

Vejle Fjord Formation: Mineralogy and geochemistry

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Rasmussen, E. S.: Vejle Fjord Formation: Mineralogy and geochemistry. *Bulletin of the Geological Society of Denmark*, vol. 42, pp. 57–67. Copenhagen, 1995-10-31. <https://doi.org/10.37570/bgsd-1995-42-06>

The Vejle Fjord Formation comprises three members; the Brejning Clay, the Vejle Fjord Clay, and the Vejle Fjord Sand (Late Oligocene-Early Miocene). The lower part of the Brejning Clay was laid down in a shelf environment with a reduced influx of siliciclastic detritus. This resulted in deposition of clay minerals enriched in iron. The early diagenesis was characterized by pyrite and siderite formation within an anoxic sedimentary environment which was established due to degradation of organic matter just below the water/ sediment surface. The clay mineral assemblages of the upper part of the Brejning Clay, Vejle Fjord Clay and Vejle Fjord Sand, which were deposited in a lagoonal environment, reflect different stages in the development of the lagoon. When the lagoon was protected from marine influence, the clay mineral assemblage was dominated by kaolinite. During periods with open marine influence the smectite and illite content increased markedly. Authigenic mineral assemblages are characterized by pyrite and siderite in the lagoonal deposits and pyrite in the tidal flats deposits. The absence of siderite from the latter is due to insufficient reactive iron to form siderite.

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Introduction

During the last two decades very few papers about the Neogene onshore Denmark have been published e.g. Radwanski, Friis & Larsen (1975), Friis (1976), Ulleberg 1987, Rasmussen & Larsen (1989), Koch (1989) and Schnetler & Beyer (1990). The aim of the present paper is to describe the mineralogical composition of shelf to nearshore deposits and to update our knowledge concerning the Late Oligocene and Early Miocene in the eastern part of Jutland.

The Vejle Fjord Formation of Late Oligocene to Early Miocene age, was established by Larsen & Dinesen (1959). The formation is subdivided into three members: The Brejning Clay, the Vejle Fjord Clay and the Vejle Fjord Sand (Fig. 1). The type locality of the formation is Skansebakke, Brejning, on the southern coast of the Vejle Fjord (Fig. 2). Radwanski et al. (1975) investigated the Vejle Fjord Sand at two localities in the Lillebælt area (Fig. 2).

The above mentioned investigations mainly dealt with the depositional environment based on interpretations of sedimentary structures, petrological investigations of the sand fraction and investigations of the foraminiferal fauna.

The purpose of the present study is to describe the mineralogical variation of the formation based on a

detailed mineralogical and geochemical study of borehole-samples from Morsholt and Hindsgavl, Lillebælt and samples from the exposure at Børup, Lillebælt.

Lithological subdivision of the Vejle Fjord Formation

In general, the Vejle Fjord Formation represents a regressive sequence from shelf to shallow marine and brackish nearshore deposits. A humid, temperate climate prevailed during deposition of the formation (Sorgenfrei 1958).

In the present study the formation has been subdivided into 4 lithofacies, A to D, since the three-part subdivision defined by Larsen & Dinesen (1959) does not fully describe the complex lateral and vertical evolution of the formation.

Facies A is a green to yellow-brown glauconitic sandy clay. The lowermost part consists mainly of elongated glauconite grains. The content of detrital grains (mainly quartz and feldspar) and organic matter increases upwards. The glauconite grains also become smaller and more rounded upwards, probably as a result of transportation. In the upper part of Facies A, in the

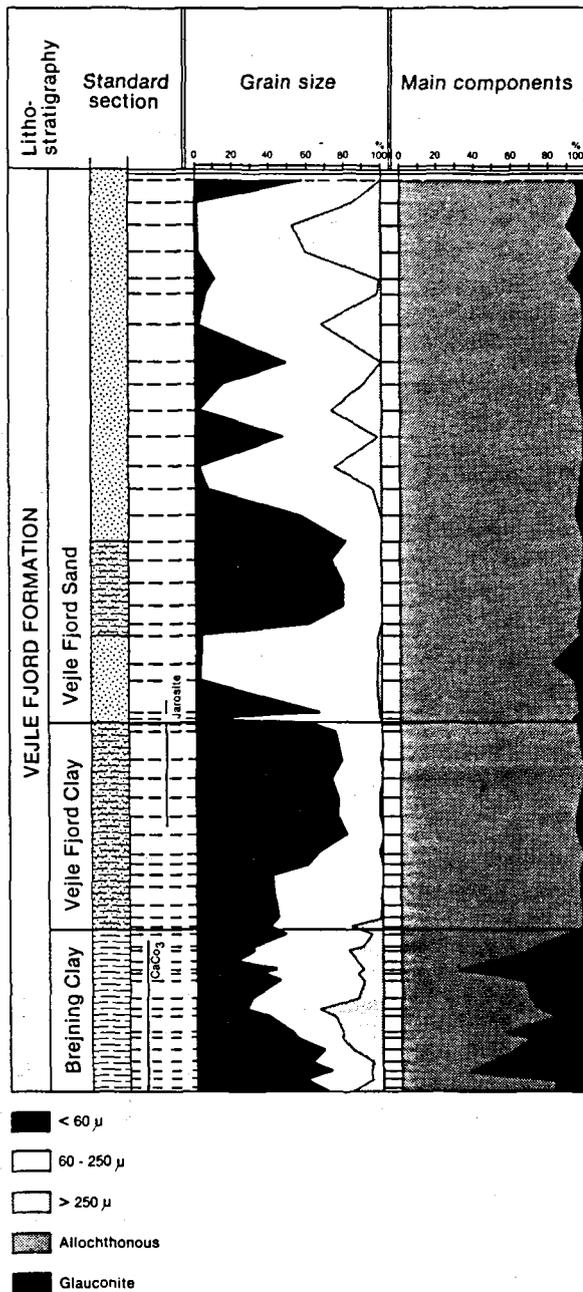


Fig. 1: Simplified lithological log from Skansebakke, Brejning. The subdivision of the Vejle Fjord Formation into the Brejning Clay, Vejle Fjord Clay, and Vejle Fjord Sand is shown, together with the main mineral components and the grain size. From Larsen and Dinesen (1959).

