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INTERNAL DOCUMENT 15

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DEEP SEA SEDIMENT TYPES ON THE NORTH ATLANTIC SEA FLOOR

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DEEP SEA SEDIMENT TYPES ON THE NORTH ATLANTIC SEA FLOOR

Robert B. Kidd,
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Prepared for A. E. R. E., Harwell, as part of initial studies of the option for high level radioactive waste disposal beneath the seabed. March 1977.

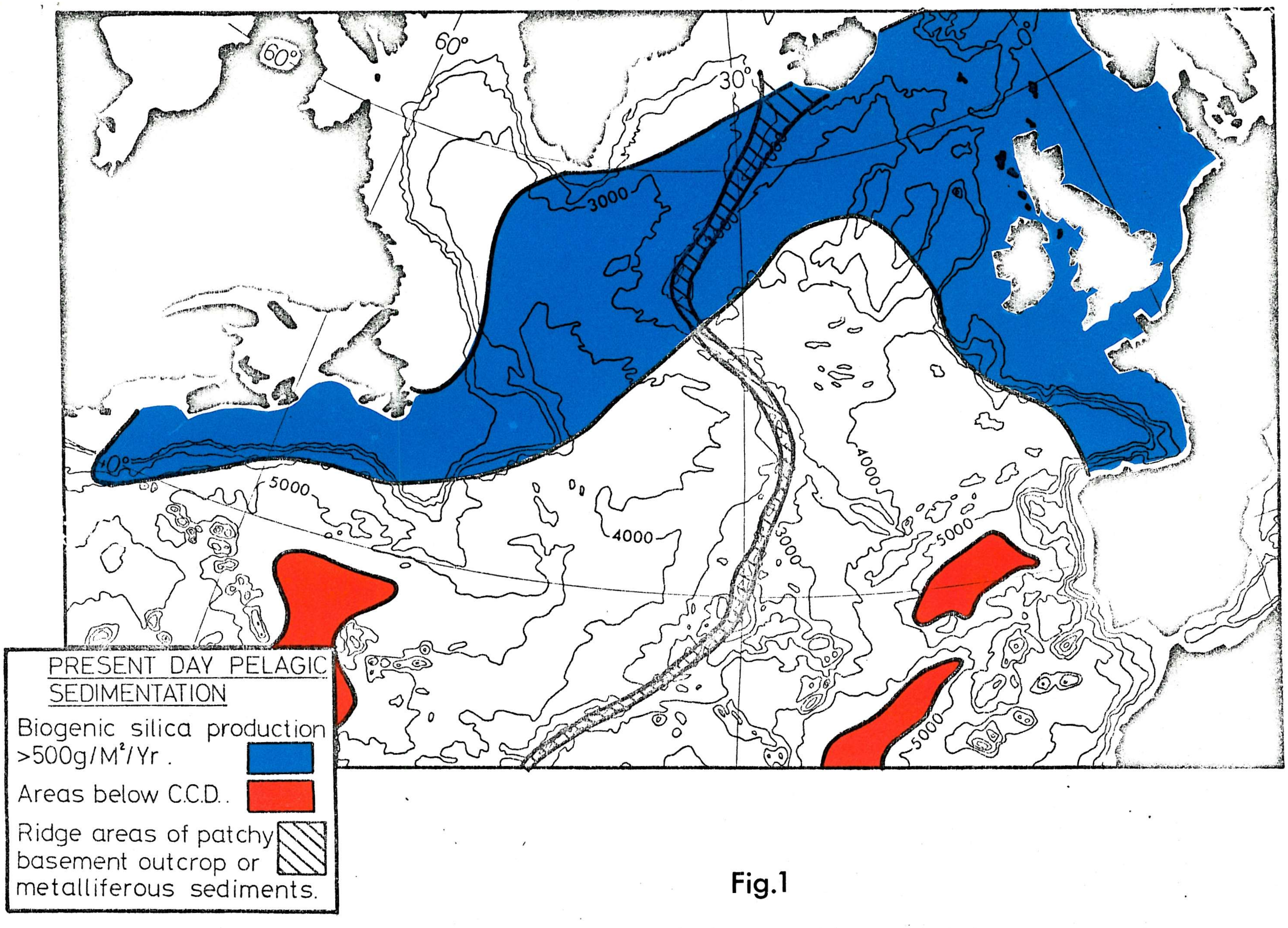
INTRODUCTION

These notes have been assembled to present a brief review of deep sea sediment types that could be encountered in the North Atlantic during a research programme linked to wast disposal. They also outline some sediment properties that might be relevant to eventual methods of disposal.

Discussion is confined to those areas of the deep ocean floor beyond the continental margins. Probably no more than 20% of the total volume of sediment in oceanic environments is located here since the great bulk of the Earth's contemporary sedimentation occurs actually on the continental margins. On the other hand, the distinction between margins and deep ocean areas is artificial as far as sediments are concerned since the terrigenous sediments (derived from the subaerial erosion of land areas) which dominate the margin province, frequently extend beyond it and onto the deep ocean floor. This is particularly true in the North Atlantic Ocean.

Perhaps as little as half of the sediment on the deep ocean floor is truly oceanic in type; that is, biogenic ooze made up of the microscopic fossil tests of oceanic organisms, or deep water pelagic clay, the bulk of which was originally dust carried by winds from the continents. There are two main types of biogenic ooze depending upon the composition of the material that made up the skeletal parts of the microscopic organisms: calcareous ooze and siliceous ooze. These oozes and clays make up the pelagic sediments and are the products of geochemical cycles within the world oceans whereas the terrigenous sediments are primarily the products of submarine physical transport of material from the land.

In the Pacific and Indian Oceans the distinct sediment types referred to above - calcareous ooze, deep sea clay, siliceous ooze and terrigenous sediment - commonly occur, as well as a complete range of mixtures of these "end-members". The occurrence as the dominant sediment type of deep sea clay and siliceous ooze, is strongly dependent upon whether there are areas that are below the critical depth at which carbonate is capable of completely dissolving. This 'carbonate compensation depth' (C. C. D.) varies between 5000 and 6000 meters in the North Atlantic. Some abyssal plains and small troughs do exist which are sufficiently deep to preclude the deposition of calcareous ooze by dissolution but these are not sufficiently remote


60°
60°
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5000
PRESENT DAY PELAGIC SEDIMENTATION
Biogenic silica production >500g/M²/Yr .
Areas below C.C.D. .
Ridge areas of patchy basement outcrop or metalliferous sediments.

Fig.1

from land areas that they cannot be reached by copious supplies of rapidly-depositing terrigenous sediment. Thus no pelagic clays are present north of 35°N. Similarly, productivity of siliceous organisms is sufficiently high in a zone south of Iceland for siliceous ooze deposition at depths below the CCD (Figure 1), but here again the seafloor is at higher elevation. In this area productivity of calcareous plankton is also very high; thus, although the calcareous oozes in this particular area are rich in siliceous fossils, there are no 'end-member' siliceous oozes accumulating anywhere in the North Atlantic. Percentages of siliceous fossils are everywhere less than 10%. This leaves two real end-member variables for the North Atlantic: calcareous ooze and terrigenous sediment.

