Clay Mineralogy and Sediment Provenance at ODP Sites 642B, 643A and 644A Vøring Plateau, Norwegian Sea (1-4°E, 67-68°N).

by

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ABSTRACT

Using X-ray diffraction, twelve sediment samples from the Vøring Plateau, Norwegian Sea (1-4° E, 67-68° N) have been analyzed for their clay mineral constituents and their relative clay mineral abundances. The results of the analysis indicate that the relative clay abundances average 10.3% smectite, 60.7% illite and 29.1% kaolinite. The presence of kaolinite is noteworthy because kaolinite is generally considered to be a low-latitude clay, and these samples were obtained from high latitudes.

From a synthesis of literature dealing with the presence of kaolinite in high latitudes, a hypothesis has been formed in order to explain the presence of kaolinite in these samples. That hypothesis is as follows: Kaolinite formed in Norway during the Devonian and Carboniferous. Paleolatitudes for Norway at this time were equatorial, so the climate was favorable for the development of this mineral. The kaolinite regolith was subsequently buried, but was re-exposed in the late Triassic, with the uplift of the present Norwegian shelf. The kaolinite-bearing sediment was later eroded, reworked, and redeposited as younger sediments. During the Pleistocene, the kaolinite-bearing rocks were removed from the land by glacial erosion and deposited seaward of the

Norwegian coast. Norwegian terrigenous sediments, including kaolinite, were transported to the continental shelf and greater depths of water by ice, icebergs, surface currents, and suspension currents. The latter were especially effective on the slopes of the Vøring Plateau, where the kaolinite was later found at ODP Sites 642B, 643A and 644A.

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1.0 INTRODUCTION / OBJECTIVES

Because of its position between the North Atlantic and the Arctic oceans, its young age, small size, and diversity of geological structures, the Norwegian Sea provides a unique opportunity for geologic studies (Talwani and White, 1976). Also of interest is that the Norwegian Sea is the northern-most part of the Atlantic Ocean where cold North Atlantic Deep Water is formed. A relationship between northern North Atlantic oceanography and northern hemisphere climatic fluctuations has long been noted (Berggren and Schnitker, 1981). Leg 104 of the Ocean Drilling Program (ODP) set out to investigate a variety of geological phenomena on the Vøring Plateau, Norwegian Sea. One of the objectives at drill Sites 642B, 643A and 644A (1-4° E, 67-68°N; see Fig. 1.) was to study the paleoclimatic history of the northern hemisphere, as recorded in the composition and distribution of pelagic sediments in the core samples, and in particular, to study the initiation and variability of the glacial-interglacial climatic fluctuations. The original purpose of this paper was to distinguish glacial-interglacial climatic fluctuations based on the clay mineralogy of twelve ODP samples from Sites 642B, 643A and 644A. In general, clay mineralogy differs in glacial and interglacial sediments;

