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Sediments of Glacial Origin in the Area of Operations of D.S.D.P. Leg 38 (Norwegian—Greenland Seas): Preliminary Results from Sites 336 and 344

by

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Zusammenfassung

Während der 38. Reise des Bohrschiffes Glomar Challenger, die in den nördlichen Nordatlantik führte, wurden an allen Bohrorten Sedimente glazialer Herkunft erschlossen. Diese Sedimente haben eine Verteilung, die andeutet, daß der norwegische Strom während der Depositionszeit wenigstens intermittierend tätig war. Die Anfänge glazialer Sedimentationsbedingungen sind an den verschiedenen Bohrorten nicht gleichaltrig. Sehr frühe Anfänge solcher Sedimentationsbedingungen sind an den Bohrorten 336 und 344 angedeutet. Hier erhält man ein Alter von 7.4 m.j.v.h. für die untersten Glazialsedimente, wenn man zur Errechnung Sedimentationsgeschwindigkeiten benutzt, die ihrerseits auf vorliegende paläontologische Unterlagen und hypothetische Pliozän-Pleistozän-Grenzen in den Bohrkernen gestützt sind. Diese Altersbestimmung erscheint zu hoch und deutet wahrscheinlich pliozäne Sedimentationsgeschwindigkeiten an, die höher als solche während des Pleistozäns waren. Wir bevorzugen ein Alter, das ungefähr mit der Miozän-Pliozän-Grenze übereinstimmt, d.h. etwa 5 m.j.v.h. Grobes Sedimentmaterial, das wahrscheinlich eisverfrachtet ist, gibt es auf verschiedenen Niveaus pliozänen und pleistozänen Alters. Besonders in Sedimenten des Oberpleistozäns gibt es (unterschiedlich) hohe Anteile groben Materials, die bedeutende Glazialepisoden andeuten. Diese Episoden müssen wenigstens teilweise mit den klassischen europäischen und nordamerikanischen Kontinentalvereisungen übereinstimmen.

Abstract

Sediments of glacial origin were encountered at all sites drilled during D.S.D.P. Leg 38 (Norwegian-Greenland Seas). These sediments form a pattern which suggests that the Norwegian Current was intermittently active throughout the time of deposition. The beginning of ice-rafting (and other mechanisms suggestive of glacial conditions) is not synchronous at the various sites. Very old ages seem to be recorded at Sites 336 and 344. By using rates

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of sedimentation based on available paleontological information and a hypothetical Plio-Pleistocene boundary in the cores, an apparent age of 7.4 m.y.B.P. is derived for the basal portions of these sediments at both sites. This age appears to be too high, and probably indicates higher-than-Pleistocene rates of sedimentation during the Pliocene. Instead, an age somewhere near the Miocene-Pliocene boundary (about 5 m.y.B.P.) is preferred. The record shows variable amounts of coarse material (ice-rafted?) at various levels in the Pliocene and lower Pleistocene portions of the sedimentary column. In the upper Pleistocene portions, high but variable amounts of coarse material suggest major glacial episodes which must be correlative with at least some of the classical European and North-American continental glaciations.

Introduction

In the months of August and September 1974, Leg 38 of the Deep Sea Drilling Project was carried out in the Norwegian and Greenland Seas (henceforth referred to as the Norwegian-Greenland Seas). Among a number of specific objectives of this voyage was an investigation of the thickness, age, and mode of deposition of glacial-marine sediments. Such sediments were known to cover the area of ope-

Fig. 1: Index map adapted from TALWANI, UDINTSEV, et. al. (1976).

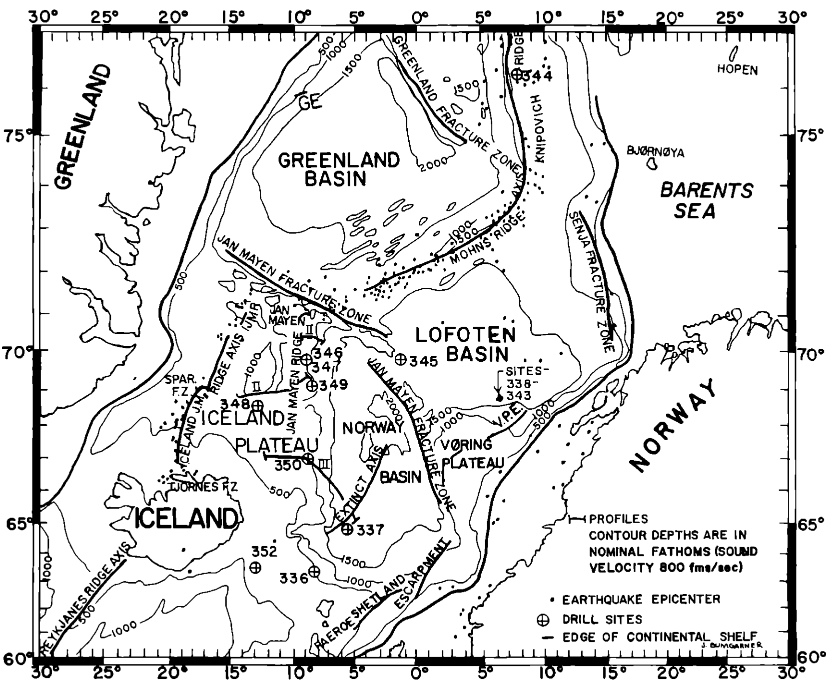


Table 1: Drill Sites, D.S.D.P. Leg 38, and thickness of "glacial" sediments.

DSDP Site Number	LATITUDE	LONGITUDE	Thickness Glacial Sediments
336	63°21.06'N	07°47.27'w	159m
337	64°52.30'N	05°20.51'N	35 m
338	67°47.11'N	05°23.26'E	112m
339	67°12.65'N	06°17.05'E	
340	67°12.47'N	06°18.38'E	
341	67°20.10'N	06°06.64'E	
342	67°57.04'N	04°56.02'E	
343	68°42.91'N	05°45.73'E	
344	76°08.89'N	07°52.52'E	372m
345	69°50.23'N	01°14.26'W	40 m
346	69°53.35'N	08°41.14'W	32 m
347	69°52.31'N	08°41.80'W	32 m
348	68°30.18'N6	12°27.72'W	64 m
349	69°12.41'N	08°05.80'W	59.3m
350	67°03.34'N	08°17.68'W	55.5m
352	63°38.97'N	13°28.26'W	54 m