It is important to stress the limited distribution of even these end-members in the North Atlantic. Sediment type at an individual location is strongly determined by processes of transportation and deposition that are active (or have been active) at that site. Most North Atlantic bottom sediments are complex mixtures of the end-members, especially of the biogenic calcareous oozes with the land-derived (terrigenous) sediments. In particular, nearly all of the sediments found between latitudes 50°N and 60°N have been transported long distances by various mechanisms before being deposited : winds; surface, intermediate and bottom currents (including deep geostrophic currents and turbidity currents); ice-rafting; volcanic eruption or a combination of any or all of these. Often the original source of the sediment is difficult to determine.

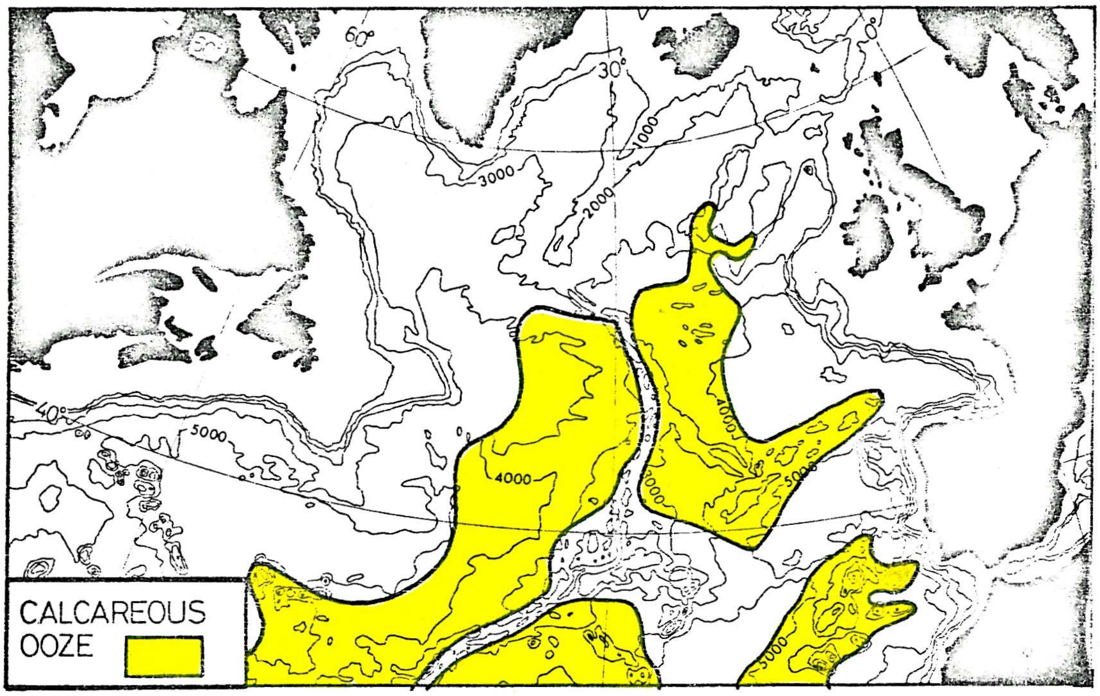
The following sections provide information on the four main deep sea sediment types or 'end-members'. It is impractical to collect similar information on mixed sediment types because of their infinite variation and dependence upon location. Quantitative information on deep sea sediments is sparse; thus most physical property values are quoted as ranges or typical average values. Variations with depth of penetration into the seafloor are quoted but it is important to note that these assume NO change in sediment type. This is frequently not the case because of changes in conditions since the last glacial period. The inset maps show likely distributions of sediment types : they are based only partially on actual sampling data. Mid-ocean ridges have little sediment cover on the basaltic crust out to 20 km distance from their crests.

CALCAREOUS OOZE

1. DISTRIBUTION IN NORTH ATLANTIC

'Pure' end member in all areas south of the belt of high biogenic silica production, that are sufficiently remote from land areas to be unaffected by terrigenous sedimentation.

MAP 1



2. COMPOSITION

End member: >90% $CaCO_3$, general range 50% - 80% $CaCO_3$. Calcium carbonate (calcite) almost entirely from microscopic skeletal remains of planktonic and benthonic organisms.

Major varieties: foraminiferal ooze, dominated by calcareous tests of planktonic animals (foraminifera).

: nannofossil ooze, dominated by calcareous skeletal remains of planktonic plants (coccoliths).

Nannofossils are the second most important constituent of foraminiferal oozes and vice versa. The non-biogenic fraction in each, made up mostly of clay minerals and quartz, comprises up to 10% of the end member and its proportion steadily increases in less pure oozes.

Other biogenic constituents that may be present in either variety (relatively minor amounts, $\leqslant$10%) include: benthonic foraminifera, ostracodes, echinoid and benthic coral remains (all calcite), pteropod and heteropod shells (aragonite), radiolaria, silicoflagellates, benthic spong remains (opaline silica), fish teeth and other vertebrate remains (phosphates).

Non-biogenic constituents, other than clay minerals and quartz, that may be present in trace amounts include: volcanic glass, mica, chert, iron and manganese aggregates, pyrite, glauconite, rock fragments (pebbles and gravel - glacial erratics), cosmic spherules, detrital and eolian carbonate (sometimes dolomite), feldspars, pyroxenes, and zeolites.

Organic carbon content is usually less than 0.2%.

Other varieties:

pteropod ooze - a relatively shallow water calcareous ooze, made up dominantly of pteropods and heteropods. These planktonic molluscs have shells made of aragonite. The ooze is confined to shallow ridges and rises in high productivity areas but may be redeposited by slumping to give distinct layers in foraminiferal or nannofossil oozes.

foraminiferal sands - very pure foraminiferal oozes which owe their coarseness to the winnowing away by currents of fine material during or after deposition of more normal ooze. These again are frequently found on rises or ridges where sea floor elevation increases near-bottom current velocities.

siliceous fossil rich calcareous ooze - presence of a belt of high biogenic silica production south of Iceland (see Figure 1) makes calcareous oozes in this area rich in siliceous biogenic material (approx. 10%).

calcareous ooze rich in volcanic material (mainly glass or zeolites) - occurs near the Azores where $CaCO_3$ values frequently drop to below 50% because of ash input from island volcanoes. This ooze occurs in association with distinct volcanic ash layers (see 'TERRIGENOUS SEDIMENTS').

3. COLOUR

End member is white or fawn. Less pure varieties tend increasingly towards shades of brown, green or grey, depending upon the degree of oxidation of the sediment or content of organic carbon.

4. TEXTURE AND GRAIN SIZE

Calcareous ooze sediments are generally soft, even soupy at the sediment surface, and become increasingly gritty with higher content of larger foraminifera and other macroscopic shell material. Below a few meters foraminiferal ooze can become very stiff. Nannofossil and fine foraminiferal oozes have a smooth creamy texture and stiffen less rapidly with depth.