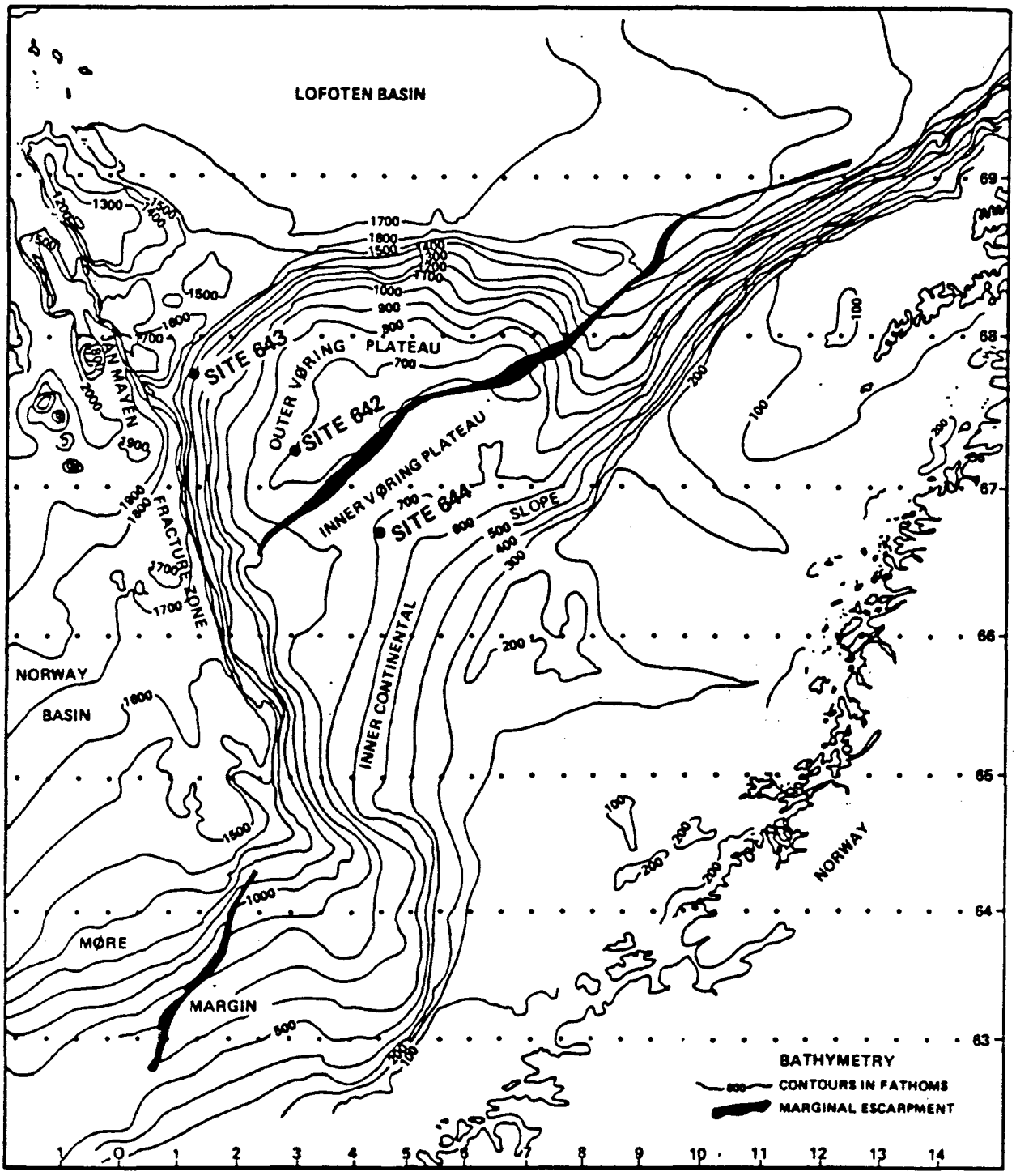

Fig.1 Geographical location of ODP Sites 642B, 643A and 644A, (1-4°E, 67-68°N) Vøring Plateau; Norwegian Sea.

however, the clay mineral data, obtained in this investigation by X-ray diffraction, was inconclusive in distinguishing glacial-interglacial periods. Of significance, though, was the presence of kaolinite, which is noteworthy because kaolinite is generally considered to be a low-latitude clay, and these samples were obtained from high latitudes. The purpose of this report, therefore, is to document the composition of these samples, and to develope an explanation for the occurrence of kaolinite in these high-latitude locations, where such a mineral is not expected. Evidence for this hypothesis will come from literature dealing with the presence of kaolinite at high latitudes.

2.0 BACKGROUND

Clay genesis is strongly influenced by the climate in which the clay forms. On the basis of this observation, Griffin et al. (1968) categorized the distribution of the various types of clays according to climatic zones. The major climatic zones of the earth generally are classified according to temperature and precipitation (Lisitzin, 1972); in this paper the climate is denoted in terms of latitude.

Chlorite was characterized by Griffin et al.(1968) as a high latitude clay mineral, as its greatest abundance lies in the polar regions of the world. Chlorite is considered to be a primary mineral that forms during metamorphic processes, and not a secondary mineral product of chemical weathering

during soil formation. In contrast to chlorite, abundant kaolinite in recent marine sediments is generally confined to low latitude regions. Kaolinite forms in geological regimes undergoing intense chemical weathering, and its distribution reflects the intensity of the soil-forming processes active in the source areas (Griffin et al., 1968). Thus, a general increase in the chlorite to kaolinite ratio is established for both Atlantic and Pacific Ocean sediments towards higher latitudes; this trend reflects a decrease in chemical weathering intensity on the adjacent continents (Griffin et al., 1968). The presence of kaolinite is required to demonstrate significant chemical weathering, because a lack of chlorite in high latitudes is simply indicative of the absence of low grade chloritic metamorphic rocks in the source area (Hurst, 1985).

3.0 METHODS OF CLAY ANALYSIS

Clay mineral (<2μm sized particles) analysis of twelve ODP core samples (Sites 642B, 643A, and 644A) was conducted using x-ray diffraction techniques. The process of analysis is detailed below.

3.1 Preparation of Core Samples

Individual core samples were diluted with distilled water to form a suspension. Each suspension was allowed

to settle for 25 minutes, after which time a volume was pipetted from a depth of 5 cm. This sample, which contained the <2μm fraction, was placed onto a glass slide and air dried, forming an oriented mount. These slides were then placed in a warm, ethylene-glycol-saturated atmosphere for 12 hours in order to expand the smectites.

3.2 X-ray Diffraction

Each slide was examined on a Norelco x-ray diffractometer using CuKα radiation. Several scanning ranges and goniometer settings, as well as a heat treatment, were used to distinguish individual clays. Data reproducibility was tested by comparing the diffraction patterns of duplicate scans for the first two slides (at the same scanning range and the same goniometer setting). The deviations in the relative peak sizes were within ±5% for the kaolinite, illite and smectite peaks.

3.2.1 3° 2θ to 15° 2θ, 1° per Minute

By scanning over the range of 3° 2θ to 15° 2θ, with a goniometer setting of 1° per minute, smectite and illite were identified according to their characteristic diffraction peaks of 17Å and 10Å respectively. Chlorite and kaolinite were not distinguishable in this range because of the proximity of the d(001) spacing of kaolinite and the d(002) spacing of chlorite at 7Å, resulting in overlapping characteristic peaks.

3.2.2 24° 2θ to 26° 2θ, ¼° per Minute

The samples were then X-rayed at a slower scanning speed of ¼° per minute in an attempt to separate the 3.57Å kaolinite peak from the 3.54Å chlorite peak. This was unsuccessful because of the overlapping of the d(002) and the d(004) spacing of kaolinite and chlorite respectively, at 3.5Å

3.2.3 X-ray Diffraction after Heating Samples at 500°C for One Hour

Finally, in order to distinguish kaolinite from chlorite, slides giving the highest intensity peak reading for the 7Å chlorite/kaolinite peak were heated at 550°C for one hour. Heating the samples in this manner causes the kaolinite structure to collapse, while the chlorite structure is unaffected. When the slides were again X-rayed over the range of 24° - 26° 2θ at ¼° per minute, the 3.5Å peak no longer appeared. Over the range of 3° - 15° 2θ at 1° per minute, the 7Å peak was again not present. X-ray data, obtained from these analyses, indicated that chlorite is not present in these samples, and that the 7Å and the 3.5Å peaks were due to the presence of kaolinite, whose structure collapsed after heating. (See Fig. 2. for sample diffraction patterns.)

