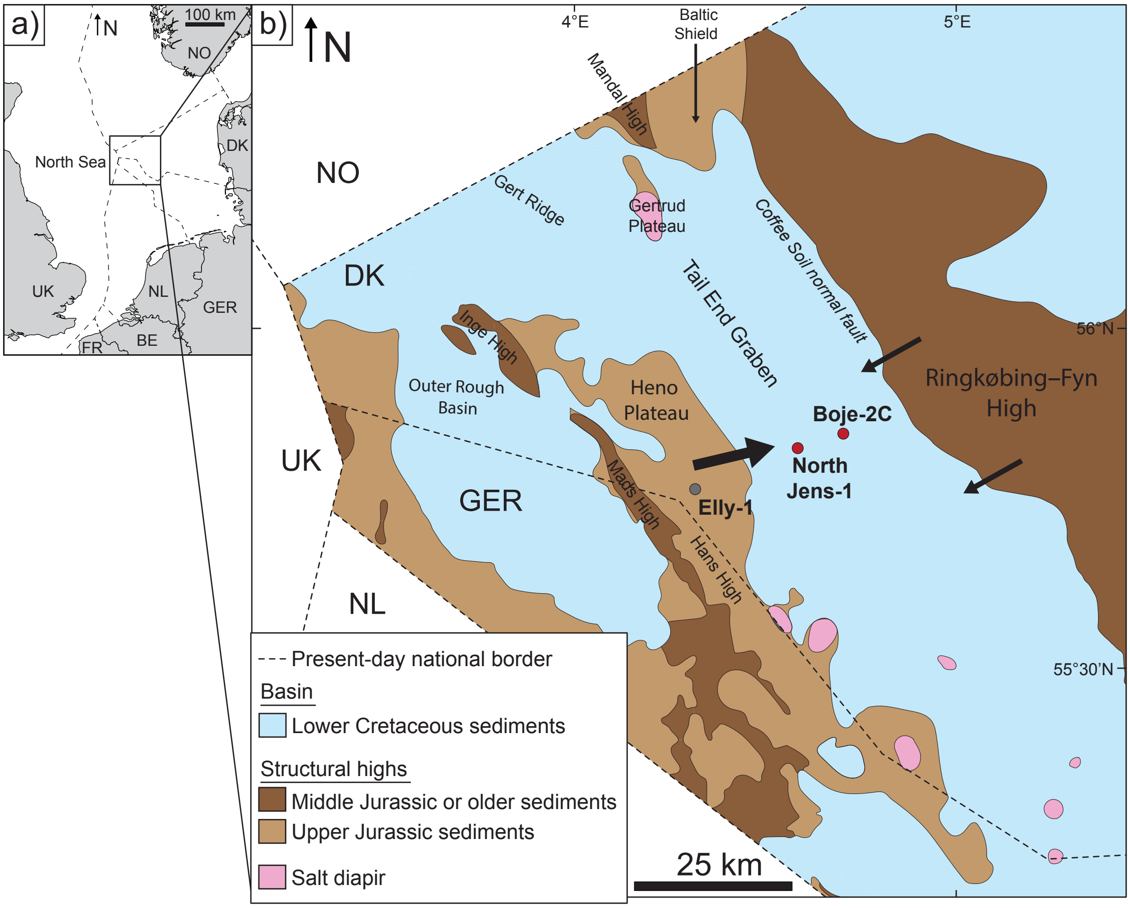

Fig. 7. a) Present-day map of the North Sea, with borders of countries. NO = Norway, DK = Denmark, GER = Germany, NL = Netherlands, BE = Belgium, FR = France, UK = United Kingdom. b) Palaeogeograpic map for the Early Cretaceous of the Danish Central Graben and north-western German North Sea based on Upper Jurassic and Lower Cretaceous isochore maps of the Danish (Vejbæk & Andersen 2002) and German (Arfai *et al.* 2014) sectors. Areas of erosion or non-deposition during the Early Cretaceous are indicated with brown colours. Blue colours indicate where Lower Cretaceous sediments were deposited. The arrows indicate the transport direction of detrital material and a bigger arrow indicates a higher influx, showing the Heno Plateau as the main source area of the DCG.