Grain size generally in the silt and clay range. Typical average proportions are: 21% sand size (2.0 - 0.06mm); 47% silt size (0.06 - 0.004 mm); 32% clay size (< 0.004 mm). Foraminifera range in size from about 500 microns (μ) diameter to about 25 μ while nannofossils range 25 μ to 1 μ. Consequently foraminiferal oozes are coarser than nannofossil varieties; similarly foraminiferal 'sands' remain in the medium to fine sand size ranges while pteropod oozes may easily reach into the very coarse sand size range (up to 2cm diameter).

Typical median diameters (Md) for calcareous oozes range between 1 μ and 80 μ. Sorting is very good, sorting indices (So) are usually 1 or 2.

5. PHYSICAL PROPERTIES

Wet Bulk Density - 1.47 to 1.55 gms/cm^3 in surface calcareous oozes increasing to approx. 1.7 gms/cm^3 in near continental margins (S.G. averages 1.70). Density also increases sharply over upper 100 meters of subbottom depth in relatively pure ooze sequences.

Porosity - 75% to 80% in upper one meter of sediment decreases to around 60% at 200 meters depth.

Water Content - averages 80% in upper 20 meters and decreases by about 1.65% per meter of subbottom penetration.

Compressional Wave Velocity - 1.45 to 1.6 km/sec in upper 1 meter of sediment but lies between 1.6 and 1.85 km/sec at subbottom depths of 1 to 200m.

Characteristics on Seismic Profiles - Largely transparent but can have closely spaced fine reflectors. Drapes pre-existing bottom features.

6. ENGINEERING PROPERTIES

Pure calcareous ooze at the seafloor is essentially non-plastic, increased plasticity values reflect higher clay content. Similarly pure ooze has effectively no shear strength right at the sea floor, higher values again reflect increased clay mineral content. Shear strength values however increase with depth because of cementation.

For design purposes DSDP technical report recommends that the effective angle of internal friction should be taken as not greater than 20° for nannofossil ooze and not greater than 25° for foraminiferal ooze. Calcareous oozes are generally very susceptible to liquefaction.

7. INTERSTITIAL WATERS

In calcareous oozes pH values are usually around 7.4 within a few meters of the surface, while salinity is about 34‰.

8. ACCUMULATION RATES

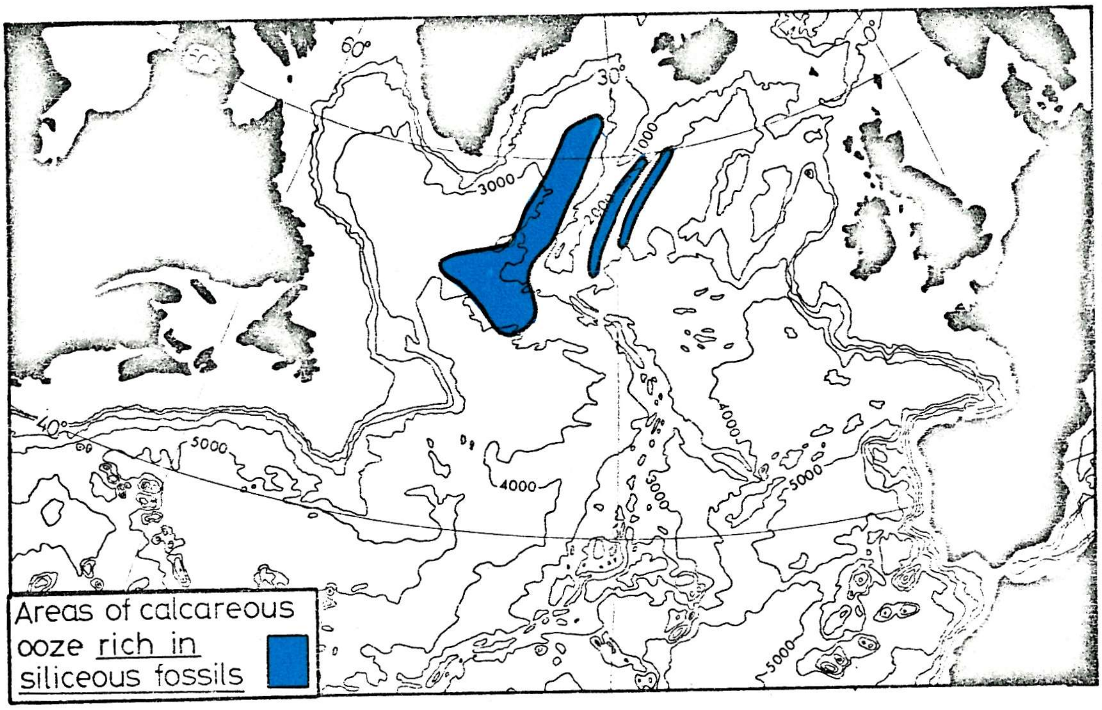
End member calcareous ooze, deposited on topographic elevations or on abyssal plains unaffected by current sedimentation, has accumulated at between 2.0 and 3.0 cm per 1000 years in the Northeast Atlantic during post-glacial time.

SILICEOUS OOZE

1. DISTRIBUTION IN NORTH ATLANTIC

NO END MEMBER. But northern belt of high biogenic silica production (see Figure 1) means that areas south of Iceland that are unaffected by terrigenous sedimentation are sites of siliceous fossil-rich calcareous ooze deposition (around 10% biogenic silica).

MAP 2



2. COMPOSITION

End member: > 50% biogenic opaline silica from microscopic remains of planktonic organisms. Siliceous ooze can only be present in areas of high biogenic productivity (i.e. polar and equatorial belts and areas of coastal upwelling) where the seafloor is at depths too great for calcareous ooze deposition (< 10% $CaCO_3$).

Major varieties: diatom ooze, dominated by the siliceous skeletal remains of unicellular plants (diatoms).

: radiolarian ooze, dominated by the siliceous tests of planktonic animals (radiolaria).

In the Antarctic and North Pacific belts of siliceous oozes, diatoms make up as much as 95% of the bulk sediment. The tests of silicoflagellates, another group of microscopic siliceous plankton, are second in importance with only traces of radiolarians. In the equatorial belt of siliceous oozes sediments dominated by diatoms can still occur, since radiolarians, which obtain their greatest abundance in equatorial waters, occur in very variable amounts in the bottom sediments. In this belt patches of radiolarian ooze with as much as 80% radiolarian debris occur, together with only minor amounts of diatoms and silicoflagellates. There are NO silicoflagellate oozes. Clay minerals make up any remaining portion of the bulk sediment in both varieties. Other biogenic constituents that may be present in trace amounts are sponge spicules, fish teeth and other vertebrate remains (NO CALCAREOUS MATERIAL).

Other than clay minerals and quartz, the non-biogenic fraction may include mica, rock fragments (pebbles and gravel : glacial erratics), volcanic glass, chert, iron and manganese mineral aggregates, cosmic spherules, feldspars, pyroxenes and zeolites.

Organic carbon content is generally less than 0.5%.