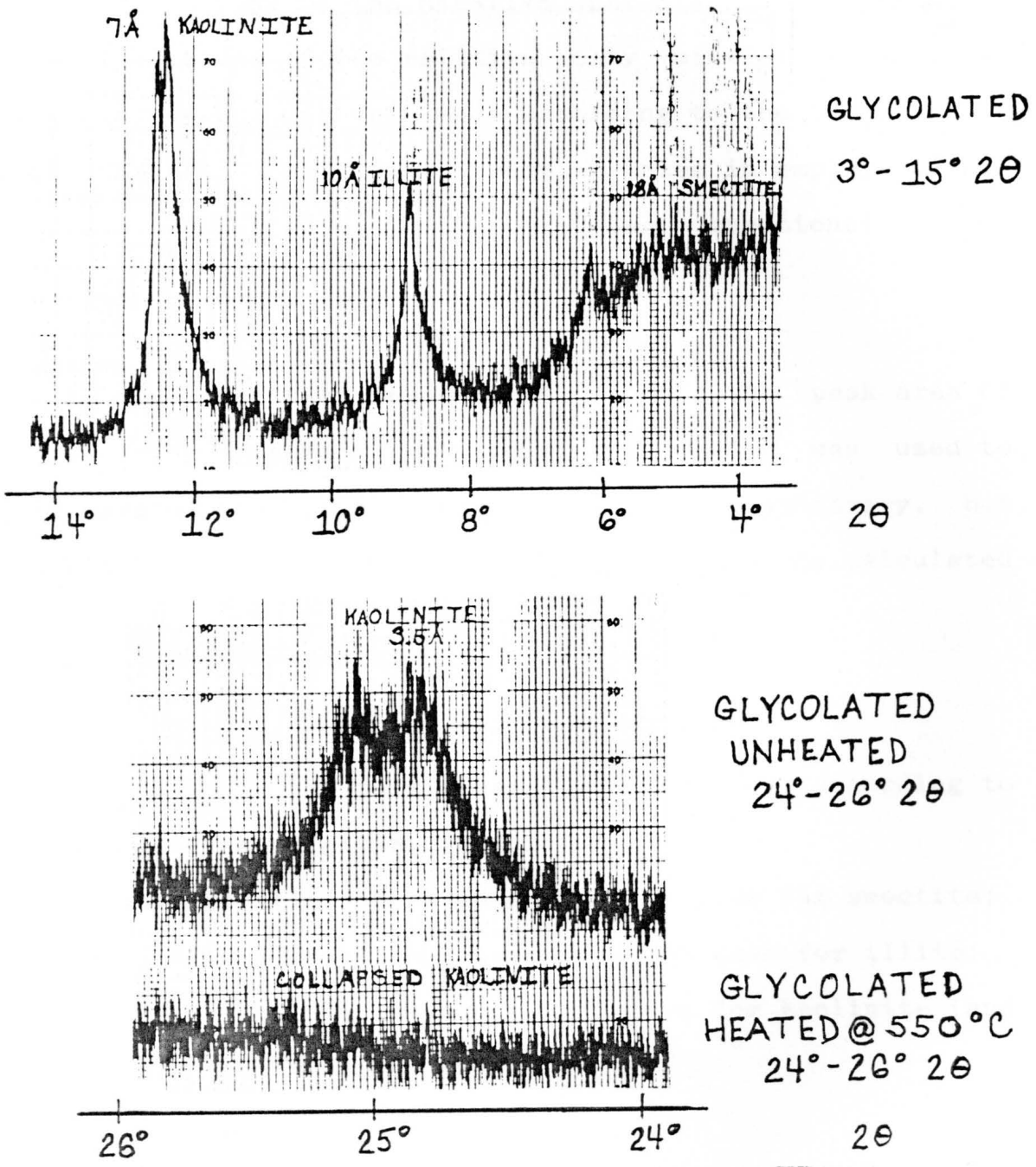

Fig 2 X-ray diffractograms of an oriented mount from a sample obtained at Site 644A, core 2, section 4, 100-102 cm below the top of section 4, using CuKα radiation

4.0 CALCULATIONS OF THE RELATIVE CLAY MINERAL ABUNDANCES

Calculations of the relative clay mineral (<2μm sized particles) abundances were made according to the technique proposed by Biscaye (1965). Steps taken in employing this technique are described in the following subsections.

4.1 Peak Area Measurements

. The first step involves calculating the peak area of each clay mineral. A polar planimeter was used to integrate the peak area; units are arbitrary, but consistent for each sample. Table I lists the calculated peak areas.

4.2 Weighting the Peak Area Mesurements

Secondly, the peak areas are weighted according to the following weighting factors:

(1) one times (1X) the area of the 17Å peak for smectite;
(2) four times (4X) the area of the 10Å peak for illite;
(3) twice (2X) the area of the 7Å peak for kaolinite (and chlorite when present).

4.3 Summation of the Weighted Areas

A third step involves summing the weighted peak areas. This sum represents the total relative amount of clay in the sample. The equation would be written as follows: smectite area + 4X(illite area) + 2X(kaolinite

area) = total amount of clay. See Table II for a list of weighted area totals.