rations (e.g., IMBRIE & KIPP, 1971; KELLOGG, 1973), and had been investigated previously (e.g., KELLOGG, 1973). However, these investigations were based on collections of piston cores which only penetrated deposits of late Pleistocene-Holocene age, or reached pre-Pleistocene deposits only where Pleistocene sediments are very thin and incomplete (e.g., SAITO et al., 1967). Therefore, rotary drilling afforded a welcome opportunity to assay the total thickness of these sediments and to get some idea on their distribution in the Norwegian-Greenland Seas (Fig. 1, Table 1). It was assumed that these materials would contain the record of initiation of ice-rafting in the Norwegian-Greenland Seas and thus provide evidence for the initiation and development of (continental) glaciation on the surrounding land masses. It should be pointed out that the selection of individual drill sites was in the main based on "tectonic" considerations, i.e., sites were chosen with a view to optimize the return of information on the history of evolution of the ocean basin. This resulted in "clumping" of drill sites in certain areas of tectonic interest such as the Vøring Plateau. Information of a sedimentary nature therefore is still very spotty and awaits more extensive drilling efforts.

This report is based on shipboard investigations, and on preliminary laboratory analyses. It describes general patterns of distribution of sediments of glacial origin, and is particularly concerned with glacial sediments at Sites 336 and 344 which seemed to offer the best hope of defining the earliest beginning of glacial conditions in the study area. Synchroneity with other sites is not inferred and indeed would be erroneous in view of the results from Site 348, not discussed here. The paper is intended to give an overview over the glacial sediments encountered on D.S.D.P. Leg 38. More detailed analyses are in progress.

Methodology

After retrieval, the cores were split and described in the Sedimentology Lab aboard D/V GLOMAR CHALLENGER. As part of the visual description, "smear slides" (see below) were prepared and described. These lithologic descriptions (of the sediments) were prepared by the Sedimentology Team as part of the general descriptions of each drill site, and are contained in Volume 38 of the Initial Reports of the Deep Sea Drilling Project (TALWANI, UDINTSEV, et al., 1976).

In addition to the above, samples of about 10 cm^3 were taken from the "working half" of the cores and shipped to our lab at California State University, Hayward. As part of these preliminary investigations, additional smear slides were prepared for Site 344, in the following manner: a small amount of the sediment was placed on a glass slide and dispersed with a few drops of distilled water. The slide was dried at 80 °C, the smear embedded in Caedax (N = 1.55) and covered. The slides were examined under a petrographic microscope and the percentages of terrigenous sand, silt and clay were estimated. In addition, the longest diameter of the largest grain in each slide was measured and recorded.

In order to check the accuracy of the visual analysis, ten smear slides were chosen at random and mechanically point counted. Predictably, the greatest error occurred in the estimate of the percentage of clay-sized material (up to 15 %). It is therefore assumed that the estimates are accurate within 15 %. These data were combined with the information contained in the core log for Site 344. Graphs were then constructed in which the percentage of sand-sized material was plotted against depth below sea floor (BSF).

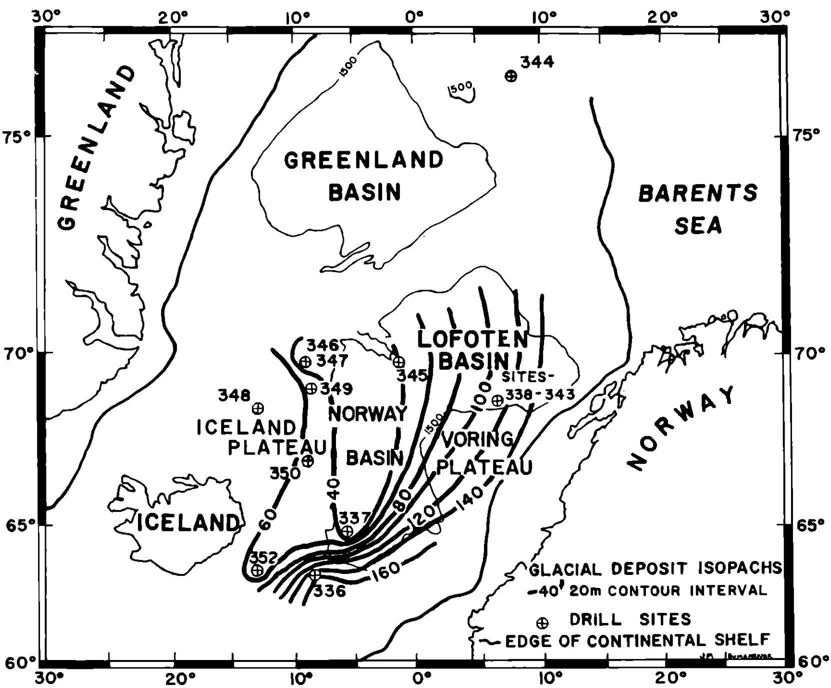
For sediment samples from a number of core catchers retrieved at Site 336, analyses of coarse fractions were performed as described later on. Details of other shipboard procedures and of classification schemes are contained in the Shipboard Handbook, Leg 38, D.S.D.P., D/V GLOMAR CHALLENGER (unpublished ms.).

Distribution

In view of the limitations indicated earlier, only a few inferences regarding the distribution pattern of sediments of glacial origin can be drawn. The isopleth map (Fig. 2) shows an apparent axis of minimum thickness in the Norway Basin, possibly an artifact because of lack of control. The thickness increases away from this apparent axis to 60m and more over the Iceland Plateau-Jan Mayen Ridge, and to similar thicknesses on the Vøring Plateau (Table 1, compare with Fig. 2). In this region a thickness of over 300m occurs at Site 341, a value which does not reflect original sedimentation, but is a result of slumping. An average thickness for all sites on the Vøring Plateau was used in the construction of the isopleth map.

The general pattern seems to indicate increasing sedimentary thicknesses towards the sediment sources in Greenland and Scandinavia. Site 344, the northernmost site, is too isolated from the rest of the sites to be included here, and will be described separately. It is interesting to compare these preliminary findings

Fig. 2: Isopleth map: thickness of "glacial" sediments.
See text for details of construction.



with the detailed studies of surface and Late Quaternary sediments in the Norwegian-Greenland Seas by KELLOGG (1973). Although details do not match, a general trend of increasing percentages of coarse material towards Scandinavia and portions of the Greenland coast seems to be indicated (see KELLOGG, 1973, Fig. 2). In addition, a calcium-carbonate percentage maximum in the Norway Basin is interpreted as reflecting relatively high productivity in the surface water, and this in turn is associated with warm surface-water circulation, i. e., the Norwegian Current. This current then profoundly influences sedimentation patterns in the Norwegian-Greenland Seas both by controlling the productivity of the surface water and by influencing the distribution of icebergs and attendant glacial-marine sediments (KELLOGG, 1973).