Other varieties: siliceous fossil-rich calcareous ooze - only siliceous variety to be found in the North Atlantic (see map) : basically a calcareous ooze with up to 10% siliceous fossils, mainly diatoms.

: siliceous fossil-rich deep sea clay - since deep sea clays are deposited in areas too deep for carbonates, they are concentrated in siliceous microfossils. This becomes extreme under areas of higher plankton productivity and such clays often contain 10 - 20% biogenic silica.

3. COLOUR

End member is pale yellow to olive grey or light brownish grey for Recent sediments; older siliceous oozes are often light bluish grey or green.

4. TEXTURE AND GRAIN SIZE

Generally soft to soupy at the sediment surface, smooth texture.

Grain size in the fine silt to clay size range. Typical average proportions are 2% sand size (2.0 - 0.06mm); 44% silt size (0.06 - 0.004mm); 54% clay size ($<$ 0.004mm).

Diatoms range in size from about 1000 microns (μ) length to about 5μ, radiolarians 250μ to 50μ, and silicoflagellates 400μ to about 50μ. But most siliceous skeletal material is broken up by the time it is incorporated in the sediment at the seafloor, especially the diatom frustules.

Typical median diameters (Md) are less than 7 μ. Sorting is good, sorting indices (So) between 2 and 2.5.

5. PHYSICAL PROPERTIES

Wet Bulk Density - little variation from the range 1.0 to 1.3 gms/cm^3 over upper 200 meters oozes. (S.G. below the range of normal land soils due to low S.G. of opaline silica.)

Porosity	-	80% to 95% in upper 100 meters.
Water Content	-	very high for end member, averages 100% over upper 120m with little variation over this depth range (entrapped water in spherical bodies).
Compressional Wave Velocity	-	approximately 1. 55 km/sec, little variation with depth.
Characteristics on Seismic Profiles	-	Almost transparent. Drapes pre-existing bottom features.

6. ENGINEERING PROPERTIES

Pure siliceous ooze right at the sea floor is essentially non-plastic; plasticity increases with greater clay content and with greater cementation at depth.

For design purposes DSDP technical report recommends that the effective angle of internal friction should be taken as not greater than 20°. Generally siliceous ooze has a high susceptibility to liquefaction.

7. INTERSTITIAL WATERS

In siliceous oozes pH values range from 7. 6 to 8. 1. Salinity is around 31‰ in the upper 20 meters.

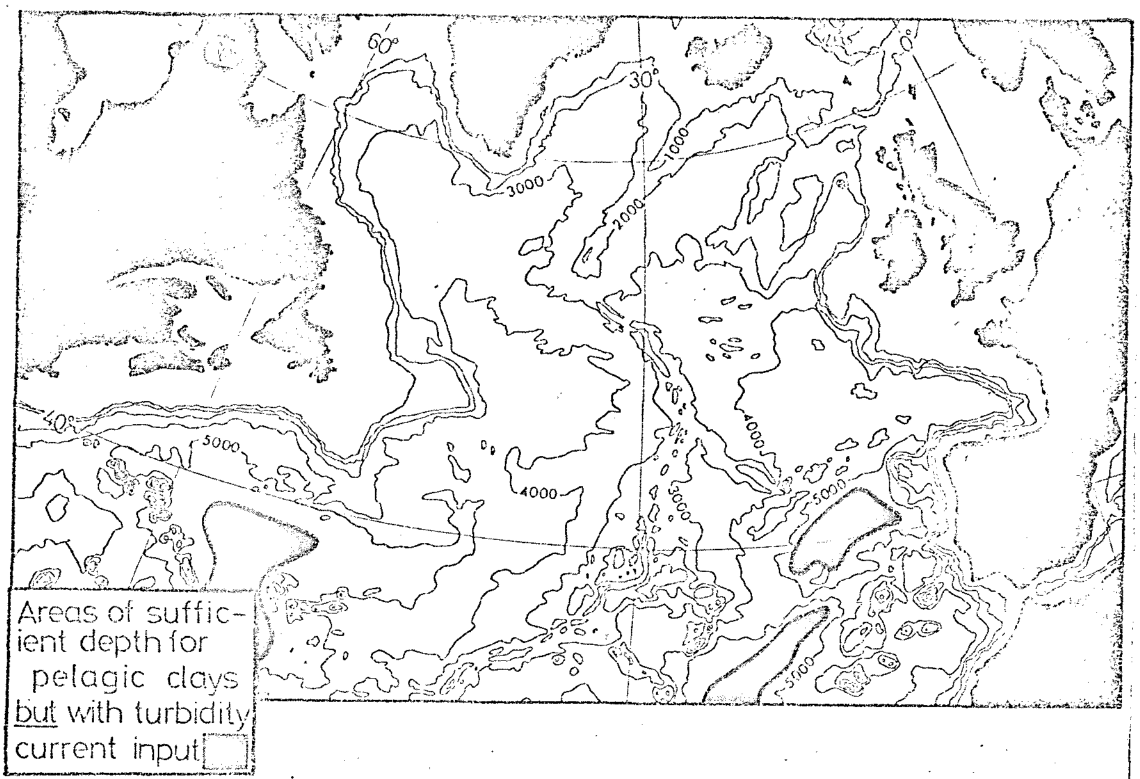
8. ACCUMULATION RATES

End member diatom oozes have accumulated over the past 2 million years at rates of between 7. 0 and 14. 0 cm per 1000 years on ridges and plateaus along the Aleutian Arc of the North Pacific.

<u>DEEP WATER PELAGIC CLAY</u>

1. DISTRIBUTION IN NORTH ATLANTIC

NO END MEMBER. Oceanic areas sufficiently deep for clay deposits exist to the south (see Figure 1) but these are within the influence of turbidity currents bringing terrigenous sediments and reworked calcareous ooze from the continents and depositing them sufficiently rapidly to preclude dissolution.



2. COMPOSITION

End member with 1% $CaCO_3$; must have less than 10% $CaCO_3$. Usually less than 1% biogenic silica (by definition never more than 50%). Made up predominantly of clay minerals and quartz, the bulk of which were originally carried as dust by winds from the continents and have been slowly deposited from fine suspensions. North Atlantic pelagic clays typically have clay mineral fractions with the composition: illite 55%, kaolinite 20%, montmorillonite 16%, chlorite 10%. Frequently compositions of Pacific pelagic clays can be matched with continental source areas and linked to prevailing wind directions.

Apart from clay minerals and quartz, deep water pelagic clays contain significant amounts of 'authigenic components', i. e. those that have formed in place geochemically, e. g. manganese and iron aggregates (especially manganese micronodules), zeolites, phosphorite, chert and apatite; together with other indicators of slow sedimentation, e. g. fish bones and cosmic spherules. Other mineral components may be volcanic glass, mica, feldspars and pyroxenes. Major biogenic constituents are siliceous diatoms, radiolaria, silicoflagellates and sponge spicules, together with the phosphatic fish teeth and other vertebrate remains.

Organic carbon content ranges between 0. 11 and 0. 25%.