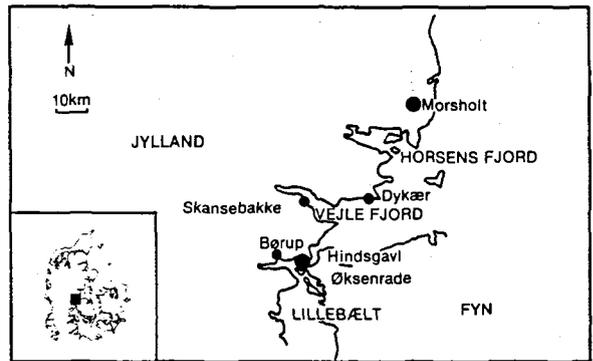


Fig. 2: The investigated area. The two boreholes are marked with a heavy dot and exposures with a small dot.

Lillebælt area, metre-thick layers of green sand are present. The green sand consists of reworked glauconite grains and quartz. Thin intercalations of clay layers are common and some of the sand is cemented by siderite. Shells and impressions of shells are frequently distributed in facies A. Facies A constitutes most of the Brejning Clay (Fig. 3), which is interpreted to have been deposited in a shelf environment, with more near-shore conditions in the upper part (Mikkelsen 1983; Rasmussen 1987).

Facies B is a yellow-brown, bioturbated, silty clay with a high content of organic matter; white sand lenses occur in places. Facies B forms the upper part of the Brejning Clay in the northern part of the investigated area, plus most of the Vejle Fjord Clay, and the clayey part of the Vejle Fjord Sand (Fig. 3). The clay was deposited under quiet conditions in a tidally-influenced lagoon (Mikkelsen 1983; Rasmussen 1987).

Facies C is an off-white sand showing parallel-lamination and trough cross-bedding with intercalations of decimetre thick clay layers. In some areas, well-sorted white sand beds up to a metre thick with heavy mineral laminations have been recognized. The trace fossil, *Ophiomorpha*, is frequently present in the sediments; some of the sand beds are intensively bioturbated. Facies C was laid down as washover fans and beach deposits at or near a barrier island, most probably on the lagoonal side. The facies forms most of the Vejle Fjord Sand (Fig. 3) (Mikkelsen 1983; Sandersen 1985).

Facies D consists of thinly interlayered sand and mud sediments; mud beds with lenticular and wavy bedding are common and internal erosional surfaces are frequent. In some areas beds with bipolar cross-stratification and channel fill sediments are present. Facies D was deposited in the intertidal environment of the lagoon and makes up parts of the Vejle Fjord Clay (Fig. 3) (Mikkelsen 1983; Sandersen 1985; Rasmussen 1987).

A correlation of the facies is shown in Fig. 3 and palaeogeographical maps are shown in Fig. 4. The

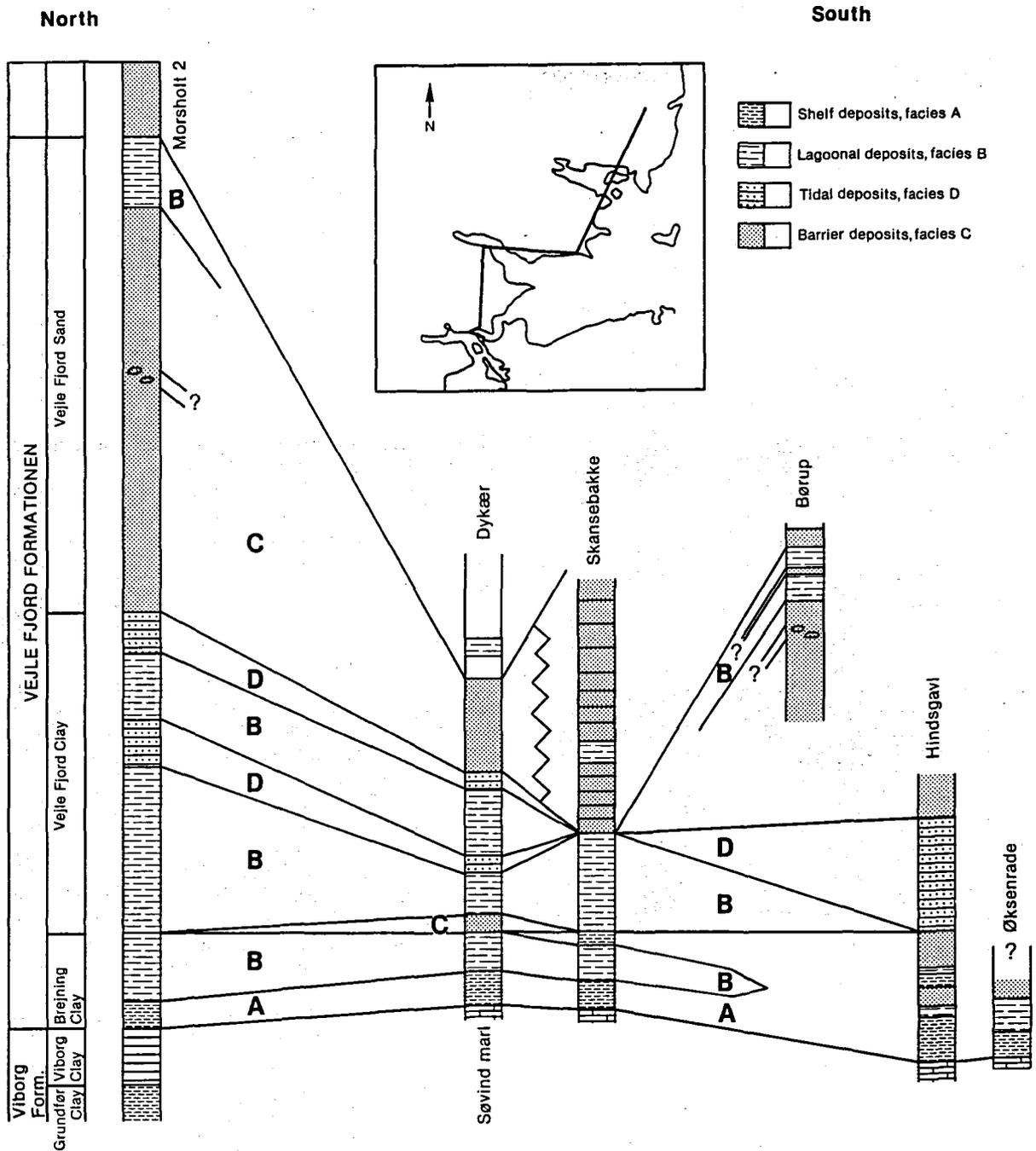


Fig. 3: Correlation of boreholes and exposures in the area and facies subdivision of the Vejle Fjord Formation. Modified from Rasmussen (1987).