Our preliminary results confirm and extend KELLOGG's observations. The apparent sediment minimum (see Fig. 2) largely coincides with the Norwegian Current. It appears from our data that in a gross fashion, this overall pattern has remained similar throughout the period of deposition of the sediments under investigation. Details of course may have changed drastically. It is KELLOGG's contention that the current was either very weak or absent during 100,000 or more do not the past 127,000 years. Gross sediment thicknesses as shown in our data do not permit any estimates of current-duration. However, the current system must have been intermittently active throughout the time-span represented by the sediments studied herein to have resulted in the observed distribution pattern.

Ages, and Dates of Initiation

Because ot the scarcity of diagnostic fossils in the sediments of glacial origin, exact determinations of the initiation and evolution of glacial-marine processes remained tenaciously elusive. Nevertheless, certain inferences can be drawn from the few diagnostic fossils that are present in these sections, from rough age estimates based on extrapolations of rates of sedimentation, and from comparisons with other regions.

Site 336

The total thickness of sediments containing materials of glacial origin is 159 m (surface to core catcher 13). Predominant lithologies are clay, mud, sand and silt (Fig. 3). Scattered pebbles were noted in several portions of the column. All of these sediments comprise one lithologic unit (Unit 1, see description in TALWANI, UDINTSEV, et al., 1976) and are separated by an unconformity from the underlying Late-Oligocene materials.

The ages of the sediments under study are given as Plio-Pleistocene (Cores 1—5, 0—45 m) and Pliocene (Cores 6—13, 45—159 m). These age determinations are based on microfossils within the section. However, no fossils were present in the basal portions of the "glacial" column, and therefore the initiation of glacial conditions, indicated by a lithologic change in core catcher 13, must be approximated by rates of sedimentation. If we take 45 m as the Plio-Pleistocene boundary, and

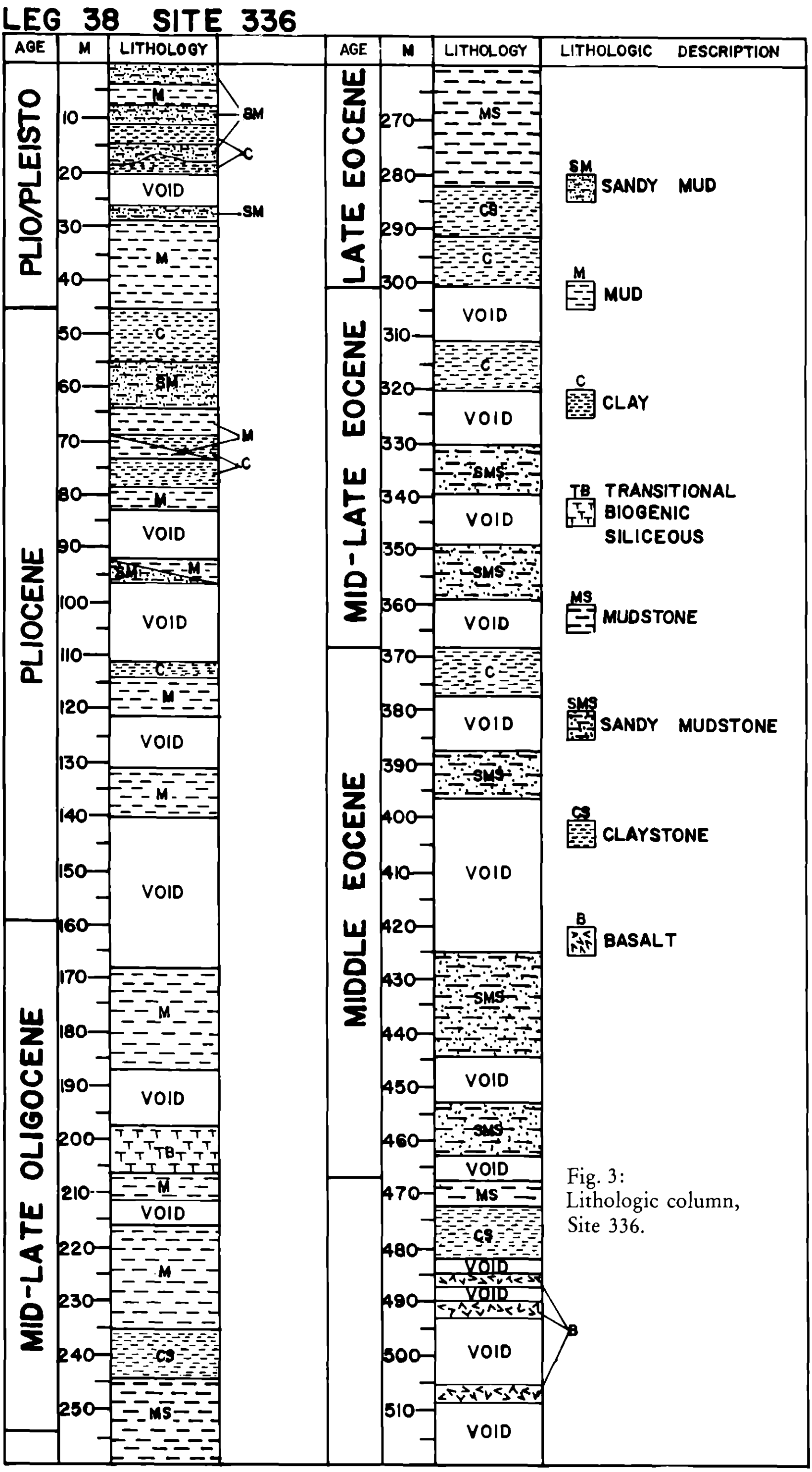


Fig. 3:
Lithologic column,
Site 336.

adjust for compaction using Table 7 of HAMILTON (1976), we obtain an original thickness of 47.7m. Taking the Plio-Pleistocene boundary as 1.8m.y.B.P. (e.g., RYAN, et al., 1974) we obtain an average rate of sedimentation of about 2.65 cm/1000 y. If we use this rate of sedimentation as a first approximation, adjust the thickness of the remaining "glacial" sediment column as above (yielding an original thickness of 196,6m) and extrapolate to the bottom of the sediments of glacial origin we obtain a date for the initiation of glacial conditions of about 7.4m.y.B.P.