Varieties: Siliceous fossil-rich clays - see 'Siliceous oozes', with greater than 50% biogenic silica these become siliceous oozes.

: Manganese micronodule-rich clays - in areas of manganese nodule pavement.

: Metalliferous clays - associated with regions of hydrothermal activity, in patches on mid-ocean ridges or on seamounts in isolated deep ocean regions.

: Deep-sea clays rich in terrigenous material - in deep basins below the CCD but close to continental margins - generally these clays have much increased sedimentation rates and contain greater amounts of organic carbon.

: Zeolite-rich clays - rich in minerals formed from the alteration of volcanic material, found close to regions of volcanic activity.

3. COLOUR

Brown to dark red brown.

4. TEXTURE AND GRAIN SIZE

Generally soft, but can be stiff where sediment surface is one of non-deposition; smooth texture.

Grain size in the clay size range (< 0.004mm). Typically average content of clay size material is higher than 90%. The remaining material is mostly in the fine silt size range.

Typical median diameters (Md) are always less than 4 μ. Sorting is extremely good, sorting indices (So) between 1 and 1.5.

5. PHYSICAL PROPERTIES

Wet Bulk Density - about 1.2 gm/cm^3 at the surface increasing to 1.3 gm/cm^3 at 50m subbottom.

Porosity - about 80% at the surface, dropping to around 60% at 50m subbottom.

Water Content - high, $>$ 95% at surface and decreasing by about 2.2% per 10 meters of subbottom penetration.

Compressional Wave Velocity - generally in the range 1.6 to 1.7 km/sec over the upper 50 meters of sediment.

Characteristics on Seismic Profiles - al most transparent. Drapes pre-existing bottom features.

6. ENGINEERING PROPERTIES

Deep water pelagic clays are very plastic, often because of high montmorillonite content. Have generally low shear strength.

For design purposes DSDP technical report recommends an effective angle of internal friction not greater than 20°. Less susceptible to liquefaction than either calcareous or siliceous oozes.

7. INTERSTITIAL WATERS

Pelagic clays drilled off West Africa at a depth of about 50 meters subbottom contained interstitial waters of pH 6.92 and salinity 34.7‰.

8. ACCUMULATION RATES

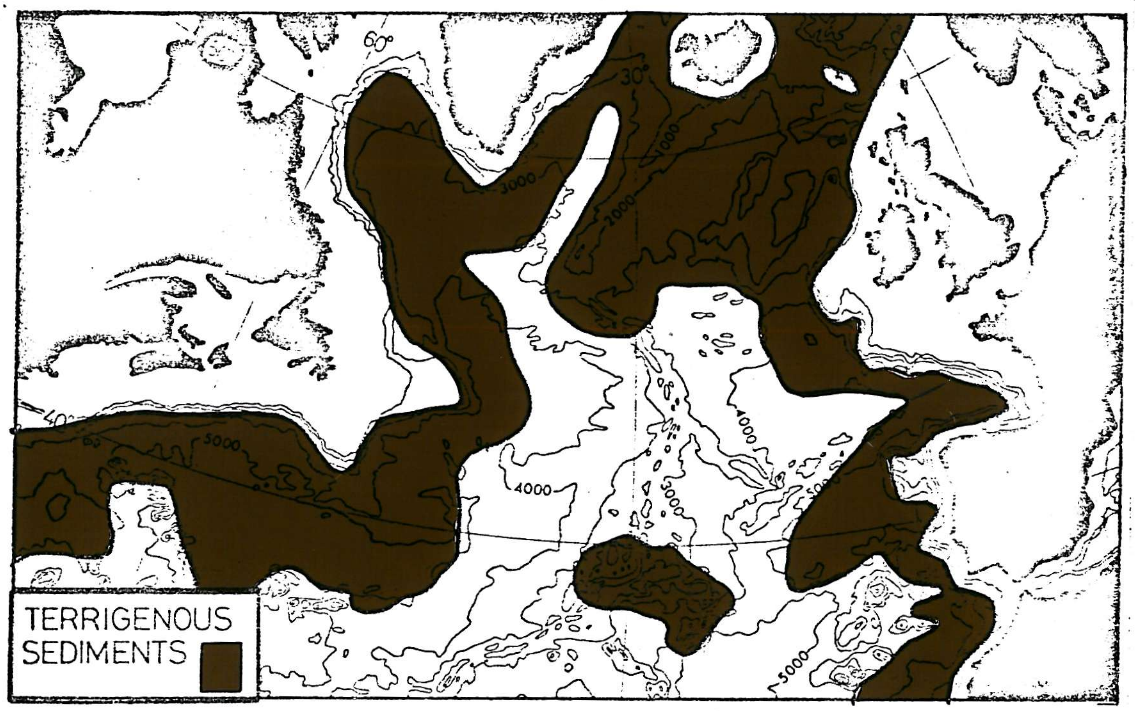
End member clays accumulate at rates of less than 0.1 cm per thousand years. In many areas covered by such clays zero deposition has occurred over millions of years. True deep-water pelagic clays may be distinguished from rapidly accumulated terrigenous sediments carried below the CCD, at a sedimentation rate of 0.5 cm/1000 yrs.

TERRIGENOUS SEDIMENTS

1. DISTRIBUTION IN NORTH ATLANTIC

Along continental margins and extending (a) into deep basins as turbidity current deposits; (b) along the continental rises and the flanks of the northern ridges and plateaus as the deposits of deep geostrophic currents, and (c) as a patch of volcanically-derived sediments around the Azores.

MAP 4



2. COMPOSITION

End member > 50% land-derived clastic detrital material (silt and sand size quartz, mica, feldspars and other minerals plus clay minerals). In practice much of the area described above is covered by a mixture of land-derived silt and clay with intercalated sandy layers plus calcareous ooze that has been reworked by bottom currents (see Figure 2). These complex sediments are frequently termed HEMIPELAGIC deposits. Composition varies widely and is strongly dependent upon sedimentation processes. Generally there is an increase of sand, silt and clay towards the land sources but much depends upon the strength and paths of the turbidity and geostrophic bottom currents, and on winds in the case of airborne volcanic detritus. The main biogenic constituents are planktonic foraminifera and nannofossils, but any of the other constituents of calcareous oozes may be present, as well as fragments of land plants and shallow water macrofossils. Apart from quartz, mica and feldspars, other minerals that may be present are pyroxenes, amphiboles, pyrite, magnetite, hematite, glauconite, goethite, detrital carbonate (often dolomite), volcanic glass, chert, and rock fragments, usually comparable with the geology of the nearest source areas.

Organic carbon content varies from 0.25% in the deep basins to around 1.0% at the base of the continental slope.

Varieties:

Turbidites (the deposits of turbidity currents) - series of discrete sandy or silty beds (5-600 cm thick) each with a well-defined base, a gradational top into fine sediment (usually clayey reworked calcareous ooze), and a characteristic sequence of internal structures. The beds contain abundant shallow water shell material and/or land-derived material strongly indicative of its upslope source e. g. volcanic material where the source was the Iceland or Azores plateaus, glacial material in polar latitudes, etc. May also contain plant material, rock fragments, and other relatively exotic debris.

