OCEANOLOGICA ACTA 1982 - VOL. 5 - N° 2

North Atlantic sedimentation and paleohydrology during the Late Quaternary - mineralogical and geochemical data

North Atlantic
Quaternary
Geochemistry
sedimentation
Paleohydrology

Atlantique Nord
Quaternaire
Géochimie
Sédimentation
Paléohydrologie

M. Parra
Institut de Géologie du Bassin d'Aquitaine, 351 Cours de la Libération, 33405 Talence, France.

Received 30/7/81, in revised form 24/10/81, accepted 26/11/81.

ABSTRACT

This mineralogical and geochemical study is based on some 40 cores taken in the main deep-sea basins of the North Atlantic sediments immediately adjacent to projected sources provided information concerning the characteristic of terrigenous materials (terrigenous acidic, volcanic basic) likely to be supplied and deposited in the deep-sea North Atlantic facies, where the existence of biogenic carbonate inputs associated with these materials may also be observed.

The distribution and origin of these materials were determined through investigation of deep-sea quaternary sediments. Our conclusion is that during glacial periods, terrigenous inputs deposited by turbidity currents are localized in the vicinity of source platforms. In the southern zones, materials of nordic origin are ice-rafted in considerable quantities, by floating ice, while carbonate materials are limited to these zones. During interglacial and postglacial periods, these 3 types of materials are transported to the central parts of the basins by Norwegian Deep Sea Water (NDSW). Close to slopes, turbidity currents are not as active as they appear to be during the Glacial period. Biogenic carbonate inputs are found throughout the basins examined.

This study has consequently thrown light on the role played by ocean water circulation where the distribution of sedimentary inputs is concerned. It has, furthermore, permitted the application, indifferently and depending on climatic conditions of two hydrological patterns for the Late Quaternary.

Oceanol. Acta, 1982, **5**, 2, 241-248.

RÉSUMÉ

Sédimentation et paléohydrologie dans l'Atlantique Nord pendant le Quaternaire terminal. Données minéralogiques et géochimiques.

Cette étude minéralogique et géochimique a été réalisée sur une quarantaine de carottes prélevées dans les principaux bassins profonds nord-atlantiques. L'étude des sédiments déposés à proximité immédiate des terres émergées a permis d'avoir une idée des caractéristiques des matériaux terrigènes susceptibles d'être entraînés et déposés dans les faciès profonds nord-atlantiques (matériaux à caractères « acides » et matériaux volcaniques à caractères « basiques »). A ces matériaux terrigènes sont venus se mélanger des apports biogéniques carbonatés.

L'étude des sédiments quaternaires profonds a permis de préciser la répartition et l'origine de ces matériaux dans les divers bassins étudiés. Aux *périodes glaciaires,* les apports terrigènes se localisent près des plates-formes émettrices et se déposent par les courants de turbidité très actifs. Dans les zones sud, les matériaux d'origine nordique sont délestés abondamment par les glaces flottantes. Quant aux matériaux carbonatés, ils sont limités aux zones sud des bassins. Pendant *les périodes interglaciaires et postglaciaires,* les trois types de matériaux sont mis en place dans les parties centrales des bassins par les eaux profondes norvégiennes. Près des talus, les courants de turbidité sont moins actifs qu'au Glaciaire. Les apports biogéniques carbonatés se généralisent à l'ensemble des bassins étudiés.

Ce travail permet de mettre en relief le rôle majeur des circulations océaniques à l'égard de la distribution des apports sédimentaires. Deux schémas hydrologiques peuvent être alors proposés suivant les fluctuations climatiques du Quaternaire Terminal.