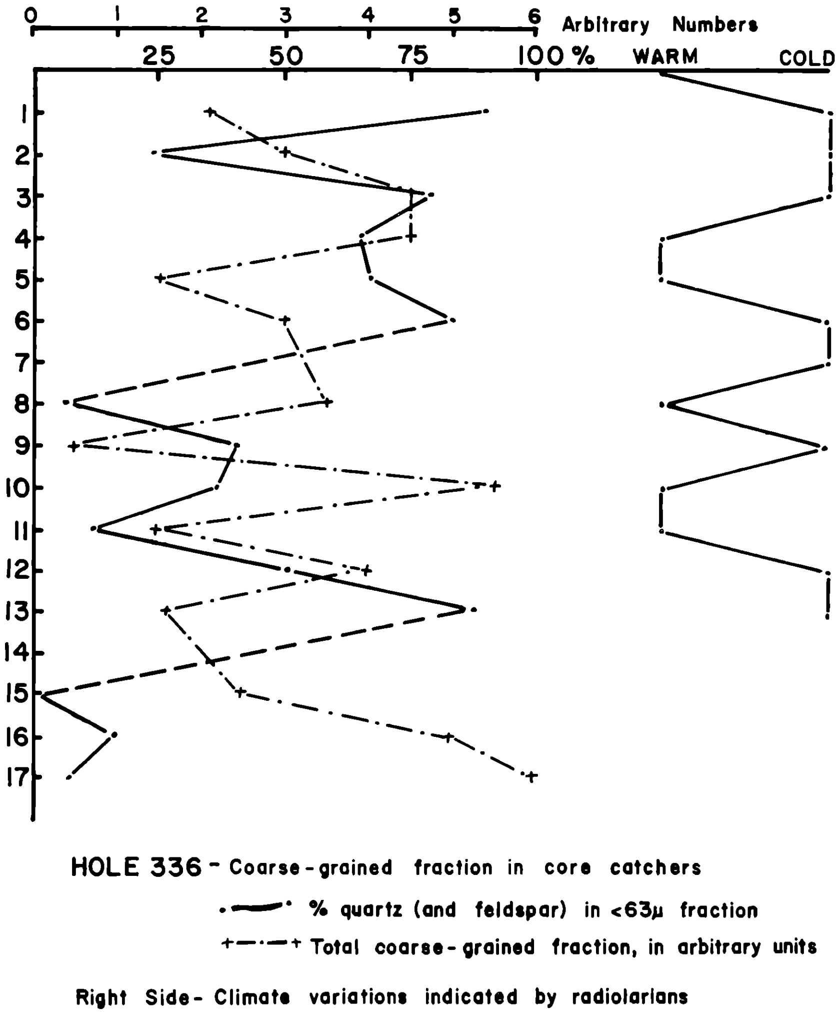
This estimate seems too high as explained below, but not unreasonably so in view of the evidence for Miocene, 9-10m.y.old glaciations in Alaska (DENTON and ARMSTRONG 1969; BANDY et al., 1969). Our estimate probably reflects higher-than-Pleistocene rates of sedimentation for the Pliocene portion of the column. Preliminary shipboard estimates placed the initiation of glacial conditions at 3 m.y.B.P. This estimate however, was based on BERGGREN's (1972) determination of the date of initiation of glacial-marine sedimentation in the northern hemisphere (3 m.y.B.P.); no independent data for Site 336 were available. Later, shore-lab analyses of microfloras from Site 336 suggested earlier dates of initiation (see SCHRADER & FENNER, 1976).

The present estimate of 7.4 m.y.B.P. is probably too high because of: a) uncertainties in the establishment of time-lines based on micropaleontology, b) variations in rates of sedimentation caused by biogenous and non-biogenous contributions and c) imprecise estimates of original thickness because of variable compaction. In any event, the beginnings of "glacial conditions" at Site 336 certainly appear to be 3 m.y.B.P. or older. Our estimate has been arrived at using an age of 1.8 m.y. for the Plio-Pleistocene boundary, following prevailing practice (e.g., RYAN et al., 1974) and consequently the initiation of "glacial conditions" at Site 336 must be placed in the early Pliocene, if not earlier. If we prefer an age of 3 m.y.B.P. for the Plio-Pleistocene boundary (Dr. Jan van Hinte, written commun.), our estimate of the initiation of these conditions would have to be suitably adjusted.

What emerges is the beginning of glacial, or at a minimum pronounced periglacial conditions in the source areas at least during the Pliocene. This ist not surprising in view of evidence from Antarctia (CRADDOCK et al., 1964), Patagonia (MERCER, et al., 1975), the Southern Ocean (e.g., KENNETT, 1972) and the northern hemisphere, both terrestrial and marine (reviewed by BERGGREN, 1972). Site 336, however, provides as yet no answer to the exact beginning of glacial conditions during (?) the Pliocene (?).

In order to test initially the hypothesis that at this relatively southern site the intensity of ice-rafting reflects the severity of climatic conditions, a few approximations of the amount of ice-rafted material per unit volume of sediment were carried out aboard the vessel. This was first approached by sieving (after deflocculation and acidification) 6 cc of sediment from each available core catcher through a 44 micron sieve, followed by an estimate of the remaining volume of the coarse fraction, using the squares on a micropaleontology slide as "volumetric index"

Fig. 4: Coarse fraction, Site 336. See text for explanation.



(see Fig. 4). These estimates, however, (shown as "arbitrary numbers" on Fig. 4) yield a non-climate sensitive index because of the large amounts of volcanic and biogenic admixtures. Point-counting of 300 grains, however, yielded a relative frequency of light-mineral grains (predominantly quartz) which can be used as a first-approximation indicator of ice-rafting, especially since a number of quartz grains display breakage features which are perhaps indicative of glacial action (e. g., KRINSLEY & MARGOLIS, 1969; KRINSLEY & DOORNKAMP, 1973).

The resulting frequency curve reflects the intensity of ice-rafting which in this area may be a direct indicator of climatic conditions. This is suggested by the correlation with the "climatic curve" (right-hand side of diagram, Fig. 4) which is based on radiolarian indicators (BJøRKLUND, 1976). The curve shows initiation of ice-rafting with Core 13 and the variations of intensity of ice-rafting with climatic conditions. A significant discrepancy exists only in Core 2, where severe difficulties in disaggregation of clay-sized material invalidated the count.