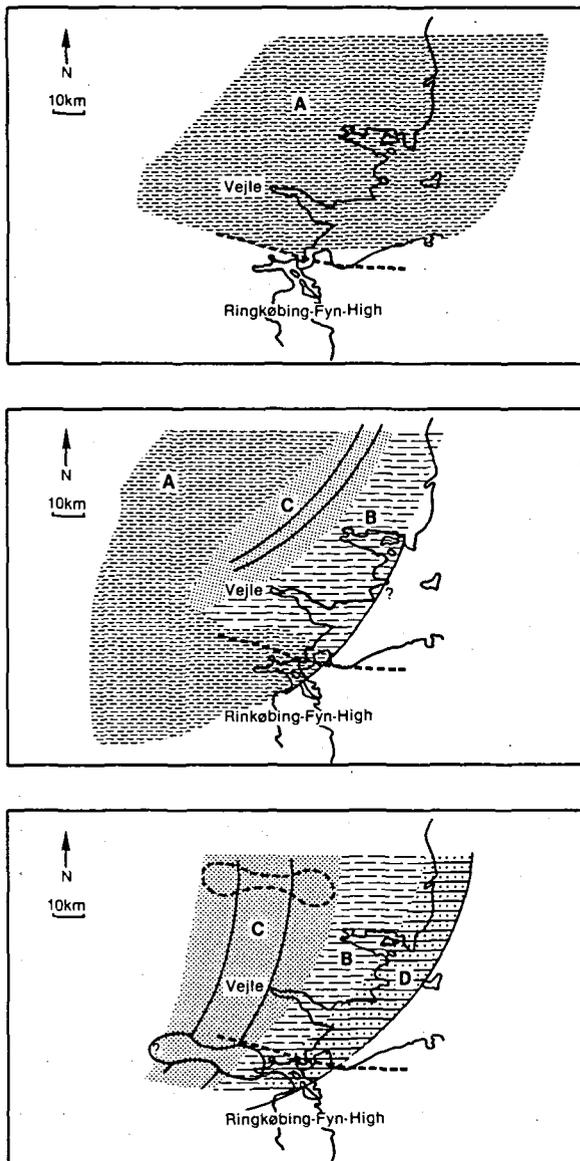


Fig. 4: Palaeogeographical maps showing the development of facies from the Late Oligocene (two upper most) to the Early Miocene. Modified from Rasmussen (1987).

paleogeographic maps have been constructed from borings and exposures shown in the figure.

Investigation of the mineralogical and geochemical composition

Method

Samples from the Morsholt borehole were selected close to lithological boundaries. In the Hindsgavl borehole the samples were taken systematically every me-

tre. The lowermost 2 m of the Brejning clay were not penetrated, due to tool damage. In the laboratory the samples were described and prepared for further laboratory treatment. Samples were dried at 105°C and prepared for bulk-mineralogical, TOC and sulphur analyses. The bulk-mineralogical analysis was carried out by X-ray diffraction using Co-K radiation. The TOC and sulphur analyses were carried out in a LECO furnace. Samples for clay mineral investigations were dried at 60°C, and the fraction < 2 µm was separated by sedimentation in a water column and prepared for X-ray diffraction (oriented slides) and chemical analysis. The mineralogy was estimated semi-quantitatively by measuring peak area of the identified minerals and corrected by empiric factors giving in Rasmussen & Larsen (1989), which are modifications of Schultz (1964). In the determination of 17 Å clay minerals no discrimination between mixed-layered illite-smectite or familiar smectitic minerals have been done, the 17 Å clay minerals are in the following referred to smectite. The chemical analysis was carried out by AAS, Perkin-Elmer 5000.

Results

The results are shown in Figs 5, 6 and Table 1. The profiles from the Hindsgavl boring and the exposure at Børup have been combined in the following figures to a standard profile representing the Lillebælt area. Note that the samples from the Vejle Fjord Sand at Lillebælt have not been used, as they were too deeply weathered.

The following minerals have been identified by x-ray analysis: quartz, potassium-feldspar, plagioclase, calcite, siderite, pyrite, gibbsite and the clay minerals kaolinite, illite, and smectite. The clay minerals identified by x-ray analysis are shown in Fig. 7. The variation within the different facies is described below. The chemical variation of the clay mineral assemblages is shown in Fig. 8.

Facies A is dominated by clay minerals and authigenic minerals. The clay minerals are mainly illite, glaucony and kaolinite (Figs. 8a and 8b). The authigenic minerals in Facies A are pyrite and a large amount of siderite. The organic matter content is above 1%, and a high iron content ($Fe_{(total)}$) was detected (Table 1).

In Facies B, an increase in detrital minerals is observed. The clay mineral assemblages consist of kaolinite, illite, and smectite. The chemical investigation of the clay minerals shows that the illite has a more normal composition than in Facies A, with a low iron content (Englund & Jørgensen 1973) (Fig. 8). The authigenic minerals detected in Facies B are pyrite and siderite. The content of organic matter is above 0.8%. Within this facies the content of detrital minerals is markedly higher than in Facies A.