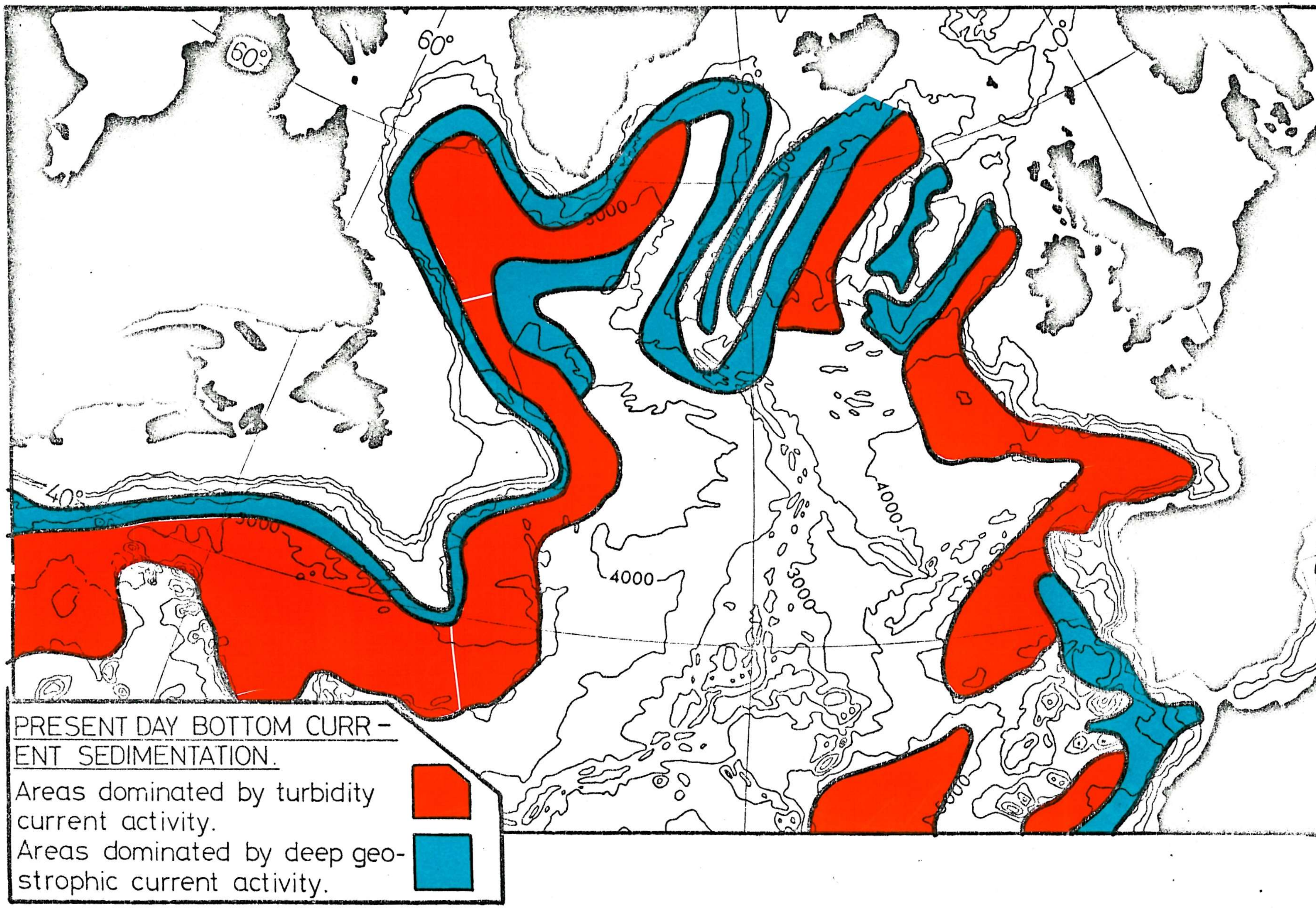
Contourites (deposits formed under the influence of deep flowing geostrophic currents which shape and modify pre-existing sediments) - series of discrete sandy or silty beds (normally less than 5 cms thick) each with a well defined base but also a sharp upper contact and its own characteristic internal structure. The beds are again set in fine sediments (usually clayey reworked calcareous ooze). They can contain some shallow water shell material since they may represent reworked turbidity current deposits but generally this is rare. Any plant or fossil material present is usually worn or broken.

Volcanic Ashes - distinct layers of coarse volcanic material (glass fragments, pumice, pyroxenes, etc.), together with alteration products such as zeolites. They occur within range of eruptive centres and so are to be found in the region of the Azores and Iceland. Many have been subsequently reworked by bottom currents (see Figure 3).

Ice-rafted Sediments - poorly sorted mixtures of detrital sediments which have been entrained in icebergs and drifted out into deep waters, eventually falling to the ocean floor during melting. The deposits include rock fragments (pebbles and gravel) and sand, silt and clay, along with minor amounts of calcareous ooze. Most ice-rafted terrigenous sediment in the North Atlantic occurs as relic sediments of the last glacial period. Thus they may be found as far south as 30°N but again they may have subsequently been reworked by bottom currents or masked by later ooze deposition. The only presently active sedimentation area for ice-rafted material lies north of the Iceland-Faeroes Ridge (see Figure 4).

3. COLOUR

Pale olive to greyish olive near continental margins, often with a thin lighter-coloured surface layer which is yellowish brown or light olive. Dark colours such as dark green or black are associated with turbidites near submarine canyons. Colours become progressively lighter with distance from margins, changing to shades of yellow or brown.


60°
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PRESENT DAY BOTTOM CURR-
ENT SEDIMENTATION.
Areas dominated by turbidity
current activity.
Areas dominated by deep geo-
strophic current activity.

Fig.2

4. TEXTURE AND GRAIN SIZE

Complete size range exhibited: one extreme is ice-rafted material in which fine muds and clays may be mixed with much coarser material including pebbles (Md = 10 to 15 mm) and even boulders; the other extreme is volcanic dust with ash particles around 1 μ in size. Average percentages in fine sediments near the continental margins are: 2% sand, 36% silt and 62% clay. Set in these are the sandy layers referred to as turbidites and contourites. These layers are easily distinguished on their sorting: turbidites are poorly sorted overall (So = 3 to 4) despite their characteristic vertical decrease in grain size (GRADING); contourites are very well sorted (So = 1 to 2) and may be non-graded, reversely graded or graded. Sorting is generally even better in wind and water transported volcanic ashes (So = approx. 1) while it is poorest in ice-rafted material (So = 4 to 5).

5. PHYSICAL PROPERTIES

Very variable and strongly dependent upon sedimentation process.