required to form kaolinite in palaeosols and/or erode it from older rocks before it is transported seawards by fluvial and/or coastal processes. In shallow-marine settings, sediments could be eroded by wave action and transported towards more basinal areas (Zecchin *et al.* 2019). Figure 7 illustrates where the Lower Cretaceous sediments are present in the DCG and German sector of the North Sea and where they are absent. This suggests that those areas were likely subaerially exposed or formed shallow marine areas subject to erosion and/or non-deposition. Potential areas that were most likely characterised by erosion or non-deposition during the Early Cretaceous include the Baltic Shield (Fig. 1; Mørk *et al.*, 2003), the Ringkøbing–Fyn High (Fig. 7; Olivarius *et al.* 2015), and the Heno Plateau (Fig. 7; Pedersen *et al.* 2018; Weibel *et al.* 2020).

Potential clay source areas

Baltic Shield

Weathering of feldspars from basement rock of the Baltic Shield (Fig. 1) could provide material that was transported into the Norwegian, Danish and Northern German basins (Olivarius *et al.* 2015). Kaolinite, of authigenic and detrital nature, was the dominant clay mineral in the Upper Triassic – Lower Jurassic, located west of the Baltic Shield (Mørk *et al.* 2003). It is therefore possible that this area, which is located at least 300 km north-east of the DCG, was a potential source area for the clay minerals preserved in the DCG and distal DB. However, given the tendency for kaolinite to accumulate close to the detrital source and the distance from the Baltic Shield to the DCG and distal parts of the DB, makes it implausible that the Baltic Shield was the main source area. Nevertheless, it is likely that small amounts of kaolinite were weathered from the shield and transported transport into the DB and DCG.

Ringkøbing–Fyn High

A closer potential source is the Ringkøbing–Fyn High, which consists of basement rock, overlain by Palaeozoic and Mesozoic sediments (Olivarius *et al.* 2015). Zircon U-Pb dating shows that the basement of the Ringkøbing–Fyn High and southern Baltic Shield was created during the same orogeny and consist of similar gneissic basement (Olivarius *et al.* 2015). The sediments on top of the basement rock mainly consist of (locally) a thin layer of the Permian evaporites, Triassic sand- and claystones and chalks from the Upper Cretaceous (Olivarius *et al.* 2015). This also indicates that the Jurassic and Lower Cretaceous sediments are absent. Non-deposition of Lower Cretaceous sediments on the Ringkøbing–Fyn High suggests that this area was subaerially exposed during the Early Cretaceous (Fig. 7; van Buchem *et al.* 2017). However, no sedimentary evidence, such as terrestrial deposits, palaeosols, plant remains or coal beds has yet been found. This could imply that the Ringkøbing–Fyn–High was a shallow marine plateau affected by wave action and/or erosion, potentially supplying sediments to the DCG and DB. The Ringkøbing–Fyn High has been proposed as a sediments source in several other studies, *e.g.* for the Lower Triassic Bunter Sandstone Formation (Olivarius *et al.* 2017) or the gravity-flow sandstone deposits of the Farsund Formation (Fig. 2; Nielsen *et al.* 2015). However, these events were related to intense uplift of the high, resulting in enhanced weathering, which has not been recognised during the Early Cretaceous (Vejbæk 1986; van Buchem *et al.* 2017). In addition, the grain size in these gravity-flow sandstones is larger than the fine-grained clay and limestone that is observed in the Vinding-1 (Fig 6; Lauridsen *et al.* 2022), Boje-2C (Fig. 4) and North Jens-1 core (Blok *et al.* 2022). Furthermore, kaolinite is primarily formed by continental chemical weathering processes and not by wave erosion of pre-existing (e.g. Exley 1976; Chamley 1989). Therefore, it seems unlikely the Ringkøbing–Fyn High was the major supplier of detrital material for the DCG or the DB, although minor influxes could have originated from the High.