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INTRODUCTION

Sedimentary differences between glacial and interglacial periods are essentially attributed to modifications in erosion and conditions of alteration in the continents and to the relatively important development of microorganisms in the North Atlantic as the result of climatic change. But the climatic factor cannot be directly responsible for all the sedimentary innovations observed in each North Atlantic basin. The consequent need to take account of hydrological changes in the North Atlantic has been pointed out by a number of researchers, on the basis of different criteria: biological (Kellogg, 1975-1976; McIntyre *et al.*, 1976; Peypouquet, 1977; Alvinerie *et al.*, 1978; Pujol, 1980); and sedimentary (Jones *et al.*, 1970; Davies, Laughton, 1972; Ruddiman, Bowles, 1976). But the impact of such changes on the mineralogical and more particularly the chemical composition of sediments has up to now been rarely considered with respect to a single basin in its entirety, and never with respect to several basins. Mineralogical and geochemical studies in the North Atlantic Ocean have merely dealt with surficial deposits and have involved, only a small number of parameters. In those which we have referred to, namely, Yeroschev-Shak (1964), Biscaye (1965), Turekian and Imbrie (1966), Rateev *et al.* (1969), Chester and Messiha-Hanna (1970), Lavrov *et al.* (1973), Yemel' Yanov and Shurko (1973), Zimmerman (1975), Biscaye *et al.* (1976), Yemel'Yanov *et al.* (1977), Kolla *et al.* (1978), the sediments investigated have, moreover, not yet been dated. Studies dealing with cored sediments of well-established stratigraphy have for the most part covered specific zones (Mid-Ocean Ridge, Horowitz, 1974), but in vast area only a few cores have been examined (Chester, Messiha-Hanna, 1970; Van der Weijden *et al.*, 1970).

Our aim was to determine the origin, transport and conditions of deposit of deep-sea materials. In the first instance, we endeavoured to identify those materials which seemed most likely to have served as privileged sources of deep-sea North Atlantic sediments; and to this end analyzed the relative abundance of certain mineralogical and geochemical components and attempted to establish partial or multiple correlations between sediment components and chemical elements.

As a result. we were able to set against the Atlantic background as a whole the findings of investigations carried out in the three most important sedimentary domains of the North Atlantic (eastern: Latouche, Parra, 1976; Parra, 1978; central: Grousset *et al.*, 1982; and western: Latouche, Parra, 1979), concerning the final four periods (Riss - Interglacial - Würm - Postglacial) of the Late Quaternary.

ANALYSIS AND INTERPRETATION METHODS

Our research was conducted on sediment cores with a precise stratigraphy (Pujol, 1980), and covered four climatic periods:

— a cold period (or Riss) to which the Climap Project Members (1976) assign a date of 127,000 yrs BP;
— a warm period (or last interglacial or zone X): 127,000 yrs BP; 75,000 yrs BP;
— a cold period (or last glacial or Würm or zone Y): 75,000-10,000 yrs BP;
— a warm period (or postglacial or Holocene or zone Z): 10,000 BP to the present day.

We analyzed 40 cores, selected to represent the major North Atlantic sedimentary basins: Norwegian Sea, Rockall Channel, Bay of Biscay, Icelandic Basin and the Northwest Atlantic Mid-Ocean Canyon (Fig. 1).

The main mineralogical and chemical components in core sediments have been determined quantitatively by X-ray diffractometry and by X-ray fluorescence spectrometry (Parra, 1980), and comprise:

minerals: quartz, calcite, dolomite, plagioclase feldspars, alkaline feldspars, illite, smectite, chlorite, kaolinite, amphiboles, pyroxenes...;
chemical elements: Fe, Ti, S, P, Mn, Sr, Rb, Ba, Zn, Cu, Ni, Pb, Zr.

The analytical data were treated in two different ways (Parra, 1980), involving:

— a comparative analysis of bulk or corrected average content samples from the same climatic stage and from each core;
— a statistical study (simple or multiple correlation coefficient calculated by factor analysis in R or Q mode (Parra, 1980; Grousset, Parra, 1982).

RESULTS AND DISCUSSION

Sample characteristics were classified in 3 groups, representing 3 types of materials (Latouche, Parra, 1970; Berthois *et al.*, 1972-1973 *b*; Parra, 1980), namely:

groupe I: quartz, calcite, illite, chlorite, kaolinite, Fe, Ti, Rb, Pb, Zr. This assemblage characterizes terrigenous detrital materials of an acidic petrographic nature (disintegration product of plutonic, sedimentary