Facies C has not been investigated in the present

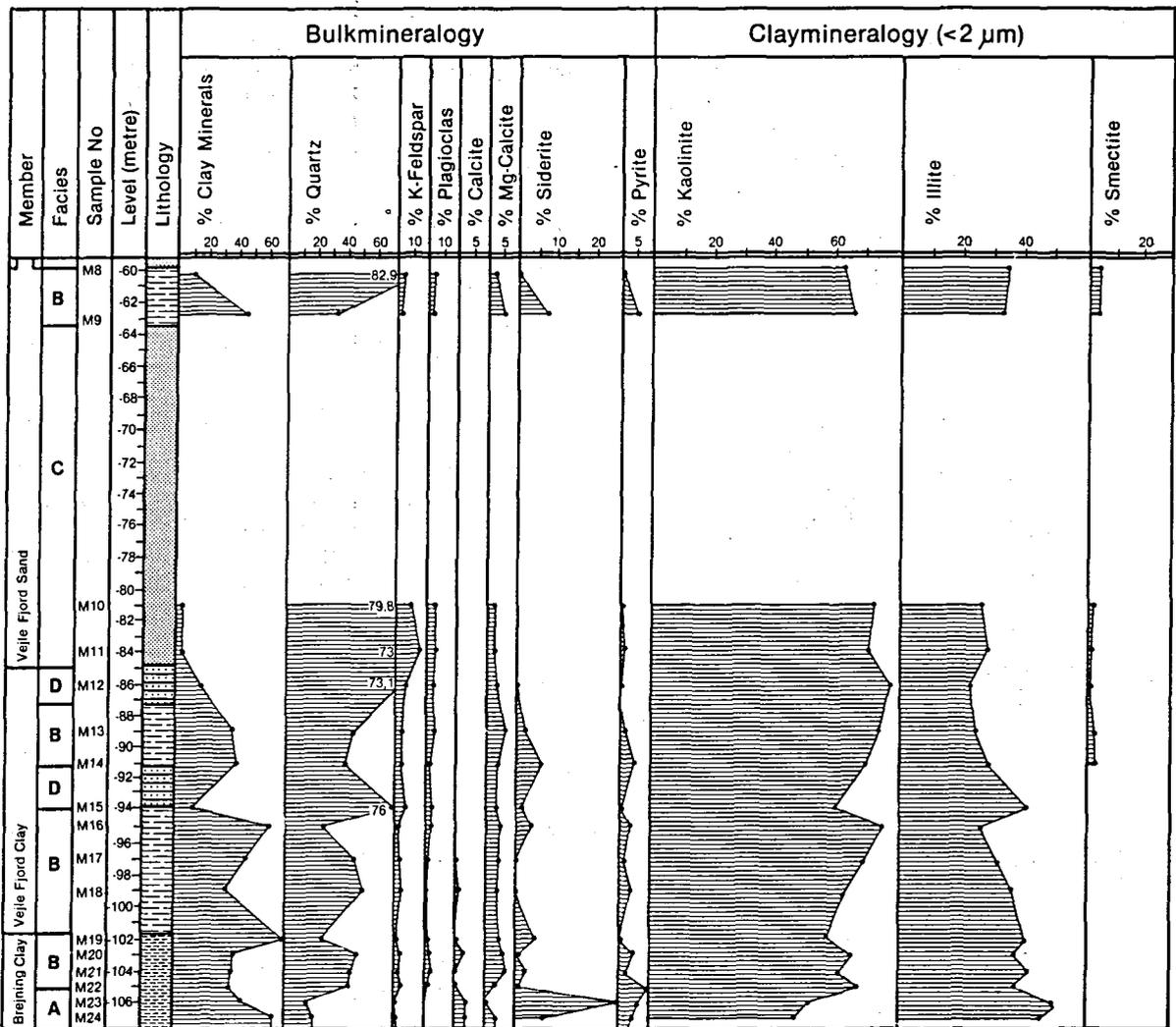


Fig. 5: Bulk and clay mineralogy of the Vejle Fjord Formation in the Morsholt-2 boring.

study, because the clay layers have not been studied systematically.

In Facies D the bulk mineral and clay mineral association and the chemical composition are comparable to Facies B. Amongst the authigenic minerals, only pyrite was detected in this facies. The content of detrital minerals is high.

Interpretation of the mineral assemblages

Facies A (Shelf deposits)

The clay mineral association of Facies A is characterized by illite, glaucony, and kaolinite. The chemical analyses of the clay fraction show high Fe contents (Fig. 8), especially in samples from the lower part of

Facies A. This reflects the high glaucony content, which has been visually identified within this facies. Marine iron-rich clay minerals are normally formed during relatively long periods of reduced influx of sediment and of incipient transgression which favours halmyrolytic processes e.g. glauconite formation or familiar green iron-rich clay minerals composing a glauconitic facies (Burst 1958a, 1958b; Pryor 1975; McRae 1972; Van Houten & Purucker 1984). This combined with intense bioturbation of the sediments, points towards an oxic marine depositional environment with a low rate of sedimentation.

In Facies A, high concentrations of the authigenic minerals pyrite and siderite have also been measured. The formation of these minerals is normally associated with anoxic environments (Berner 1970, 1981; Curtis 1980, 1983) in contrast to the above-mentioned inter-