Several large climatic oscillations are clearly shown. Because of the large sampling interval, no inferences concerning the number of climatic oscillations (number of pulses of ice-rafting activity) can be drawn, nor should the number of frequency of quartz grains be taken as a direct indicator of temperature. Nevertheless, these preliminary data do show the relatively sudden initiation of ice-rafting in the late Tertiary (above a hiatus separating these terrigenous sediments from older, more biogenous materials). They also show variations in ice-rafting directly linked to climatic oscillations, making this area a prime target for more detailed investigations of paleo-climatic and paleo-oceanographic changes in the North Atlantic during the Late Quaternary ice ages.

Site 344

This site was of particular interest from a paleo-climatic point of view, since it was hoped to yield information on the initiation of glacial conditions at these high latitudes and to provide an opportunity for correlation between high northern and southern latitudes. The entire sequence consists of terrigenous sediments as summarized in Fig. 5. Detailed descriptions as well as technical information is contained in TALWANI, UDINTSEV, et al. (1976).

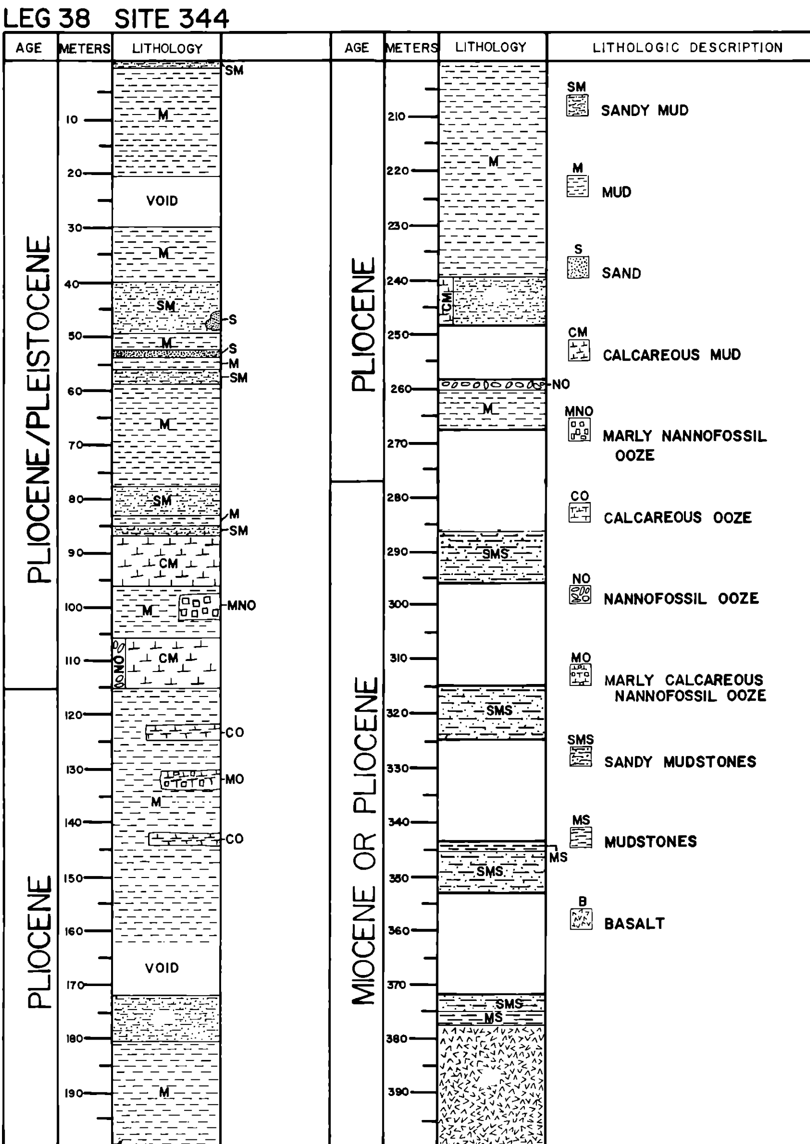
Briefly, the lithologic units of the sedimentary column consist of the following:

Unit 1: (Cores 1 to 20; 0—182 m); The unit has been subdivided into Subunit **A** (Cores 1 to 5; 0—40 m) consisting of muds and sandy muds, with volcanic components, and Subunit **B** (Cores 6—20; 40—182 m) consisting of muds, sandy muds, diamictons, and clays, with minor stringers of sand and volcanic ash. Pebbles are unevenly (?) distributed, turbidites occur in the center of Subunit **B**. Burrows, nanno ooze and glauconite are also present.

The entire Unit 1 is interpreted as terrigenous, i. e., mainly glacial-marine, in addition to sediments derived from suspensoids and deposited by other mass-transport media.

Unit 2: (Cores 20 to 28; 182—258 m): Sandy muds and diamictons, with pebbles prominent in Core 27 (239—248.5 m). Foraminifera in this unit show discoloration, beginning with Core 24 (210.5—220 m) and increasing in intensity downward. These sediments are largely glacial-marine; the discoloration of the foram tests is attributed to baking from an underlying sill.

Fig. 5: Lithologic column, Site 344.



Unit 3: (Cores 28 to 33; 258—378 m): This unit is subdivided as follows: Subunit **A** (Cores 28 to 33; 258—372 m): Mud and sandy mud are dominant; muddy sandstone and sandstones also occur. Cross-bedding, bioturbation textures, and pyrite are also present. These sediments are interpreted as terrigenous, deposited by turbidity currents and similar mechanisms, and by ice-rafting (indicated by pebbles).

The underlying Subunit **B** (Core 33; 372—378 m), is similar to Subunit A, but contains no identifiable ice-rafted materials (pebbles). The sections display a series of sedimentary sequences beginning with coarse (sandy) beds at the bottom and becoming finer upward. Bioturbation is particularly extensive in parts of this subunit. This entire sequence may represent turbidites or similar deposits, laid down in the time span between the genesis of the seafloor and the beginning of glacial-marine conditions. Subunit B terminates in basalt.

Laboratory analysis: Two hundred and eight samples from this site were used to prepare smear slides as described in the methodology section. The results of this examination show the following (refer to Fig. 6):

The sediments at Site 344 are of variable texture. They range from apparently well-sorted sands through very poorly sorted muds to clays. According to the present tabulations, 66 % of the sediments are muds, clay composes 21 %, sandy mud 8 %, silts 2 % and sands a surprisingly low 1 %. The mud layers in the investigated portions of the column are generally 1—2 m thick but do occasionally attain a thickness of 8 m. The layers of other materials are usually less than 1 m thick.