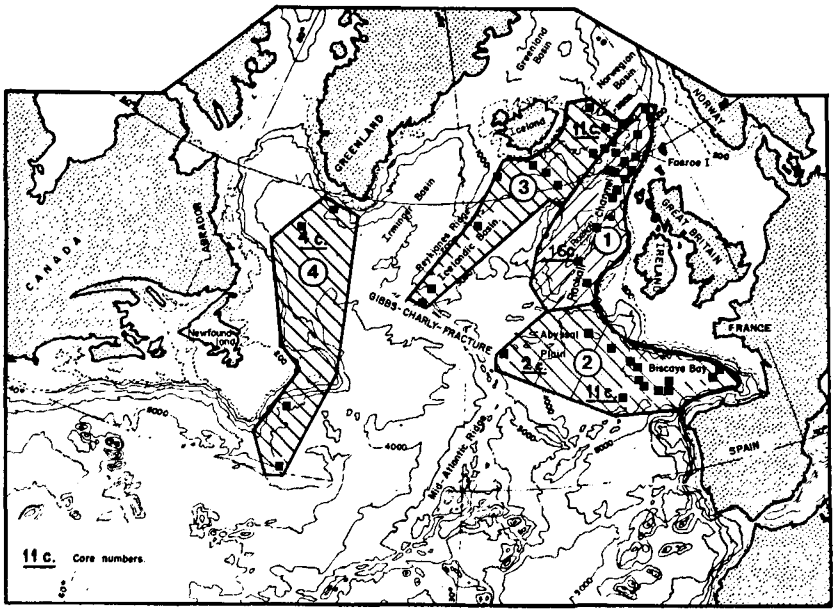


Figure 1

Location of the deep-sea areas investigated
North-Eastern area :
1. *Norwegian Basin-Bay of Biscay.*
2. *Bay of Biscay and Abyssal Plain.*

North-Central area :
3. *Norwegian Sea-Gibbs Fracture.*

North-Western area :
4. *Northwest Atlantic Mid-Ocean Canyon.*

Localisation des zones profondes étudiées.
Zone Nord-Est :
1. Bassin de Norvège - Golfe de Gascogne.
2. Golfe de Gascogne et plaine abyssale.

Zone Nord-centrale :
3. Mer de Norvège - Fracture de Gibbs.

Zone Nord-Ouest :
4. Northwest Atlantic Mid-Ocean Canyon.

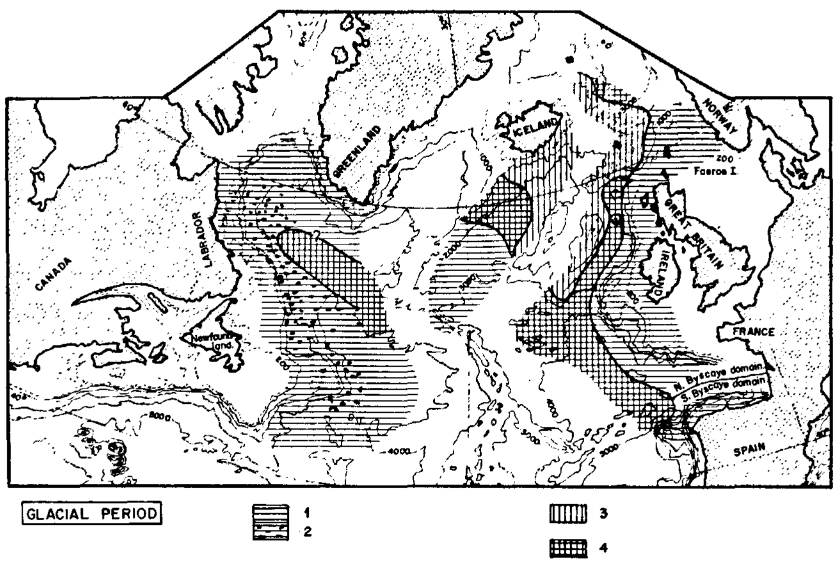


Figure 2

Detrital material distribution in the North Atlantic Ocean during glacial periods.
1. *Acidic terrigenous and*
2. *carbonate materials.*
3. *basic volcanic detrital materials.*
4. *acidic terrigenous materials* (50 %). *Volcanic detrital materials* (50%).

Distribution des matériaux détritiques dans l'Océan Nord Atlantique pendant les périodes glaciaires.
1. Matériaux terrigènes acides et
2. carbonatés.
3. matériaux détritiques volcaniques basiques.
4. matériaux terrigènes acides (50 %) + matériaux détritiques volcaniques (50 %).

or metamorphic rocks) and of mainly cratonic continental origin: northwestern Europe (Scandinavia, Bristish Isles, Greenland, Canada and Newfoundland); *group II*: plagioclase feldspars, smectite, heavy minerals (augite, peridot, hypersthene), Fe, Ti, P, Mn, Ni, Cu, Sr. This assemblage characterizes volcanic detrital materials of a basic petrographic nature (effusion and disintegration product of eruptive rocks) found in oceanic volcanic areas: Iceland, Faeroe Islands, Rockall Bank and Mid-Atlantic Ridge; *group III*: calcite, Sr, Ba. This assemblage characterizes biogenic carbonate materials originating in planktonic tests of the oceanic environment.

The relative importance of these 3 types of materials in deep-sea sediments was determined by the Q mode of factor analysis.