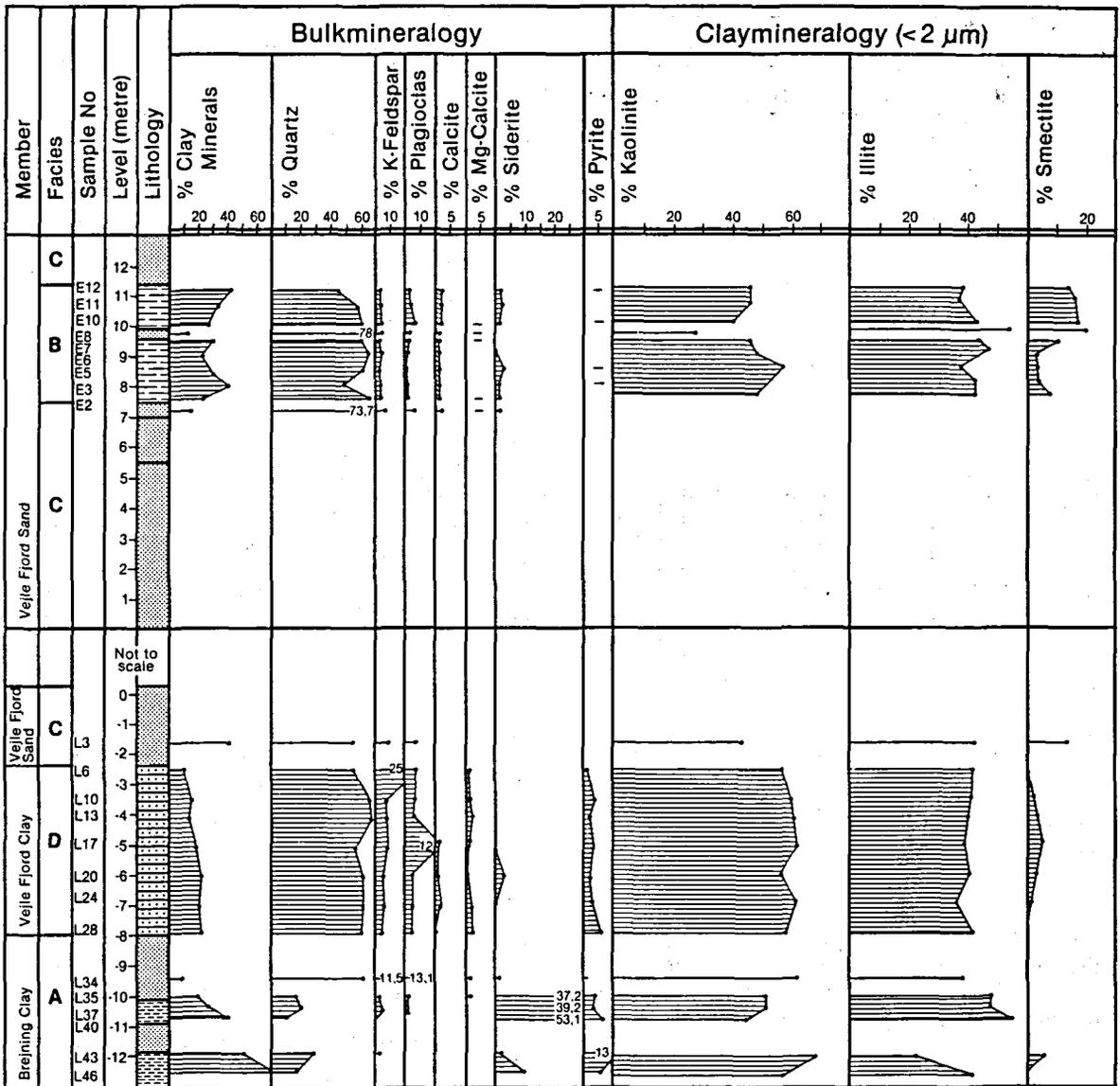


Fig. 6: Bulk and clay mineralogy of the Vejle Fjord Formation in the Lillebælt area (compiled from the Hindsgavl boring and the exposure at Børup).

pretation. There may be two explanation for this discrepancy: 1) The sedimentary environment may have been anoxic just below the sediment/water surface or 2) these authigenic minerals may have been formed later. The present of organic matter indicates that degradation of such matter may have created anoxic conditions within the sediments; the formation of the authigenic minerals probably was thus in the early diagenesis.

A common element in the formation of the three identified authigenic minerals (glaucony, pyrite, and siderite) is iron. During the deposition of Facies A, relatively high amounts of reactive iron must have been

available in the marine setting. There are a number of different explanations for the transport of iron e.g. transportation by rivers in solution, colloidal suspension as coatings on clay minerals, transport by groundwater from swamps and marshes or dissolution of ferrous minerals as listed by Van Houten & Purucker (1984). In the case of the investigated Oligocene sediments, a probable explanation may be the uplift of Fenno-Scandia during the Neogene (Jensen & Michelsen 1991; Japsen 1993). Neogene uplift would have exposed older sediments and probably sediments containing pyrite e.g. Jurassic deposits and Palaeozoic black shales. Pyritiferous sediments may have released

Facies	Sample	Total			Clay Fraction						
		TOC	S(tot)	Fe(tot)	CaO	MgO	MnO	K ₂ O	Fe	SiO ₂	Al ₂ O ₃
C	M10	0.26	0.76	0.20	0.18	1.16	0.41	1.55	5.07	37.48	24.87
C	M11	0.42	0.91	0.40	0.12	0.85	0.00	1.16	0.00	27.61	14.40
D	M12	—	—	—	0.70	1.23	0.07	1.45	0.00	31.14	18.50
B	M13	—	—	—	0.29	1.11	0.02	1.69	6.86	30.90	16.27
B	M14	6.96	2.00	4.95	0.33	1.28	0.03	1.92	4.54	33.54	19.48
D	M15	0.67	0.40	2.22	2.25	1.77	0.08	2.02	10.93	42.59	20.77
B	M16	2.45	1.60	4.99	1.36	1.66	0.04	2.00	4.78	41.48	29.44
B	M17	—	—	—	0.52	1.08	0.04	1.47	4.75	37.97	27.37
B	M18	3.74	2.10	3.88	1.34	1.78	0.05	2.48	4.20	37.80	25.34
B	M19	1.15	0.10	4.70	0.70	1.79	0.02	3.47	3.56	47.02	29.33
B	M20	7.00	2.90	4.22	1.16	1.64	0.02	2.31	7.53	33.99	20.09
B	M21	—	—	—	2.53	2.49	0.02	2.32	4.89	33.28	18.43
B	M22	—	—	—	1.06	1.69	0.02	2.37	8.42	32.28	19.14
A	M23	4.42	3.60	17.48	4.10	2.72	0.06	2.35	16.18	27.83	15.89
A	M24	—	—	—	2.62	2.75	0.04	3.01	3.74	33.07	16.46
D	L3	7.80	0.50	2.40	—	1.58	0.02	2.83	4.67	40.75	17.36
D	L6	3.00	0.80	2.30	0.55	1.41	0.01	2.48	5.25	38.76	18.81
D	L10	4.20	1.40	3.50	0.64	1.82	0.03	2.51	6.36	36.99	16.99
D	L13	2.70	0.90	2.70	1.23	1.41	0.02	2.71	3.90	40.52	15.99
D	L17	4.60	1.60	3.80	0.63	1.79	0.03	2.48	6.13	38.25	16.16
D	L20	3.20	1.40	3.30	0.55	1.71	0.02	2.37	5.81	37.09	16.42
D	L24	4.40	1.50	3.50	0.38	1.74	0.02	2.66	5.55	38.23	15.48
D	L28	5.00	2.30	5.00	0.55	1.74	0.02	2.72	4.92	37.71	18.33
A	L34	1.50	1.50	3.60	0.52	1.71	0.03	2.84	8.60	35.27	14.37
A	L35	4.30	2.00	19.90	1.27	1.70	0.07	2.90	12.81	32.21	12.06
A	L37	2.20	1.30	22.50	1.41	2.24	0.06	2.79	19.75	31.66	10.98
A	L40	2.60	1.10	28.10	1.72	2.55	0.08	2.83	23.07	29.88	9.32
A	L43	8.40	4.10	15.00	1.48	2.10	0.02	2.67	15.49	30.61	10.83
A	L46	2.00	1.21	27.70	1.41	2.52	0.05	2.43	24.04	28.94	9.49