Wet Bulk Density - fine ice-rafted material approx. 1.5 to 1.75 gm/cm³; contourite sequences approx. 1.4 to 1.5 gm/cm³; turbidite sequences approx. 1.5 to >2.0 gm/cm³ (range of increase exhibited over upper 50 meters)

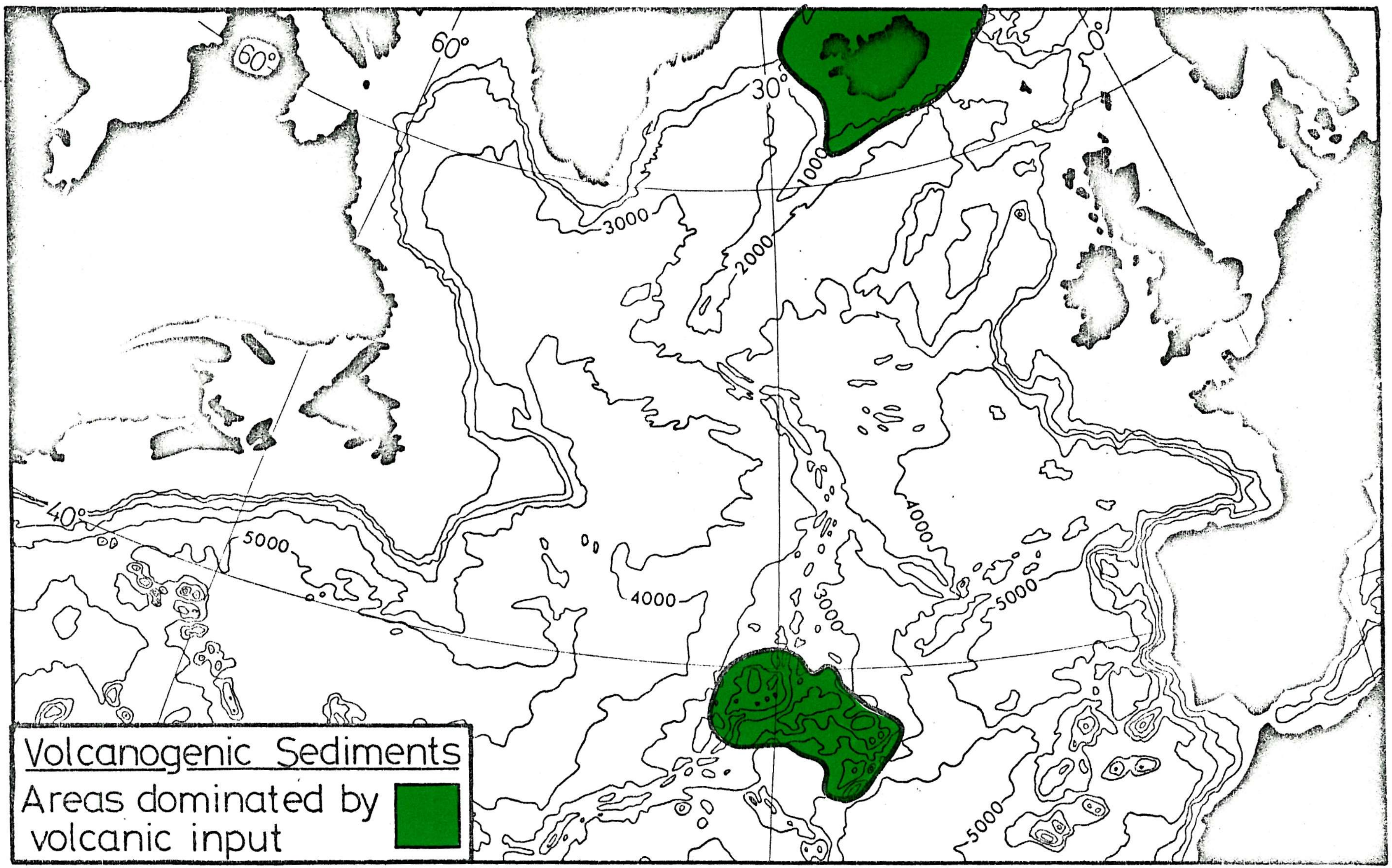
Porosity - fine ice-rafted material approx. 60 - 80%; contourite sequences approx. 60 - 80% (range of decrease exhibited over upper 50 meters); turbidite sequences approx. 75% (little variation)

Water Content - generally very high in fine clays near margins and in contourite and turbidite sequences: decreases from up to 97% in upper 20 meters to around 50% at 200 meters subbottom (about 2.2% per 10 meters of penetration).

Compressional Wave Velocity - generally within the range 1.4 - 1.8 km/sec; strong variations often to over 2.0 km/sec in turbidite and contourite sequences, because of major velocity increases in intercalated sandy layers.

Characteristics on Seismic Profiles

- Turbidite sequences
  - high sea bed reflectivity with no waves or ridges.
  - strong stratification.
  - 'ponded' in depressions in pre-existing bottom relief.
- Contourite sequences
  - heaped into waves or ridges on sea bed.
  - generally transparent but with fine internal layering.
  - often exhibit 'moating' around upstanding features in pre-existing bottom relief.



60°
60°
30°
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1000
2000
3000
3000
4000
4000
4000
5000
5000
5000
40°
Volcanogenic Sediments
Areas dominated by volcanic input

Fig. 3

- Ice-rafted sediment - if deposited in great quantity, may show hummocky terrain plastering pre-existing relief.

6. ENGINEERING PROPERTIES

Margin clays are moderately plastic, although they do not have the very high plasticity of montmorillonite-rich deep water pelagic clays occuring below the CCD. Shear strengths are significantly lower than those encountered on the continental shelf (e. g. North Sea) but show a fourfold increase in strength over the upper 100 meters of subbottom penetration. For design purposes the DSDP technical report recommends that the effective angle of internal friction be taken as not greater than 20°.

7. INTERSTITIAL WATERS

Fine ice-rafted glacial clays in the Norwegian Sea have pH 7.9 and salinity 34.4‰ in upper few meters, changing to pH 8.1 and salinity 33.8‰ at 70 meters subbottom. Hemipelagic muds (clayey and silty sediments associated with turbidites and contourites) have pH values between 7.5 and 8.0).

8. ACCUMULATION RATES

Calculated sedimentation rates in turbidite sequences on the margins of the North Atlantic range upwards from 20 cms per 1000 yrs. while those of contourite sequences range between 5 to 15 cms per 1000 yrs. It is recognised however that deposition from turbidity currents is extremely spasmodic.

Accumulation rates of fine ice-rafted material in the Norwegian Sea have been at around 5 to 6 cm/1000 yrs since the last glacial period. Volcanic ash deposition is again spasmodic around the Azores and Iceland, since it is dependent upon the incidence of subaerial volcanic activity.