In the deep-sea North Atlantic environment, we investigated the sedimentation products of the mixing of the 3 types of materials described above. Their distribution and relative abundance were found to vary according to the climatic period (glacial or interglacial).

During the two glacial periods (Riss and Würn) (Fig. 2)

North Atlantic sediments result from the juxtaposition of two kinds of terrigenous materials recognized and identified on the North Atlantic continental and insular platforms. Terrigenous materials of an acidic nature were for the most part deposited on deep-sea facies close to continental platforms rich in these materials, namely the south Norwegian Basin, the east Faeroe-Shetland Channel, the west Rockall Channel, the Bay of Biscay and the Northwest Atlantic Mid-Ocean Canyon. Detrital volcanic materials of a basic nature, transported mainly from basaltic formations in Iceland, Faeroe Islands, Rockall Bank and occasionally from the Mid-Atlantic Ridge, are deposited in large quantities in deep facies near volcanogenic zones: southwest Norwegian Basin, south Greenland Basin, west Faeroe-Shetland Channel, Faeroe Bank Channel, west Rockall Channel, north Icelandic Basin and Maury Fan. These materials are not common, except in the Bay of Biscay and Maury Fan, where coarse-grained detrital materials are widespread.

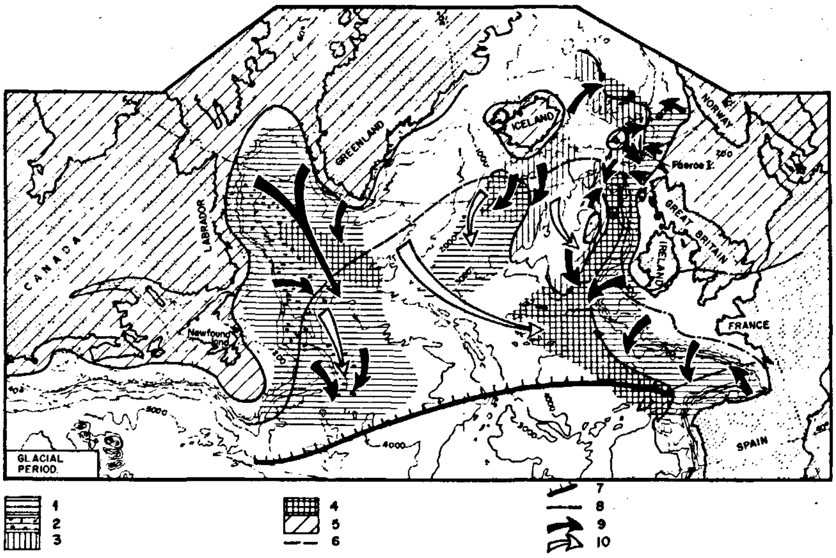


Figure 3

Sedimentary scheme and physiography in the North Atlantic Ocean during glacial periods.
1. *Acidic terrigenous and*
2. *carbonate materials.*
3. *basic volcanic detrital materials.*
4. *acidic terrigenous materials. volcanic detrital materials.*
5. *continental ice-sheet (Ice-cap, Flint,* 1971).
6. *pack-ice limit.*
7. *polar front.*
8. *marine level* (– 120 m).
9. *turbidity currents.*
10. *ice-rafting.*

Schéma sédimentaire et physiographie dans l'océan Nord-Atlantique pendant les périodes glaciaires.

1. Matériaux terrigènes acides et
2. carbonatés.
3. matériaux détritiques volcaniques basiques.
4. matériaux détritiques acides + matériaux détritiques basiques.
5. continent recouvert de glace (Flint, 1971).
6. limite du « Pack Ice ».
7. front polaire.
8. niveau marin (– 120 m).
9. courants de turbidité.
10. « Ice-Rafting ».

Sedimentary inputs are thus mainly located close to platforms where glacial sediment thickness is maximum, and are deposited in the immediate vicinity of transmitting sources. The existence of quartz episodes packed in fine-grained facies (Gonthier *et al.*, 1977) implies that glacial sediments in the northern zones of the basins are deposited by gravity and for the most part by turbidity currents (Fig. 3).