Heno Plateau

The Heno Plateau is located to the west of the North Jens-1 and Boje-2C wells and the DCG (Fig. 7). The absence of Lower Cretaceous sediments on the Heno Plateau, as indicated by seismic profiles (van Buchem *et al.* 2017), isopach maps (Vejbæk & Andersen 2002) and isochore maps (Ineson *et al.* 2022a), suggest that it is highly likely that the plateau was subaerially exposed or subject to wave erosion. This is observed in the Elly-1 well, where the feldspar-rich sandstones of the Heno Formation (upper Kimmeridgian – lowermost Volgian/Tithonian) were partly eroded and are overlain by Upper Cretaceous chalk (Michelsen *et al.* 2003; van Buchem *et al.* 2017; Pedersen *et al.* 2018). During the Volgian (Tithonian), most highs and basins in the DCG were overlain by offshore mudstones of the Farsund Formation (Fig. 2; Johannessen *et al.* 2010; Ineson *et al.* 2022b). However, the Elly-1 well shows that parts of the Heno Plateau were not covered by the offshore mudstone during the Early Cretaceous, either due to non-deposition or Late Jurassic – Early Cretaceous erosion. Early Cretaceous exposure of the Heno Formation might therefor be limited to a fault block in the southern part of the plateau in the Danish sector, though likely extending into the German sector (Fig. 7).

The Heno Formation is divided into the Gert Member, composed of very fine- to fine-grained quartz and feldspar sandstones, formed in the back-barrier and shoreface and the Ravn Member, encompassing shoreface sandstones, with quartz and K-feldspar as the dominant minerals (Michelsen *et al.* 2003; Weibel *et al.* 2020). Partial dissolution of the K-feldspars is common in the Ravn Member, which could be related to early weathering or instability during burial (Johannessen *et al.* 2010; Pedersen *et al.* 2018). Burial diagenesis plays an important role in the dissolution of K-feldspar in various wells in the DCG (e.g. Weibel *et al.* 2020). The Upper Jurassic succession on the Heno Plateau is at present buried at *c.* 3.5–4 km (Pedersen *et al.* 2018; Weibel *et al.* 2020), initiating illitisation of both feldspars and if present, kaolinite (Lanson *et al.* 2002; Mantovani & Becerro 2010). However, at various locations in the DCG, limited traces of illitisation and dissolution traces on feldspar grains, lack of feldspar grains and kaolinite substitute indicate intense pre-burial weathering of the Heno Formation (Weibel *et al.* 2020). It is very likely that, similar conditions were established around the Elly-1 well and that the Upper Jurassic succession was subject to intense weathering, providing substantial amounts of kaolinite. The Heno Formation is sandstone-rich, and the North Jens-1 well is located closest to the plateau (Fig. 7). Kaolinite is one of the largest clay mineral, thus prone to settling first (Ruffell *et al.* 2002), and the Heno Plateau is considered to be the main source area for the North Jens-1 and Boje-2C wells. This implies that transport of detrital material into the DCG was dominated by influx from the west to south west. The DB is unlikely to contain sediments eroded from the Heno Plateau, since the Ringkøbing–Fyn High acts as a barrier between the high and the basin.

Early Cretaceous palaeoclimate

Kaolinite in the DCG has two origins: 1) part was formed in soils due to changes in palaeoclimate and 2) part was weathered or reworked from a kaolinite- or feldspar-rich source. The high influx of kaolinite into the DCG is thus partially related to a kaolinite-rich source close to the North Jens-1 well, which gives the