Table 1: Chemical analyses. For location of the samples see figures 5 and 6.

iron to the drainage system during the weathering of the rocks, as for example occurs in the present day Skjern Å River (Jacobsen 1976) during the weathering of Miocene coal-bearing sediments.

Facies B (Lagoonal deposits)

The increased influx of siliciclastic sediments, during the uppermost Oligocene and Early Miocene, resulted in a progradation of the shoreline from the east towards the west. This did not occur by progradation of deltas in the study area, but rather by longshore transportation of sediments that were deposited as marine bars, which subsequently migrated onshore to form barrier islands (Sandersen 1985; Rasmussen 1987).

In Facies B, a higher kaolinite content has been measured than in Facies A. The chemical analyses of the clay minerals show a more normal composition, characteristic of detrital clays (Englund & Jørgensen 1973). A distinct change of the clay mineral assemblage has, however, been recognized within Facies B (see upperpart of the Lillebælt profile, Fig. 9). Here the content of smectite, and to some extent also illite,

changes dramatically within the middle part of the facies. The increase in these clay minerals coincides with increased marine influence in the lagoonal environment (Radwanski et al. 1975). A probable explanation for this is that during restricted periods the lagoon received detrital clay minerals from rivers draining the middle and southern parts of Fennoscandia, whereas the marine clay mineral assemblages were derived clays from a variety of areas, e.g. the smectite-rich Eocene sediments in Northern Jutland which became exposed for erosion during the Neogene uplift. Consequently, periods with marine influence are recorded by a change in the clay mineral assemblages.

A similar development of barrier complexes along the northern part of the Gulf of Mexico has been suggested by Weaver (1960). The lagoons of the eastern part of the Gulf of Mexico derive their sediments from the southern Appalachians, a kaolinite clay assemblage. The sediments sea-ward of the barriers are dominated by smectite sourced from the drainage system of the Mississippi River. When the sea transgressed over these barriers and bays, the sediment deposited on top of them may show a predominantly smectite suite. Consequently, a change in clay assemblage may indi-

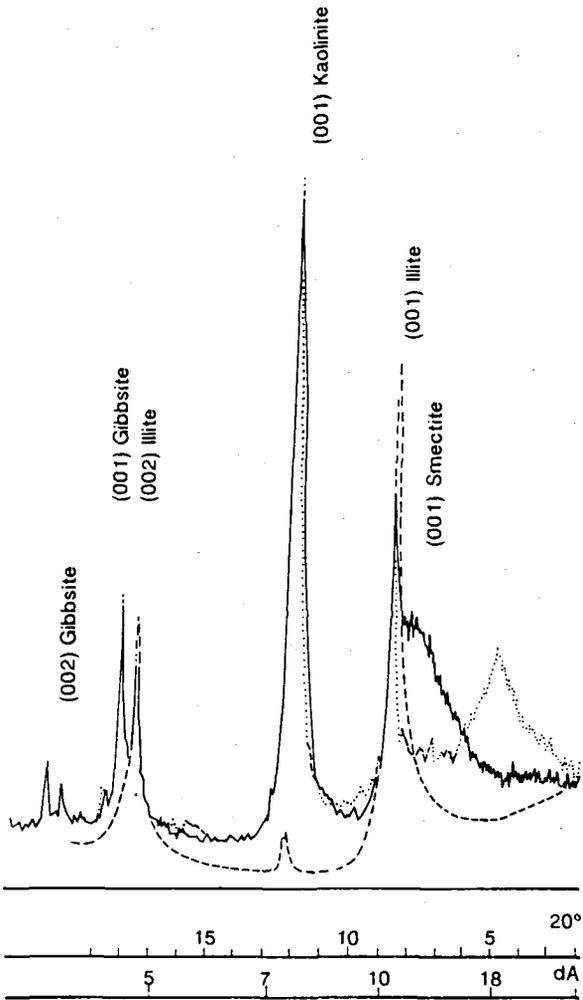


Fig. 7: An x-ray diffractogram showing the clay minerals. The full line indicates the untreated samples, the dotted line is the glycolated trace and the dashed line is the sample heated to 500°C. The sample is from Facies B (Børup).

cate that a transgression has occurred and that a barrier may be located basin-wards and therefore useful in predicting sandbodies.

The authigenic minerals identified within this facies are pyrite and siderite. Minor amounts of glaucony grains have also been recognized, but the glaucony clearly shows evidence of transportation and consequently is interpreted as reworked. The formation of pyrite and siderite probably took place within the sediment since bioturbation of the sediment indicates that the bottom waters and uppermost intervals were oxygenated.

Facies C (Barrier deposits)

This facies is dominated by sandy sediments deposited in near-shore environments. Therefore, no analyses have been carried out on this interval.