South of the Icelandic Basin, fine acidic materials associated with silt and sand are relatively abundant; their most likely origin is in Greenland, Canada or Scandinavia (illite here is associated with traces such as Rb, Pb, Zn, quartz, detrital calcite without strontium and dolomite). To the south of the Rockall Channel and west of the Bay of Biscay, terrigenous volcanic materials, probably originating in Iceland, are predominant. Glacial deposits, both in the southern zones and in the region of the Northwest Atlantic Mid-Ocean Canyon, often contain small quantities of coarse elements in the clay mud matrix (volcanic ash layers, badly separated levels of silt, sand and gravel, dispersed throughout the glacial episodes) (Faugères *et al.*, 1978). All these elements indicate the transport of detrital, nordic materials by floating ice over long distances. Ice-rafting appears to be an essential mode of transport and deposition of sediment in the southern parts of the North Atlantic basins during glacial periods (Fig. 3) — an assumption which is also made in studies by Conolly and Ewing (1965), Ruddiman and Glover (1972-1975), Ruddiman (1977), and Ruddiman and McIntyre (1981). These authors locate ice-rafted material maxima at a 50°N latitude. Biogenic carbonate materials are, however, generally limited in quantity in the southern parts of the basins, and are sometimes entirely absent in the northern parts and in the Norwegian Sea.

Higher turbide current activity, the appearance of ice-rafting and the decrease of even complete absence of pelagic inputs suggest that the circulation of the North Atlantic water masses is slowed down during glacial periods, or may be interrupted altogether when glaciation reaches its maximum level. This assumption is made in the studies on microfauna planktonic association by McIntyre *et al.* (1976), Ruddiman and McIntyre (1976), Peypouquet (1977), and Thiede (1977); and in the analyses of oxygen isotopes by Duplessy *et al.* (1975). This lack of biogenic constituents in the Norwegian Sea and in the North Atlantic basins reveals the extent of isolation of the Norwegian Sea with respect to the remainder of the North Atlantic. Schnitcker (1974), Kellogg (1975-1976), McIntyre *et al.* (1976) fully agree with this statement, especially where the association of planktonic microfauna is concerned.

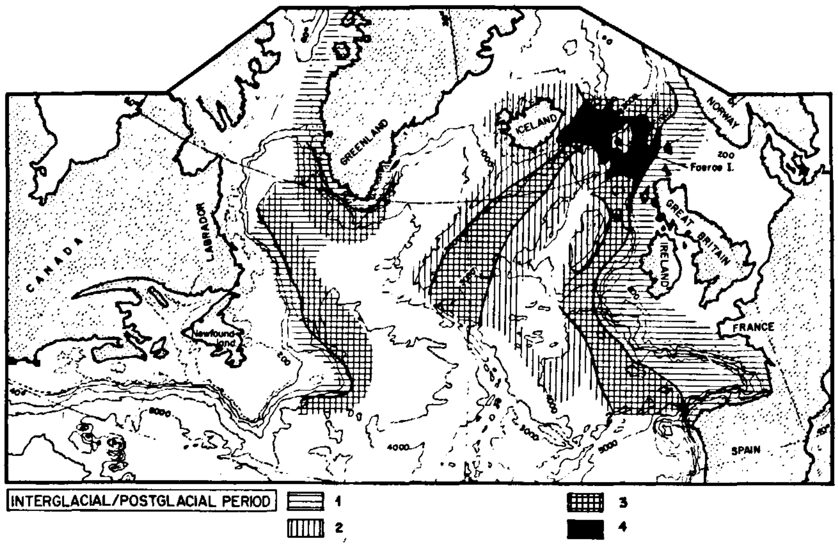
During postglacial (Holocene) and interglacial Riss-Würm periods

Central basin sediments (Fig. 4) are uniformly composed of materials with intermediary characteristics : terrigenous acid and volcanogenic basic materials, recognized on continental or insular platforms around the North Atlantic. Finer-grained nordic sediments from the Norwegian Sea and Rockall Channel on the one hand, and from the Icelandic Basin and Northwest Atlantic Mid-Ocean Canyon on the other, were finally deposited in great quantities during warm spells (sedimentation rates > 30 cm/1 000 yrs). In the northern parts of these basins, sedimentation is coarser and less important. The geographic distribution and ratios of such materials as smectite/illite and feldspars/quartz, iron, titanium, nickel, rubidium, copper or strontium-not-linked-carbonate account for a significant sorting

Figure 4

Detrital material distribution in the North Atlantic Ocean during interglacial and postglacial periods.
1. *Acidic terrigenous materials;*
2. *volcanic detrital materials;*
3. *acidic terrigenous materials* (50 %);
+ *volcanic detrital materials* (50 %);
4. *non or little post/interglacial materials.*

Distribution des matériaux détritiques dans l'Océan Nord-Atlantique pendant les périodes interglaciaires et postglaciaires.
1. Matériaux terrigènes acides;
2. matériaux détritiques volcaniques;
3. matériaux terrigènes acides (50 %) + matériaux détritiques volcaniques (50 %);
4. peu ou pas de matériaux post/interglaciaires.