Table I

X-Ray Mineralogy; Peak areas[1], Sites 642B,643A, and 644A

Sample[2] (Interval in cm)	depth (m)	17Å-Smectite	10Å-Illite	7Å-Kaolinite
Site 642B				
1-2, 75- 78	2.3	205	266	173
3-4, 57- 60	18.5	300	380	310
4-2, 128-131	26.1	---	380	420
5-5, 68- 71	38.4	120	312	297
Site 643A				
1-2, 48- 50	2.0	73	266	165
2-2, 134-136	8.2	61	102	90
2-6, 105-107	13.9	342	167	330
5-4, 99-101	39.3	246	144	96
Site 644A				
1-2, 59- 61	2.1	50	237	233
2-4, 100-102	17.7	143	263	590
3-6, 30- 32	23.9	360	380	310
5-4, 124-126	39.4	232	380	420

Notes:
1) Arbitrary units.
2) Notation is as follows: "core number" - "core section", "distance interval into core section", as measured from the top of the section

4.4 Clay Mineral Percentages

Ultimately, Biscaye's method is used to calculate the clay mineral percentages, which represent the relative clay mineral abundances. This is done by dividing the weighted peak area of a particular clay by the total weighted peak area of that sample and multiplying by 100%. Table II lists the relative percentages of the clay

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Table II

Relative Percentages[1] of Clay Minerals: Sites 642B,643A, and 644A

Sample[2] (Interval in cm)	depth (m)	Total[3] Area	Smectite (%)	Illite (%)	Kaolinite (%)
Site 642B					
1-2, 75- 78	2.3	1615	12.7	65.9	21.4
3-4, 57- 60	18.5	2440	12.3	62.3	25.4
4-2, 128-131	26.1	354	----	75.7	24.3
5-5, 68- 71	38.4	1962	6.1	63.6	30.3
Site 643A					
1-2, 48- 50	2.0	1467	5.0	72.5	22.5
2-2, 134-136	8.2	649	9.4	62.9	27.7
2-6, 105-107	13.9	1670	20.5	40.0	39.5
5-4, 99-101	39.3	1014	24.3	56.8	18.9
Site 644A					
1-2, 59- 61	2.1	1464	3.4	64.8	31.8
2-4, 100-102	17.7	2375	6.0	44.3	49.7
3-6, 30- 32	23.9	2500	14.4	60.8	24.8
5-4, 124-126	39.4	2592	9.0	58.6	32.4

Notes:
1) Percentages quoted for clay mineral component only, not total composition.
2) Notation is as follows: "core number" - "core section", "distance interval into core section", as measured from the top of the section.
3) Arbitrary units representing the total weighted area.

minerals in each sample. Percentages are quoted for clay mineral components only, and not for total composition.

5.0 CONCLUSIONS OF CLAY ANAYSIS

I have found that the relative clay abundances average 10.3% smectite, 60.7% illite and 29.1% kaolinite. As stated in the introduction, the original purpose of this project was to distinguish glacial-interglacial deposits on the basis of clay mineralogy. Samples were categorized as glacial or interglacial on the basis of independent data, such as bulk characteristics and micropaleontology, and their clay mineral abundances were then plotted on a ternary diagram. No glacial/interglacial differences in the clay mineral assemblages were observed in this diagram (see Fig. 3). However, such a high percentage of kaolinite in these samples is noteworthy because kaolinite is generally accepted to form at low latitudes. Kaolinite tends to form in a humid, subtropical environment from chemical weathering; its distribution reflects the intensity of soil-forming processes (Griffin et al., 1968). Why then is kaolinite present in these high-latitude core samples if conditions are unfavorable for modern kaolinite formation ?

6.0 INTRODUCTION TO KAOLINITE HYPOTHESIS

Based on evidence obtained from past studies dealing with the unexpected presence of kaolinite at high latitudes,

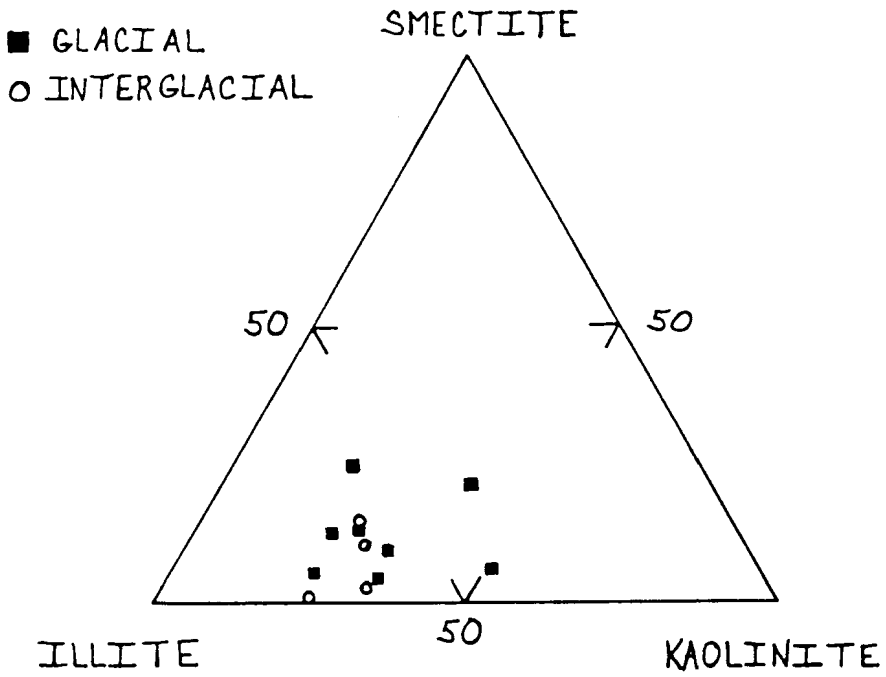

Fig. 3 Ternary plot of clay mineral percentages from twelve core samples recovered on ODP Leg 108 at Sites 642B,643A, and 644A - Vøring Plateau (Norwegian Sea; 1-4° E, 67-68° N). Glacial-interglacial period sediments could not be separated using this plot.

a hypothesis will be developed to explain the presence of kaolinite in these high-latitude ODP core samples. A synthesis of various studies is presented in the following sections in order to develop my hypothesis.