The following history of sedimentation is suggested: Deposition commenced with turbidites (?) of Subunit 3 B, above the basalt. These sediments in part may have been deposited by "distal" turbidity currents. In addition, winnowing by bottom currents is indicated by silt beds (e.g., 376.3 m BSF) perhaps indicating intensified circulation caused by freezing of surface water. The overlying Subunit 3 A contains pebbles which may have been ice-rafted. Slumping cannot be excluded but the graded nature of, and cross bedding present in, Subunit 3 A make this alternative less attractive. Inspection of Fig. 6 shows that coarse material was sporadically introduced into the environment, but the nature of the depositional processes remains speculative.

Only a few pebbles have been encountered in Unit 2. The bulk of this sediment may have been settled out from suspensoids which were generated at least under periglacial (?) conditions.

Unit 1 shows again increasing amounts of sand sized material (Fig. 6) mostly in discrete layers with very little transition between layers of different textures. Interesting is also the occurrence of silt beds (e.g., at 51.3, 53.3, 135.3, 154.3 and 376.3 m BSF) indicative of episodes of increased bottom-current activity. These variable sediments are interpreted as reflecting deposition during a changing glacial regime. There is a noticeable coarsening of the material from Core 15 (125.0—134.5 m) on upwards, and particularly in Subunit 1 A. These coarse-

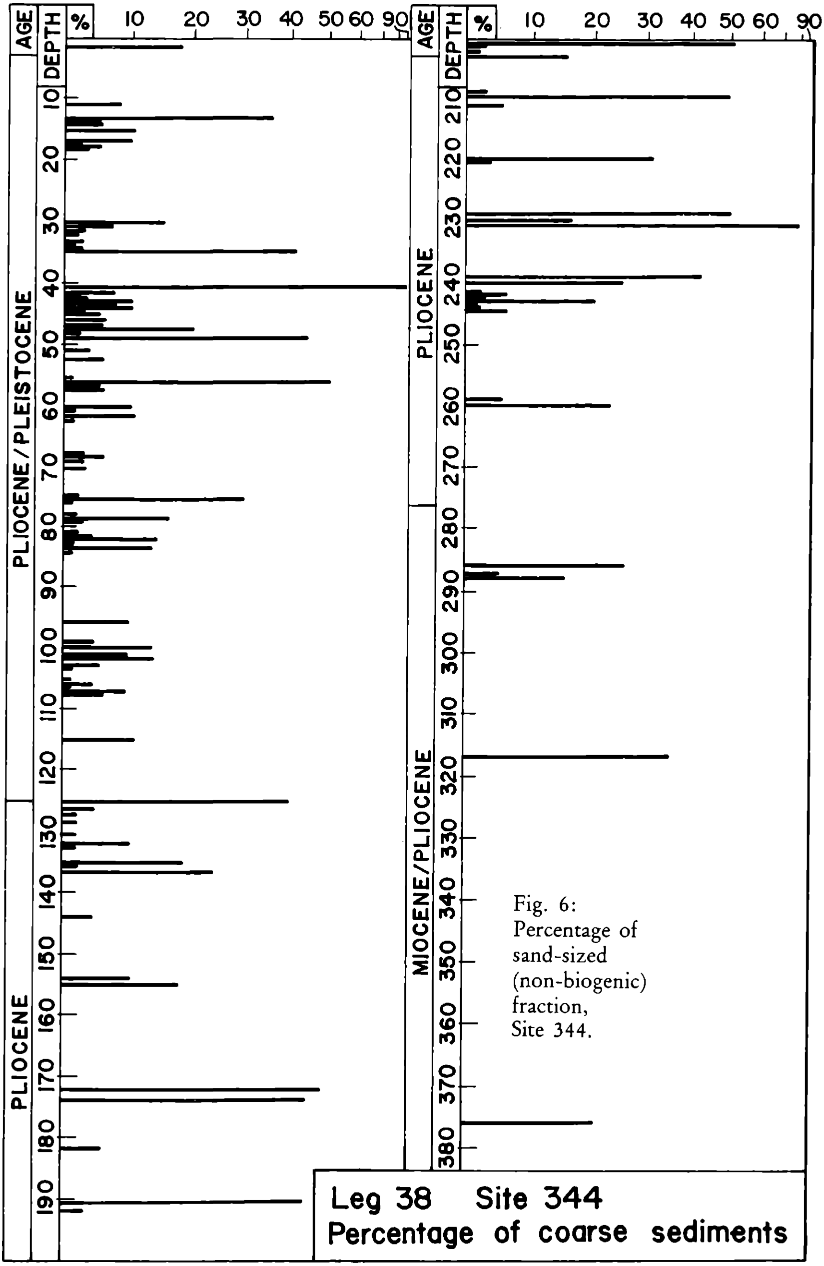


Fig. 6:
Percentage of sand-sized (non-biogenic) fraction, Site 344.

grained layers, interbedded with finer-grained material, probably reflect the existence of major waxing and waning, continental ice sheets.

The historical framework for the depositional history of these sediments can only be approximated because of uncertainties in the interpretation of the scarce paleontological record. This is expressed in the age-labelling of Fig. 5 (see Biostratigraphic Summary, Site 344, in TALWANI, UDINTSEV, et al., 1976). Only as a working hypothesis can we assume a Pleistocene age for the sediments (below the surface layer of Holocene sediments) down to and including Core 13 (115.5 m BSF). The age assignment of the basal sediments is beset with even more uncertainties. A review of the biostratigraphic information for this site (in TALWANI, UDINTSEV, et al., 1976) shows the consensus that the basal layers may be of early Pliocene, or perhaps Miocene age.

Therefore, as a first approximation we may equate the beginning of ice-rafting (at 372 m BSF) with the vicinity of the Miocene-Pliocene boundary, (about 5 m. y. B. P., according to SAITO et al., 1975, p. 239).

If we use the calculated sedimentation rate for the Pleistocene (?) section of the column (7.4 cm/1000 y, adjusting for compaction as above) and extrapolate to the bottom of the „glacial" sediments we obtain an age of approximately 7.4 m. y. This calculated age is probably too high, and reflects a higher (than Pleistocene) rate of sedimentation as has also been postulated by LAUGHTON, BERGGREN et al. (1972) for Site 113. Nevertheless, this calculated age lends some support to the suggestion that ice-rafting at Site 344 started at least in the vicinity of the 5 m. y. B. P. time line. Neither the presently available sediment-petrographic evidence, nor the paleontological evidence presented in TALWANI, UDINTSEV, et al. (1976) excludes an even earlier beginning (during the late Miocene).