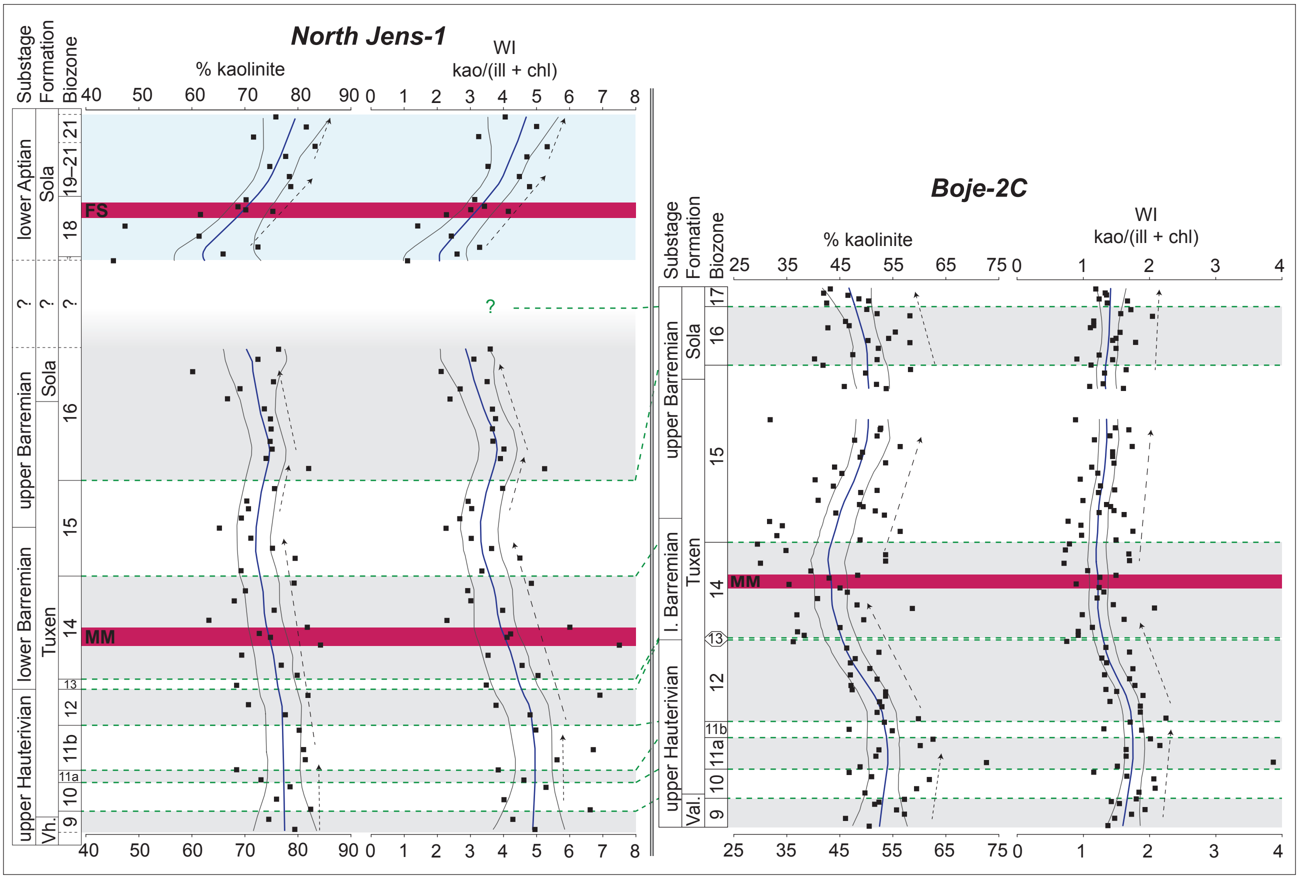

Fig. 8. Comparison of kaolinite percentage and the weathering index (WI) of the North Jens-1 (Blok *et al.* 2022) and Boje-2C wells (this study). The trend lines are based on the LOESS curve (blue line) and a 95% confidence curve (dark grey lines), using the PAST software (Hammer *et al.* 2001). Note that the lower Aptian (NJ-1; blue box) is not absent in the Boje-2C well. FS = Fischschiefer Member, MM = Munk Marl Bed.

clay mineral record a high background signal superimposed on the palaeoclimatic signal.