7.0 HIGH-LATITUDE KAOLINITE

Kaolinite is not forming today in high latitudes. Core samples from the Artic Ocean that contained between 15% and

30% kaolinite were examined by Naidu et al. (1971) and Darby (1975). Both researchers concluded that the kaolinite had been derived from pre-existing terrestrial sources. Based on pollen and ^{14}C data, kaolinite-rich Arctic soils have been interpreted as relicts of warmer climates, developed 11,000-8,000 years before the present (Tedrow, 1966). Thus, kaolinite is not forming today at high latitudes, such as in the Arctic, but its accumulation in modern deep-sea sediments is due to a reworking of terrestrial relict deposits (Darby, 1975).

A similar line of reasoning may be applied to these core samples from the Norwegian Sea, i.e., that the kaolinite has been derived from a terrestrial source containing relict soils developed during a warmer climate. Because of the close proximity of ODP Sites 642B, 643A and 644A to Norway (and the Norwegian coast), Norway was selected as the most likely geographical source area for the kaolinite. Other possibilities include Greenland, Scotland and other northwestern European countries; I will limit my research to Norway.

8.0 NORWEGIAN PLEISTOCENE GLACIATION

According to Holtedahl and Bjerkli (1975), the Norwegian continental shelf has been greatly influenced by Pleistocene glacial activities. The high mountains of western parts of Norway were ice accumulation centers, producing glaciers that extended from the continental shelf to varying distances from

the coast. The great depths present near the coast in the Norwegian Channel area, as well as off the west coast, are probably due to intense glacial erosion in rocks with limited resistance.

Kaolinite-bearing rocks have a restricted geographical distribution in Norway today. Thus, the majority of the kaolinite content in the investigated ODP core samples cannot be explained by the transport of this mineral from Norway during post-glacial time. However, one might expect that the weathering products formed in pre-glacial times were mineralogically different from most of the surface sediments found in Norway today. The greater part of these old weathering products, i.e. kaolinite, were removed from the land during the Pleistocene, and then redeposited somewhere outside of the Norwegian coast (Haldorsen, 1974).

9.0 LITHOLOGY OF COASTAL WESTERN NORWAY AND THE CONTINENTAL SHELF, AS INFLUENCED BY PLEISTOCENE GLACIATION

9.1 Coastal Sediments Off Møre, Norway

In the areas between latitudes 62°N and 71°N (off the coast of Møre, western Norway; see Fig.4), Holtedahl and Bjerkli (1975) collected information from echo-soundings, from continuous seismic profiles, and from analyzed sediment samples (grab, dredge, core). They divided the surface sediments into four categories, based on the information collected:

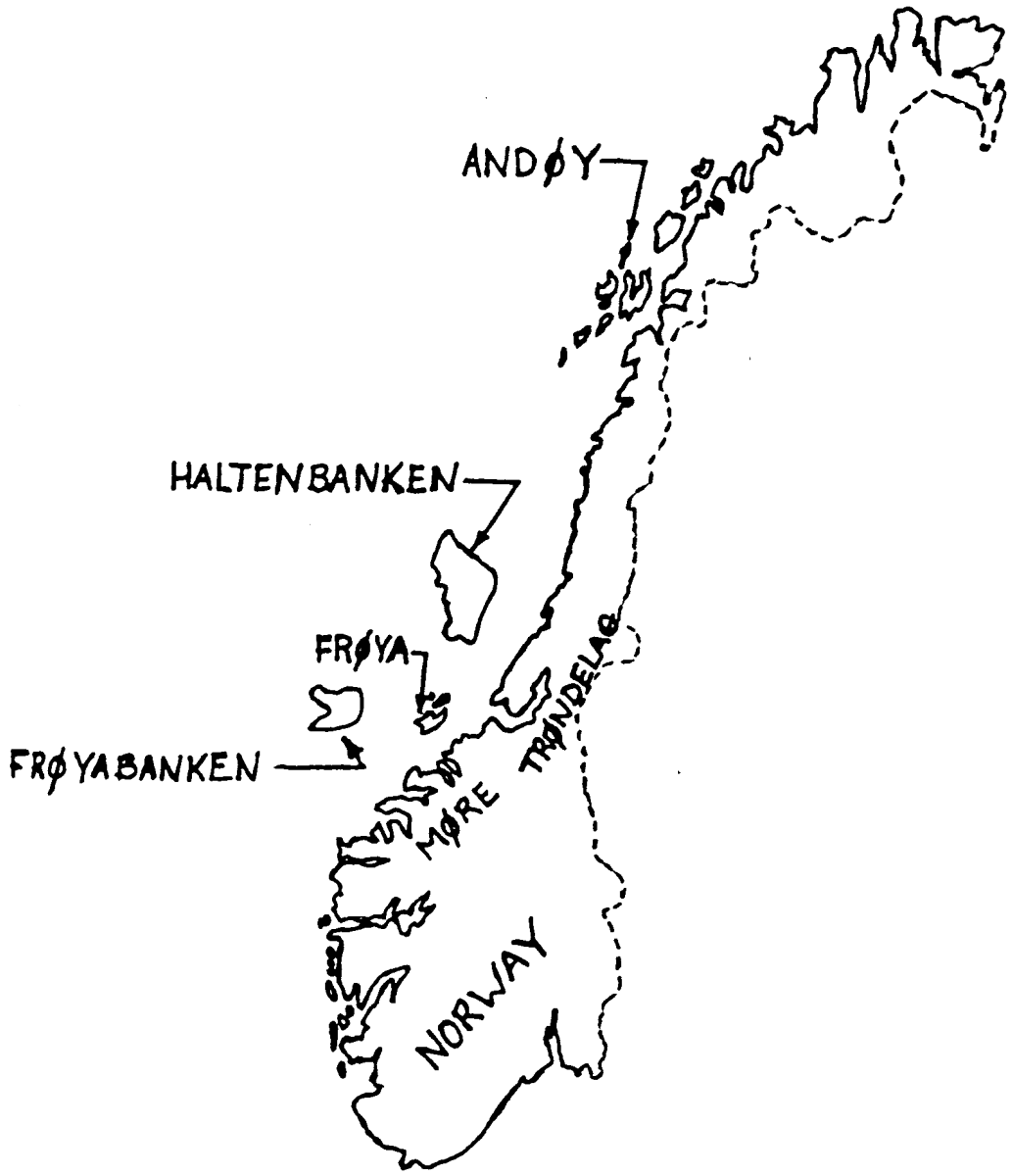

Fig.4. Map of Norway and the continental shelf.

1. Till, mainly composed of material derived from the adjacent mainland.
2. Till mainly containing material derived from Mesozoic-Tertiary bedrock on the continental shelf.
3. Lag deposits from 1 & 2, mainly in shallow areas.
4. Secondarily transported sand and finer material winnowed out from 1 & 2, and deposited at intermediate and greater depths.

Categories 1 & 2 were distinguished by lithological analysis of sediments (textural investigations and mineralogy), and fossil assemblages, especially belemnite rostra.

9.1.1 Sediment Distribution

The distribution of the various categories, identified by lithology and fossil assemblages, is clearly related to water depth. Shallow areas (<200m) off the coast contained coarse lag deposits and sand, which is secondarily transported by the action of waves and currents. Sand is also found at greater depths, where it is also thought to have been secondarily transported (Holtedall and Bjerkli, 1975). On the deeper parts of the shelf, as well as on the continental slope, boulder clay occurs; silty clays are present in other deep areas. Holtedahl and Sellevol (1971) suggest that the clay and silt materal in the

deeper areas of the continental shelf may have been winnowed from the shallower parts of the shelf. Thus the clay and silt material found at greater depths on the Norwegian shelf is redeposited from till material, and has been recycled from the shallower parts of the shelf. Holtedahl and Bjerkli (1975), however, believe that very little of the fine sediment load brought to the sea from land would have actually settled on the continental shelf. They claim that most of the very fine fraction would have bypassed the shelf in suspension, and then have been deposited at greater depths. The clay material being examined in this project may be a portion of the fine-grained sediment that bypassed the shelf and was redeposited in deeper water.

9.2 Lithology of Sediment Core from a Submarine Ridge Off Western Norway

A sediment core from the northwest slope of a submarine ridge between Haltenbanken and Frøyabanken, western Norway (see Fig. 4.), was examined by Holtedahl and Bjerkli (1975). The core consisted of an upper, 150 cm thick postglacial clay, and a lower clayey deposit with disintegrated rock fragments and high organic content, supposedly representing glacial till. Fossil assemblages indicated the rock fragments were of Middle and Late Jurassic, Cretaceous and Early Tertiary age. Furthermore,

the clay mineral assemblage had a high content of kaolinite (approximately 30-40%, although the method involved in calculating the kaolinite percentage was unspecified). Thus, the kaolinite in the core sample is at least Early Tertiary in age, and may be as old as Middle Jurassic.

9.3 Other Lithological Studies

Several other studies of sediment cores obtained from the continental shelf off western Norway have also indicated a notable presence of kaolinite. Haldorsen (1974) and Bugge et al. (1975) found kaolinite percentages to be between 10 and 30% on the shelf outside Trøndelag. Haldorsen (1974) also analyzed sediments obtained northwest of the island of Frøya (see Fig. 4.). She found that kaolinite percentages were also between 10 and 30% in that area. These studies indicate that kaolinite is commonly found on the Norwegian continental shelf today, and that during its geologic history, kaolinite was likely to have been found in Norway. Thus, the selection of Norway as a source area for kaolinites found in the ODP core samples is valid.

10.0 PLEISTOCENE HISTORY OF NORWEGIAN KAOLINITE

10.1 Glacial Erosion

The studies previously mentioned indicate that kaolinite is commonly found along the Norwegian

continental shelf, as the glacial till and clays examined contain 10 - 40% kaolinite. Studies indicate that glacial movement between latitudes 62°N and 71°N on the continental shelf, during the maximum extent of the Pleistocene glaciation, was directed towards the west and northwest (Holtedahl and Bjerkli, 1975). From this information, it can be inferred that kaolinite-rich bedrock from Norway was subjected to erosion, the disintegrated rock was then transported westward by ice and icebergs, and the kaolinite-rich till was deposited off the Norwegian coast.

10.2 Current and Wave Erosion

Sea levels experienced major fluctuations during the Pleistocene. This suggests that current and wave erosion on the continental shelf may have been extensive. The finest fractions of the till material on the eroding shelf would have been winnowed out from these areas by currents, carried in suspension, and then redeposited in deeper waters (Haldorsen, 1974).