Because of the lack of cored sections above the described boundary, little can be said about sedimentary processes just above that boundary, i. e., during the remainder of Unit 3 time. The nature of the described sections show that turbidity-current activity was dominant.

During the time represented by Unit 2 sedimentation was largely (but certainly not exclusively) glacial-marine. The coarseness of many of these sediments (refer to Fig. 6) is typical.

During the following time represented by the lower portions of Unit 1, ice-rafting did take place in addition to depositional and winnowing activity by bottom currents (refer to silt beds described above). Our data also show a remarkable increase in coarseness, and general textural variability, of the sediments from the 60 m level upward. This level is just below the Brunhes-Matuyama boundary which is at approximately 52 m BSF as again established by rates of sedimentation. It seems that during Brunhes time (represented by the upper portions of Subunit B, and Subunit A) glacial-marine processes became dominant. These processes are perhaps reflections of major waxing and waning, continental, ice sheets, as pointed out earlier. It must be reemphasized that the use of "magnetic" time-stratigraphic terminology does not mean that paleomagnetic information is presently available. This terminology is merely employed for reasons of convenience and to facilitate discussion.

Discussion

Nature of the Sediments

In the foregoing, reference has been made to sediments of "glacial" origin. From the appearance of the sediments it is clear that they are not entirely, and in many portions of the cores not even predominantly, "glacial-marine". Sedimentary processes other than ice-rafting were at many times predominant or even were the exclusive agents of sediment transport and deposition.

Sedimentary materials that "diluted" the ice-rafted materials were for instance minor biogenic contributions (e.g., Site 336), and turbidity-current deposits (e.g., the lower portions of the sedimentary column at Site 344). The predominant impression of the sediments under discussion is their terrigenous provenance. Generally, in the Norwegian-Greenland Seas, terrigenous, clastic sediments occur in two positions in the sedimentary column: a) at and near the basement, and b) in the top portions of the column. An exception is Site 344 where the entire sediment column is terrigenous. While the "basal" terrigenous sediments are probably related to the vicinity of land source-areas, the "top" terrigenous sediments must be related to tectonic movements and/or climatic conditions in the source areas. The terrigenous sediments at the two sites discussed herein are of Pliocene? (Miocene?) to Holocene age, and are therefore likely to reflect orogenic movements in the source areas as well as climatic deterioration and ultimately, glaciation.

Transport Mechanism at Sites 344 and 336

Our present analyses are as yet not detailed enough to sort out the relative importance of individual conditions and transport mechanisms. It is nevertheless clear that the nature of the sediments in the Pliocene portions of Site 344, for instance, as well as their high rate of sedimentation, indicate the importance of turbidity-current activity. The fine texture of these sediments suggests their deposition from "distal" turbidity currents. These currents in turn may have been triggered by erosional processes in the nearby West Spitzbergen mobile belt, perhaps accelerated by climatic deterioration leading to periglacial conditions. Finally, glacial conditions are indicated by the pebbles in Subunit 3 A and scattered through the sediment column. However, much of the fine-grained sediment may also be glacial-marine. These sediments show apparent poor sorting and polymodality which are indicative of ice-rafting (see KAGAMI, 1964). Although the sediments at Site 344 are not identical to sediments carried in floating icebergs (see WARNKE and RICHTER, 1970), they do seem to fall within the range of glacial-marine sediments described from the Antarctic Peninsula (WARNKE, et al., 1973), i.e., modified after initial settling out (see a.o. ANGINO and ANDREWS, 1968; KEANY, et al., 1976, for discussions of modifying processes). Some of the clay beds in the sedimentary column probably represent times of complete ice cover and deposition from suspensoids. The pebbles which are occasionally found within them are probably dropstones, indicating that even under these conditions the entire pack ice moved, similar to present conditions in the Arctic Ocean.

The available X-ray data for Site 344 (Table 2, from TALWANI, UDINTSEV, et al., 1976) do not shed much light on the origin of the sediments. Somewhat surprising is the high percentage of montmorillonite, generally in excess of the percentages reported by BERRY and JOHNS (1966) for the Greenland Sea. An ill-defined trend from higher to lower montmorillonite values towards the top of the cores may be present, perhaps reflecting instability of the montmorillonite phase. More detailed clay-mineral analyses are needed. In any event, the available data seem to point to a nearby land source (indicated by high montmorillonite values) but cannot be used to document climatic changes. These conclusions are in agreement with those reached by BERRY and JOHNS (1966).

At Site 336 turbidites are also present, particularly in the interval 7.0—113.0m BSF. Although the nature of the sediment at this site (finer grained at the bottom, coarser at the top of the "glacial" sequence), has been interpreted as reflecting low sedimentation rates in the lower portions of the sequence (see TALWANI, UDINTSEV, et al., 1976) our calculations of sedimentation rates indicate that this may not be the case. Perhaps at this site also, turbidity current activity was predominant in the beginning of the sequence, although difficult to recognize in the cores.

At both sites, coarse-grained material increases towards the top of the sedimentary column, strongly indicative of increased importance of ice-rafting. This increased aount of ice-rafted material in turn may reflect either: availability of large amounts of debris in the source areas at the beginning of periglacial conditions, or intensity of glacial erosion, not necessarily directly correlated with thickness of ice cover, climate, etc., (see WARNKE, 1970; WEAVER and DINKELMAN, 1976, a.o.)

Historical Framework

As pointed out earlier, the overall historical framework of glacial-marine sedimentation can only be approximately established. If our inferences concerning the nature of the "glacial" materials at Site 336, and the pebbles in Subunit 3A at Site 344 are correct, then a beginning of "glacial" conditions prior to 3 m.y.B.P. is certainly indicated. That our rough approximations of this initiation indicate an age of about 7.4 m.y.B.P. for both sites is probably coincidental, but it does point to a beginning of glacial conditions somewhere in the vicinity of the Miocene-Pliocene boundary, about 5m.y.B.P This interpretation allows for synchronous establishment of continental glaciation in both the northern and the southern hemisphere, but our data do not shed light upon the controversy surrounding the evolution of continental glaciation near the Miocene-Pliocene boundary. For

Table 2: Results of X-Ray Analysis, Site 344 (courtesy British Petroleum Co. From TALWANI, UDINTSEV, et al., 1976).