Facies D (Tidal deposits)

The clay mineral assemblage of Facies D is quite similar to Facies B. Pyrite is the only mineral identified as authigenic. According to Berner (1981) and Curtis (1980, 1983) siderite is formed during early diagenesis if enough reactive iron is available for both pyrite and siderite formation, but iron will preferentially enter into pyrite. Pyrite consists of iron and sulphur, and depletion of one of these components prevents pyrite formation. A high rate of organic sedimentation may shorten the period during which the sediment remains within the anoxic sulphidic zone (the zone containing dissolved sulphur) (e.g. Jørgensen, Bang & Blackburn 1990). Consequently pyrite formation will stop sooner due to depletion of sulphur and the excess reactive iron will react with bicarbonate and form siderite. In the present study, siderite was formed in Facies B, where the rate of sedimentation is interpreted to have been lower than in Facies D. Therefore it is suggested that the availability of reactive iron was the controlling factor for the siderite formation in Facies B and D were deposited within the same lagoonal environment; Facies B represents the central part of the lagoon and Facies D the marginal part. The iron distribution (in the form of ironoxyhydroxides) in such an environment has been described by Willumsen (1976). He found that the highest iron content occurs in the deepest part of the lagoon (Ringkøbing Fjord) and that the deposition of ironoxyhydroxides requires a quiet environment. The same conditions may have been prevalent during the deposition of Facies B and D, where Facies B was laid down in the deeper part of the lagoon (no tidal influence) and Facies D in the marginal areas with low influx of iron and therefore no siderite formation. Another factor that may have been responsible for a low content of reactive iron in the tidal flat sediments was the different source of the sediments. Van Straaten & Kuenen (1957) have described the transport of fine-grained material in a tidal environment. Most of the sediments deposited on tidal flats are transported by tidal currents from the open sea and hence may have a lower content of reactive iron than the sediments laid down in the central part of the lagoon which may originate from the land area and consequently be more enriched in weathering products such as iron oxides. In Figures 10 and 11 correlations of iron and sulphur, from samples from lagoonal deposits (Facies B and D) and solely tidal deposits (Facies D) are shown respectively. A very good correlation has been found between iron and sulphur in Facies D (Fig. 11) and furthermore with a gradient similar to the stoichiometric line for pyrite (FeS_2). This supports the above interpretation that reactive iron was depleted before sulphide supply was exhausted.

A common mineral for all facies is gibbsite. Investigations of Oligocene and Miocene sediments in Denmark show that gibbsite is found in Upper Oligocene and Miocene deposits (e.g. Rasmussen 1987; Rasmus-

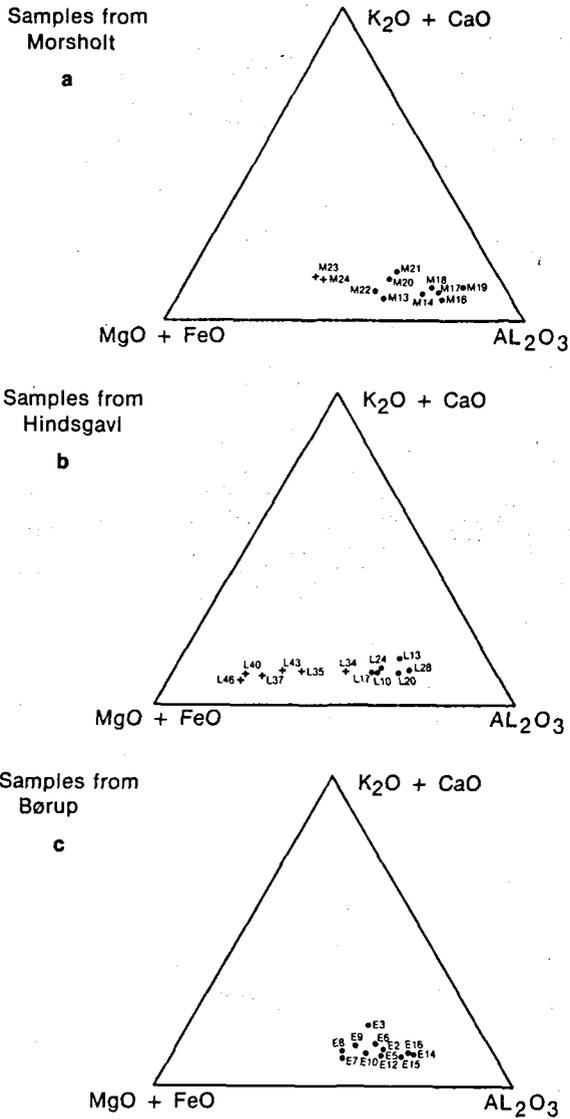


Fig. 8: Chemical composition of the clay fraction. Samples from facies A are marked with a + and samples from facies B and D are marked with a o.

sen & Larsen 1989). Gibbsite is normally formed during weathering of soils in humid tropical climates (Velde 1985) and thus should not be expected in the Vejle Fjord Formation, which was deposited during a temperate period (Sorgenfrei 1958). A likely explanation for the origin of the observed gibbsite is that it was formed during the Paleocene and Eocene, where the climate was distinctively warmer (Buchhardt 1978). These gibbsite-rich sediments of Paleocene or Eocene age were then eroded during the Neogene uplift and laid down in the investigated area in Oligocene and Miocene times.

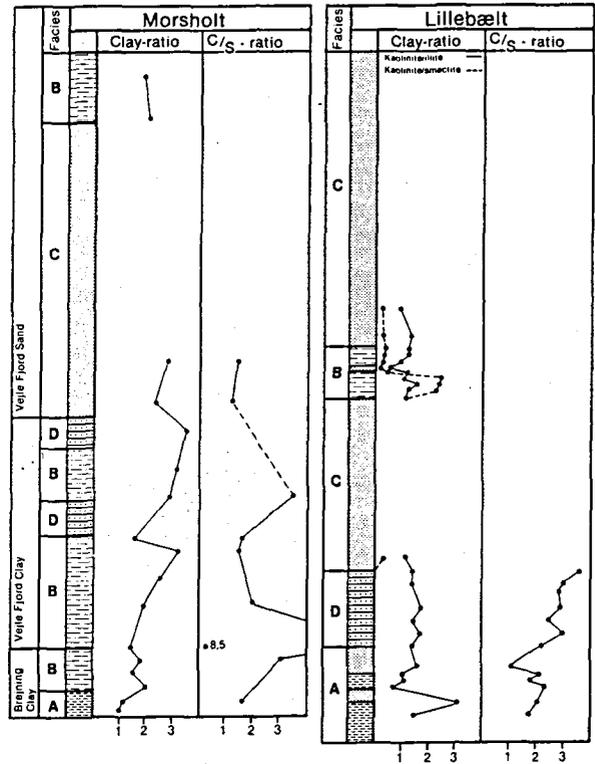


Fig. 9: Clay ratios and C/S ratios from the Morsholt-2 borehole and the Lillebælt area.