10.3 RELATION BETWEEN KAOLINITE PLEISTOCENE HISTORY AND THE INVESTIGATED ODP SEDIMENT CORE SAMPLES

It is quite likely that the kaolinite in the samples investigated here experienced a multi-step history of transport and deposition during the Pleistocene, similar to that described previously. The majority of the

kaolinite-bearing rocks, which were weathering products formed during pre-glacial times, were removed from the land during the Pleistocene and deposited on the continental shelf, seaward of the Norwegian coast. The shelf area was subsequently exposed to glacial, current, and wave erosion, and the old weathering products were transported further seaward, perhaps in suspension, and deposited in deeper water. Some of these sediments were deposited on the Vøring Plateau, and were subsequently recovered during ODP Leg 104. Mineralogical data from Deep Sea Drilling Project Sites 341 and 343, drilled during Leg 38, on the Vøring Plateau (Emelyanov et al., 1978), indicated a relationship between the glacial sediments within the cores and the crystalline rocks (granites) of eastern Norway, which would have contributed sediments. The kaolinites observed here may have also come from eastern Norway.

11.0 KAOLINITE AGE DETERMINATION

The rock fragments recovered from the submarine ridge between Haltenbanken and Frøyabanken by Holtedahl and Bjerkli (1975) contained a high content of kaolinite (30 - 40%). Fossil assemblages, in particular belemnite rostra, indicated that these rock fragments were of Middle and Late Jurassic, Cretaceous, and Early Tertiary age. Thus, the kaolinite in the rock fragments is recycled material that is at least

Tertiary in age, and perhaps as old as Middle Jurassic. If the source of the kaolinites sampled at various locations along the northwest coast of Norway is the same as that from the submarine ridge between Haltenbanken and Frøyabanken, then the age of the other kaolinites is at least Tertiary, and may be as old as Mid-Jurassic. Kaolinite found in these ODP cores at Sites 642B, 643A and 644A may also be recycled Mid-Jurassic to Tertiary kaolinite. This conclusion is supported by unpublished compositional data from ODP Site 642B which indicate that kaolinite was found throughout the entire drilled core (Krissek, 1986, unpublished data). Since the oldest sediments obtained during drilling were Eocene in age, the presence of kaolinite throughout the core suggests that the kaolinite is at least Eocene in age.

Sediments of Jurassic-Early Cretaceous age, which contain a clay fraction with 90% kaolinite, occupy an area of about 8km^2 along the northeast coast of Andøy, Norway, an island situated just to the northwest of Norway (see Fig. 4.). These sediments have escaped erosion because of down-faulting (Dalland, 1975).

Results from K-Ar dating (Sturt, et al. 1979) indicate the possibility that the kaolinite weathering event was of Devonian or earliest Carboniferous age; a minimum age of 342 million years was derived from the dating. The development of such a weathering profile requires humid, sub-equatorial climatic conditions. Paleolatitude reconstructions for the

Early Carboniferous shows Andøy lying approximately 20° north of the equator, while Andøy lies at approximately 5°N during the Devonian (Sturt et al., 1979). These locations suggest that the environment during the Devonian and Early Carboniferous was favorable for kaolinite formation.

Sturt et al. (1979) interpret the initial development of the kaolinitic regolith on Andøy as occurring during Late Devonian time. From Carboniferous to Late Triassic times, the regolith was buried. Changes in tectonic regime during the Late Triassic produced phases of block-faulting, tilting and erosion, culminating in the uplift of the eastern part of the present Norwegian shelf (including Andøy). As the kaolinitic regolith was eroded, during and after the Middle Jurassic, the recycled kaolinite was redeposited in Jurassic and Cretaceous sediments. Evidence for erosion and reworking is seen in resedimented clay materials, clastic sediments and spores in Jurassic to Lower Cretaceous sediments (Sturt et al., 1979).

Several studies indicate that kaolinite-rich weathering profiles, of which the Andøy example is just a small relict, were formerly widespread across the region. Pre-Jurassic kaolinitic regoliths are also known from Greenland, Bornholm, southern Sweden and various localities within the Carboniferous of Scotland (see Fig. 5; Hurst, 1985).

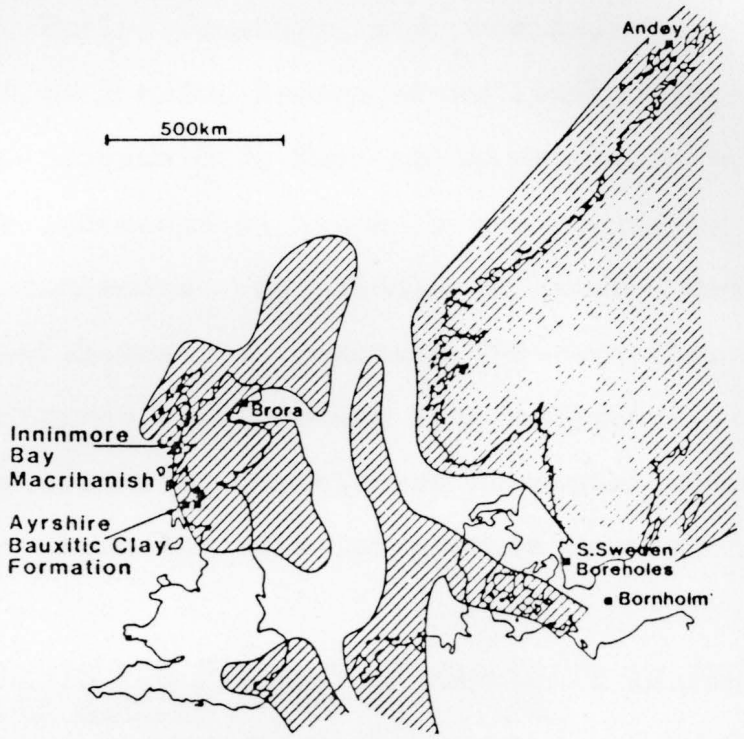

Fig 5 Paleogeographic map of NW Europe during the lower Jurassic with present-day outcrops of Carboniferous kaolinitic regoliths shown Major landmasses are shaded (Modified from Hurst, 1985)