In the Boreal Realm, the palaeoclimatic changes from the Hauterivian to the late Barremian record a long-term transition to dryer conditions based on the blooming of nannoconids (Malkoč & Mutterlose 2010; Mutterlose & Bottini 2013), decreasing kaolinite contents in England (Ruffell & Batten 1990) and recently published kaolinite data from the DCG (Blok *et al.* 2022). This is also observed in the Tethyan Realm, based on a change towards more oxygenated oceans (Ce anomaly) and decreasing nutrients in the basin (phosphorus accumulation rates; Bodin *et al.* 2006; Bodin *et al.* 2013). In both realms, the latest Barremian – early Aptian was characterised by a trend towards more humid conditions, peaking during Oceanic Anoxic Event 1a, although this change is slightly delayed in the Boreal Realm (e.g. Ruffell & Worden 2000; Bodin *et al.* 2013; Mutterlose & Bottini 2013; Godet *et al.* 2014; Blok *et al.* 2022).

However, the Boje-2C core (this study) has an even higher resolution of clay mineral data for the late Hauterivian – late Barremian, permitting a more precise palaeoclimatic interpretation. The Boje-2C core shows overall decreasing kaolinite values, as in the North Jens-1 core, although the WI is more stable in the Boje-2C core than in the North Jens-1 core. (Fig. 8; Blok *et al.* 2022). The kaolinite values show an increase with time towards nannofossil subzone 11b, a decrease towards the Munk Marl Bed, and a slight increase towards the end of deposition of the Tuxen Formation (zone 15). In the Sola Formation the values decrease slightly upwards towards zone 17. The overall evolution towards drier conditions is interrupted by small fluctuations to more humid conditions as seen by increases in kaolinite. These fluctuations can be observed in the North Jens-1 well, but are better expressed in the Boje-2C well (Fig. 8).

Conclusions

A detailed clay-mineral study, specifically of kaolinite, has led to a better understanding of detrital input and source-to-sink patterns in the Danish Central Graben during the Early Cretaceous.

1. The high kaolinite percentages in Boje-2C and NJ-1 core indicate that the detrital input into the DCG have a dual origin during the Early Cretaceous: i) palaeoclimatic changes and ii) reworking of kaolinite-rich sediments located closest to the North Jens-1 well and providing substantial amounts of kaolinite.

2. A palaeogeographic map has been constructed and indicates areas where the Lower Cretaceous is missing or very thin. Those areas were very likely subaerially exposed and subject to erosion or non-deposition. They are potential source areas for detrital material that was washed into the basin during the Early Cretaceous.

3. Possible highs and their corresponding lithologies that could have acted as source areas were i) the granitic basement in the Baltic Shield and its Upper Triassic to Lower Jurassic succession, ii) the basement rocks and overlying Palaeozoic and Early Mesozoic sediments of the Ringkøbing–Fyn High and iii) the Upper Jurassic sandstones of the Heno Plateau.

4. The Heno Plateau is considered to have been the main source area for the DCG, based on clay mineral assemblages. The North Jens-1 well contains the highest amounts of kaolinite and therefore a kaolinite-rich source close to this well is very likely. The feldspar-rich sandstones of the Heno Formation were subject to weathering before burial. The Baltic Shield and Ringkøbing–Fyn High probably only provided minor amounts of detrital material for the basin.

5. The combination of clay mineral assemblages from the North Jens-1 core and the Boje-2C core give very clear indications of palaeoclimatic conditions during late Hauterivian – early Aptian. A long-term decrease in kaolinite in the late Hauterivian – late Barremian also indicates changes towards drier palaeoclimatic conditions. Small variations in this record imply slight fluctuations between more humid and drier periods.

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Supplementary data I: Whole-rock and clay mineralogy of the Boje-2C core.

Supplementary data II: Whole-rock and clay mineralogy of the Vinding-1 core.