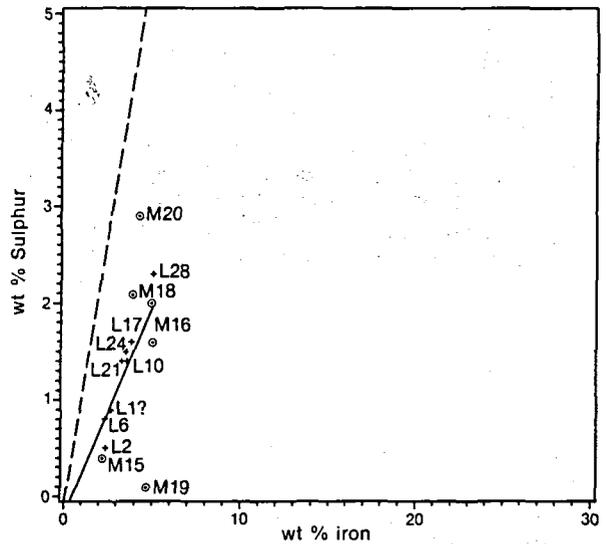


Fig. 10: Plots of sulphur versus total iron from facies B and D. The solid line is the regression line for the present data and the dashed line is the stoichiometric line for pyrite (FeS_2).

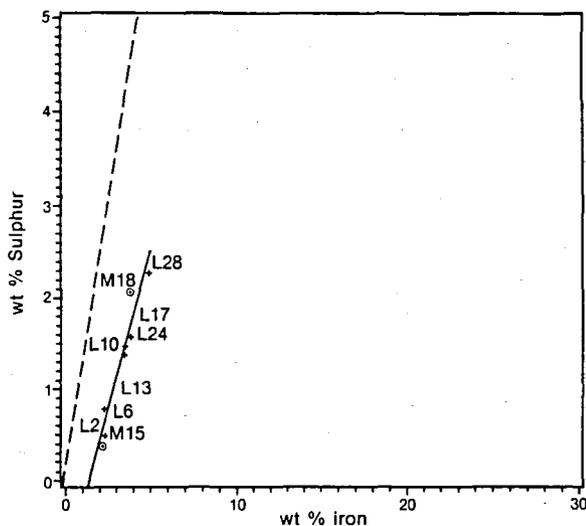


Fig. 11: Plots of sulphur versus total iron from samples without siderite, solid line. The dashed line is the stoichiometric line for pyrite (FeS_2).

Indications of palaeosalinity

Carbon/sulphur ratios (Fig. 9) can be interpreted in terms of salinity of the depositional environment (Bernier & Raiswell 1984); typically ratios under 6 indicate marine environments. For samples from Facies A, ratios about 2 have been found. Ratios from Facies B and D are found to be between 3 and 6 which still corresponds to normal marine conditions. However, the ratios are higher than in Facies A and may reflect a more brackish water environment. The same trend towards brackish conditions in the upper part of the Brejning Clay and Vejle Fjord Clay has also been suggested on the basis of the foraminiferal fauna by Dinesen in Larsen & Dinesen (1959). Consequently, both geochemical data and fauna support the depositional model of an initial open marine environment during the deposition of Facies A with the progressive development of a more brackish water environment in a back-barrier environment during deposition of Facies B, C, and D.

Conclusion

The Neogene sediments in Denmark are characterized by a general progradation from the east towards the west. During the Upper Oligocene and Lower Miocene the coast line was located just east of, or within, the investigated area. This early stage in the infill of the North Sea Basin, which was markedly increased in the Upper Miocene (Nielsen, Sørensen, Thiede, & Skarbo 1986) was a consequence of the Neogene uplift

of Fenno-Scandia (Jensen & Michelsen 1991; Japsen 1993).

The present study shows that the lower part of the Brejning Clay (Facies A) was laid down in a shelf environment with a reduced influx of siliciclastic materials. This resulted in deposition of clay minerals enriched in iron. The diagenesis within the sediments was characterized by formation of pyrite and siderite within the anoxic zone just below the water/sediment surface.

The clay mineral assemblage of the lagoonal deposits (Facies B and D) representing the Vejle Fjord Clay and Vejle Fjord Sand, reflects different stages in the development of the lagoon. When the lagoon was restricted from marine influence, the clay mineral assemblage was dominated by kaolinite. During periods with open connection between the sea and the lagoon, the content of smectite and illite increased markedly. The formation of authigenic minerals was characterized by the formation of pyrite and siderite in an anoxic sedimentary environment. However, only pyrite was formed within the tidal sediments probably because reductive iron was depleted before sulphur.

Acknowledgement

I thank Ole Bjørnslev Nielsen and the staff at the Exogene Lab. Aarhus University, Ion Ineson for correcting the English, and Annabeth Andersen and Alice Rosenstand, who made the figures. The review by Dr. J. Huggett significantly improved the final version of the manuscript.

Dansk sammendrag

Den øvre oligocæne - nedre miocæne Vejle Fjord Formation er blevet undersøgt mineralogisk og geokemisk. Formationen er formelt opdelt i tre enheder: Brejning Leret, Vejle Fjord Leret og Vejle Fjord Sandet.

Den nedre del af Brejning Leret er blevet aflejret i et shelf miljø med lavt tilførelse af klastiske materialer. I dette miljø aflejredes hovedsageligt finkornede sedimentter beriget med jern. Det er sandsynligt at halmyrolitiske processer har fundet sted i de øverste sedimentlag. Under den tidlige diagenese dannedes pyrit og siderit under anaerobe forhold.

Lermineralselskabet i den øverste del af Brejning Leret, Vejle Fjord Leret og Vejle Fjord Sandet, som blev aflejret i et lagunalt miljø, afspejler udviklingen af lagunen. Under forhold med lav marin indflydelse var lermineralselskabet domineret af kaolinit og i perioder med forøgede marin påvirkning ses et højere indhold af lerminerallerne smektit og illit. I den tidlige diagenese dannedes også pyrit og siderit i et anaerobisk sediment miljø, dog kun pyrit på tidevands-

fladerne pga. lav indhold af reaktivt jern i sedimenterne her.

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