Paleoclimatic and paleogeographic reconstructions show that a tropical climate extended over all these areas, shown in Fig 5, during the Carboniferous This climatic environment was favorable for the formation of a kaolinitic regolith (Hurst, 1985) Hurst (1985) agrees with Sturt et

al. (1979) that kaolinitic regoliths formed in these areas during the Carboniferous. Because of regional tectonism, these sources were uplifted and eroded, beginning in the Late Triassic to Early Jurassic and continuing onwards. These sources acted as a major source of kaolinitic detritus during the Middle Jurassic. The multi-cyclic nature of the Carboniferous sediments is shown by the occurence of reworked spores and sediments. As Middle Jurassic and Cretaceous sediments were themselves reworked by erosion, the relict kaolinite contained in them was also recycled. In this way, the kaolinite became a constituent Norwegian pre-Pleistocene sediments all along the coast of western Norway.

12.0 HYPOTHESIS FOR PRESENCE OF KAOLINITE IN THE NORWEGIAN SEA CORE SAMPLES

A synthesis can be developed from the various kaolinite-related research articles presented in the previous sections of this paper in order to present a working hypothesis to explain why kaolinite occurs in these ODP drilling core samples.

The hypothesis is as follows:

During Devonian and Carboniferous time, Norway, as well as other geographical areas shown in Figure 5, was positioned near the equator, resulting in a tropical climate. Such a humid climate was favorable for kaolinite formation. As time progressed, the kaolinite, which had begun its development in the Devonian, was buried by a variety of younger sediments;

burial continued until the Late Triassic. At that time, changes in the tectonic regime resulted in the uplift of part of the present Norwegian shelf, forming topographical highs, which served as sites of erosion. Middle Jurassic through Cretaceous erosion removed the overlying sediment from the kaolinite, and eventually exposed the kaolinitic regolith, which was subsequently eroded and re-deposited in the Jurassic and Cretaceous sediments. As the mid-Jurassic and Cretaceous sediments were themselves reworked by erosion, the relict kaolinite contained in these sediments was also redistributed, and continued erosion spread the kaolinite into many pre-Pleistocene sediments in Norway. During the Pleistocene, Norway was heavily glaciated. Transportation of Norwegian terrigenous sediments, including the kaolinite, was provided by ice, by icebergs, by currents, and, on the slopes of the Vøring Plateau, by suspension currents. As a result, kaolinite has a very restricted occurrence on Norway today, but was removed from the land during the Pleistocene, and was deposited outside the Norwegian coast before being transported out to greater depths of water. This is the history of the kaolinite recovered at the ODP Leg 104 sites in the high-latitude Norwegian Sea on the Vøring Plateau.

13.0 CONCLUSION

Clay mineralogy alone is obviously not enough to independently indicate the kaolinite history of ODP sites

642B, 643A, and 644A. Other information, such as a complete core description of mineral and chemical data and the types of sedimentary structures present, would provide more conclusive evidence, especially when combined with clay mineral constituent data. However, the purpose of this report was to gather information on the presence of kaolinite at high latitudes in order to present a hypothesis as to why kaolinite is present in these core samples when not expected. In order to provide such a hypothesis, this paper presented a synthesis of research conducted by other geologists on topics related to the topic of interest, i.e., why kaolinite is found at high latitudes, where conditions are unfavorable for its formation.

Kaolinite has been shown to not be forming on the continents adjacent to the Norwegian Sea today; instead, the kaolinite has been derived from terrestrial sources containing relict soils developed during a warmer climate. Because of the close proximity of ODP Leg 104 sites to Norway, Norway was selected as the most likely terrestrial source from which the kaolinite in these core samples was derived. (Other possible source areas include Greenland, Scotland and other northwestern European countries, but these locations are all farther away from the drilling sites; I have limited my research to Norway.)

During Devonian and Carboniferous time, Norway, as well as the other geographical areas listed in Figure 5,

experienced an equatorial climate, resulting in the formation of kaolinite. (K-Ar dating of kaolinitic deposits in Andøy, Norway indicate a Devonian age (Sturt et al., 1979)). During the Tertiary, as changes in the tectonic regime caused the opening of the Norwegian-Greenland Sea, the kaolinite-bearing deposits were uplifted and subsequently eroded, resulting in the resedimentation of pre-existing Mid-Jurassic and Cretaceous sediments. Mid-Jurassic and Cretaceous sediments were reworked by erosion, and the relict kaolinite contained in those sediments was gradually eroded and redistributed into many pre-Pleistocene sediments. During the Pleistocene, the kaolinite-bearing rocks were intensely eroded from the land by glaciers, and were deposited on the Norwegian continental margin. Transportation of Norwegian terrigenous sediments, including kaolinite, from the margin to greater water depths was provided by ice, icebergs, and currents, and by suspension currents on the slopes of the Vøring Plateau. This recycled material, including kaolinite, was later found at ODP Sites 642B, 643A and 644A.

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