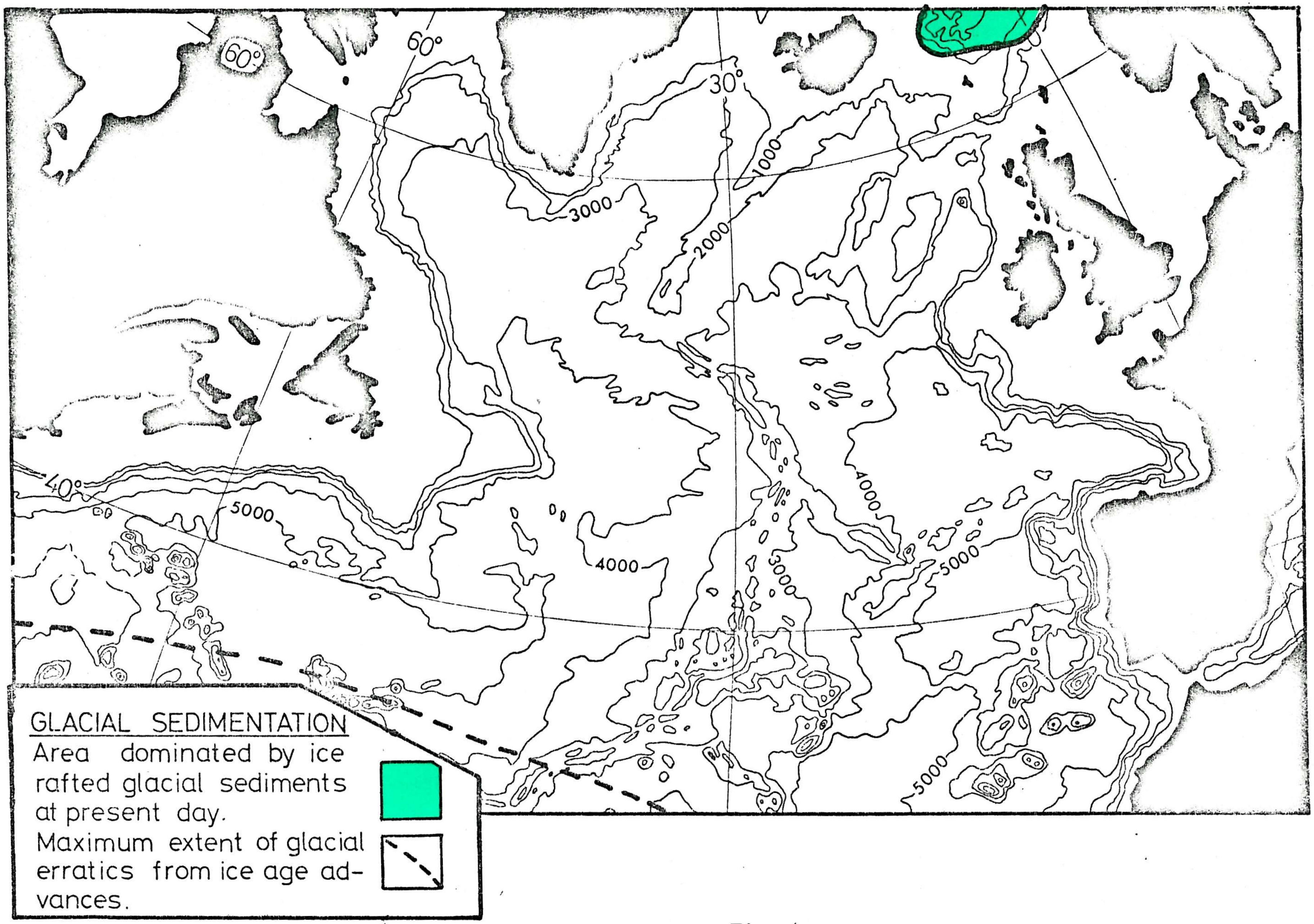
60°
60°
30°
3000
1000
2000
40°
5000
4000
4000
3000
5000
5000
GLACIAL SEDIMENTATION
Area dominated by ice rafted glacial sediments at present day.
Maximum extent of glacial erratics from ice age advances.

Fig.4

ADDITIONAL POINTS

1. RELICT SEDIMENTS

Most of the information on sediment distributions in these notes refers to sedimentation at the present day. However at the climax of the last glacial period the limit of loose pack ice reached a line arcing northwards from Brittany to Nova Scotia. This meant that huge quantities of ice-rafted sediment plastered much of the northernmost Atlantic and these deposits remain at or near the surface as 'relict sediments' in many areas. Similarly, icebergs were able to float much further south before eventual melting so that glacial erratics, pebbles or even boulders, may now be encountered at the sediment surface as far as 30°S.

2. DEEP SEA EROSION

As well as their capacity for deposition of sediments, deep geostrophic currents, linked to large scale movements of deep water masses, have the ability to erode pre-existing surface sediments. This occurs where they encounter solid objects such as ridges or seamounts, which accelerate their flow velocities. Numerous examples of 'moats' around seamounts and 'marginal channels' along the flanks of ridges have been identified in the northernmost Atlantic. These features are up to 100 meters deep and attest to the erosive and/or modifying effect of these geostrophic currents. In such areas rates of flow can be expected to range from 5 cm/sec to 50 cm/sec. The paths of these deep currents are only generally known at present and are likely to have changed since the last glacial maximum (18,000 yrs B. P.).

3. POST-DEPOSITIONAL PROCESSES

Once sediment has been deposited on the seafloor, it may experience a wide variety of physical processes. Numerous types of deep sea organism rely on the sediments for their food and/or refuge. Burrowing can stir sediment to depths of up to 30 cm but is most usual in the upper 4 to 5 cm. Current reworking, especially that by deep geostrophic OR turbidity currents, may erode and redeposit, or simply modify the sediment (e. g. winnowed oozes). On slopes slumping or sliding may occur in response to oversteepening or minor geological movements.

(A book which gives a well illustrated and comprehensive review of marine geological knowledge on processes active on the deep ocean floor, but written with the layman in mind, is:

HEEZEN, B. C., and HOLLISTER, C. D., 1971. 'THE FACE OF THE DEEP' OXFORD UNIVERSITY PRESS, NEW YORK 659pp.)

Processes which chemically and physically alter the sediment during burial (DIAGENESIS) eventually cause compaction and lithification. For example, calcareous ooze over the upper 1 meter of subbottom depth will have certainly undergone slight compaction, burrowing, destruction caused by ingestion through organisms, and solution. Over the 1 meter to 200 meters subbottom depth range, the ooze will have undergone gravitational compaction, firming of grain contacts, dissolution of both carbonate and silica, overgrowth on most of its contained skeletal fossils and often lithification.

4. ENGINEERING PROPERTIES

Very little engineering data is available relevant to the placing of structures on the floor of the deep ocean. A recent technical report by the Deep Sea Drilling Project (D. S. D. P. TECHNICAL REPORT NO. 9 : 'SOILS STUDY. CONTINENTAL MARGIN SITES AND BEARING CAPACITY STUDY OF SEAFLOOR SOILS, MID-ATLANTIC RIDGE, ATLANTIC OCEAN') concludes that the engineering properties of deep floor sediments are markedly different to those encountered on the continental shelves, e. g. the North Sea and Gulf of Mexico. Calcareous and siliceous oozes and deep sea clays all exhibit "apparent overconsolidation" probably brought about by interparticle bonding over long periods of time. Structures placed on these should experience little settlement until the maximum apparent past pressure is exceeded, after which extensive settlement is likely to occur.