Depth	Core	Sec.	Cm	Mont	Ill	Kaol	Chlor
3.7	2	2	70	30	28	16	24
15.1	3	3	110	19	40	18	22
34.1	5	3	110	34	30	18	17
43.4	6	3	90	29	36	17	17
54.4	7	4	86	22	42	16	18
63.5	8	4	49	24	28	23	24
71.7	9	3	68	17	37	19	25
80.7	10	3	19	31	48	9	10
100	12	3	49	41	31	13	13
106.5	13	1	50	25	43	14	17
116	14	1	50	39	31	11	17
128.5	15	3	50	45	31	11	11
136.5	16	2	50	34	35	14	15
144.5	17	1	50	15	62	5	16
154	18	1	50	59	25	7	7
154.1	18	1	60	40	19	20	20
184	21	2	50	48	33	8	9
203	23	2	50	54	27	7	10
211.7	24	1	120	65	26	4	4
220.7	25	1	70	42	33	10	13
230.9	26	1	140	42	11	14	17
260	28	2	50	26	40	13	17
318.8	31	3	83		40	24	36
345.8	32	2	78		43	57 k/c	
					34	65 k/c	

instance, paleotemperatures based on silicoflagellates delineate a major cooling trend between 4.30 and 3.70m.y.B.P. in the Southern Ocean (CIESIELSKI & WEAVER 1974). This trend in turn reflects a major climatic deterioration and establishment of true Antarctic conditions. Such a finding is in agreement with the results of BLANK & MARGOLIS, (1973) who noted a great increase in ice-rafted material during Gilbert "a" (3.9—3.7m.y.B.P.) in cores from the Southern Ocean, and with evidence from Patagonia (MERCER et al., 1975) where the age of the earliest known Cenozoic glacial event has been established at about 3.5m.y.B.P. However, CIESIELSKI & WEAVER's (1974) interpretation is contradictory with evidence from New Zealand where a profound cooling period was identified with the Kapitean Stage (4.75—4.3m.y.B.P. KENNETT & WATKINS, 1974). This stage was placed by these authors in the late Miocene, although they also suggested its placement in the early Pliocene, while RYAN, et al. (1974), reinterpreting KENNETT & WATKINS' (1974) data, consider the Kapitean Stage to straddle the Mio-Pliocene boundary. An interpretation of the molluscan evidence as indicative of warm sea temperatures during the Kapitean in New Zealand (BEU, 1974) adds to the confusion. In any event, widespread ice-rafting in the Southern Ocean during the late Miocene- early Pliocene has been suggested by a number of authors (e.g., GOODELL et al., 1968; KENNETT, 1972; BANDY et al., 1971). Our data suggest that during this general time period ice-rafting occurred also in parts of the Norwegian-Greenland Seas, but the data do not aid in the precise timing of these episodes within the Miocene or Pliocene.

Oxygen-isotope data from D.S.D.P. Site 284 (40°30.48'S, 167°40.81'E) presented by SHACKLETON and KENNETT (1975) were interpreted to mean that during the Kapitean the volume of ice stored in Antarctia was 50% greater than today. Foraminiferal evidence suggested a following period of prolonged relative warmth (4.1—2.6m.y.B.P.) interrupted only by a minor cooling about 3.5 to 3.4m.y.B.P. (KENNETT & VELLA, 1975). At about 2.6m.y.B.P. the accumulation of northern hemisphere ice commenced, leading ultimately to the Pleistocene glaciations (SHACKLETON & KENNETT, 1975; KENNETT & VELLA, 1975).

The suggestion of a significantly larger-than-present Antarctic ice cap during the Kapitean Stage may be in accord with some of the evidence as described above, but it is nevertheless puzzling, since such extensive Antarctic ice cover should have severe world-wide climatic repercussions. We cannot discern such severe climatic conditions in our data, largely because of lack of material since unfortunately, we do not have enough cores from the critical interval to investigate this problem. If SHACKLETON & KENNETT's (1975) data in any way could be re-interpreted in terms of a minor cooling during the Kapitean Stage and a significant ice accumulation at about 3.5 m.y.B.P., greater harmony at least with the data of CIESIELSKI & WEAVER (1974) and MERCER et al., (1975) could be achieved. It is also interesting that DENTON & ARMSTRONG (1969) describe a tillite from the Wrangell Mountains, Alaska, that is juxaposed with a 3.6 + 0.2. m.y. — old lava flow.

The period of relative warmth from 4.1 to 2.6 m.y.B.P. postulated by SHACKLETON & KENNETT, (1975) cannot be discerned in our data either, perhaps again because of lack of control. Still, coarse-grained material, perhaps indicative of ice-rafting, is quite conspicuous in the assumed interval. This does not necessarily indicate very cold temperatures but does at least suggest conditions favorable to extensive ice-rafting. It is also noteworthy that within this time interval (at about $t = 3.0$ m.y.) occurred not only the first glaciation in California (CURRY, 1968; DALRYMPLE, 1972) and Iceland (McDOUGALL & WENSINK, 1966; EINARSSON et al., 1967), but also the first influx of ice-rafted material at D.S.D.P. Site 116 (BERGGREN, 1972). Lower and middle portions of the upper half of the borehole show only moderate coarse-grain peaks without dramatic changes at the assumed Pliocene-Pleistocene boundary (at 115.5 B.S.F., Site 344). The Matuyama-Brunhes boundary (0.69 m.y.B.P.) is at about 52m B.S.F., using the above described assumptions. A significant influx of coarse-grained material just below the assumed Brunhes-Matuyama boundary, and during the Brunhes Epoch, is clearly shown (Figure6). Particularly noteworthy in this interval are the pronounced variations in the percentages of coarse-grained material (from 0 % up to 90 %) reflecting large, waxing and waning, continental ice sheets, as pointed out earlier.

As a working hypothesis we propose the following: an early beginning of ice-rafting episodes (near the Miocene-Pliocene boundary), followed by episodes of significant ice-rafting thereafter, not necessarily indicative of extremely cold temperatures but of conditions favorable to glacial erosion in the beginning of groups of major glaciations (WARNKE, 1970). Sediments assumed to have been deposited during the upper Pliocene and lower Pleistocene Epochs show relatively minor amounts of "glacial" material, a fact whose significance remains problematic. High, but variable amounts of "glacial" material in the upper Pleistocene portions of the sediment column indicate major glacial episodes which must be correlative with at least some of the classical European and North-American continental glaciations.

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