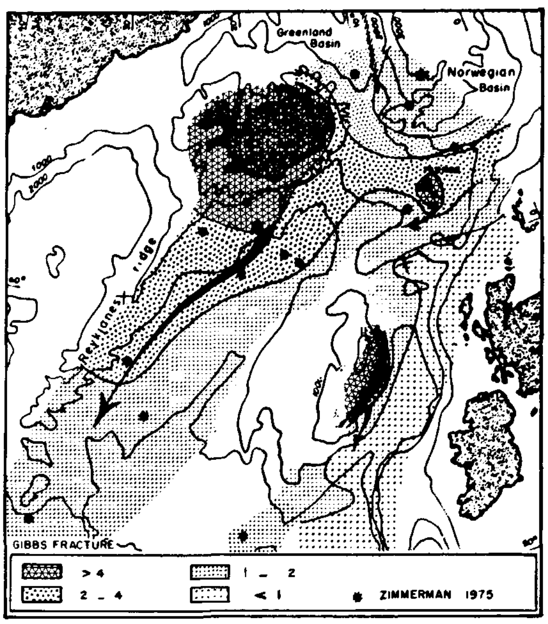


Figure 5

Postglacial: distribution of smectite/illite ratios in postglacial sediments.

Postglaciaire : distribution des rapports smectite/illite des sédiments glaciaires.

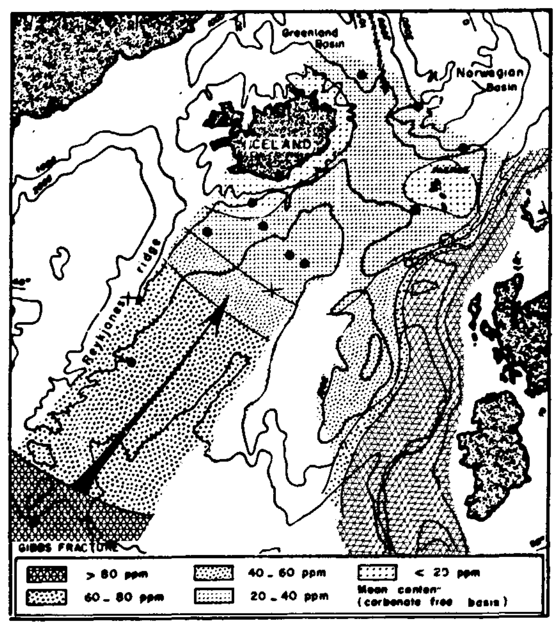


Figure 6

Postglacial: distribution of rubidium in postglacial sediments.

Postglaciaire : distribution du Rubidium des sédiments postglaciaires.

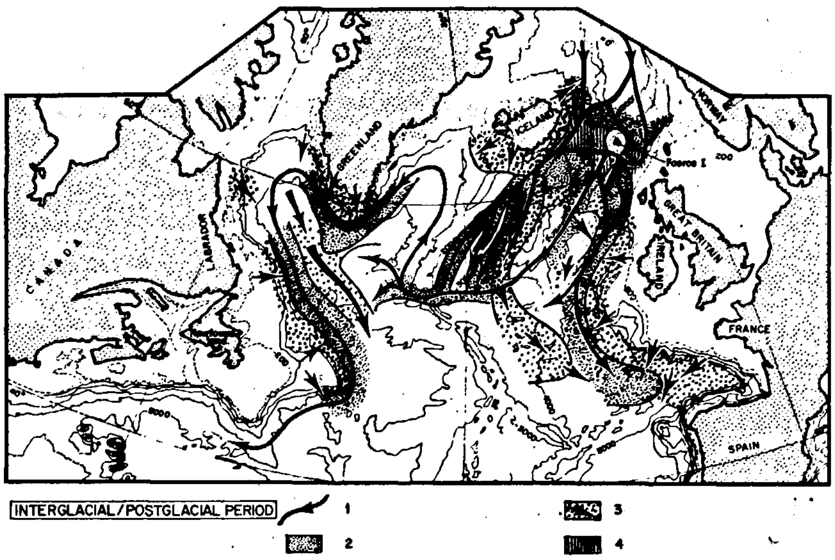
of terrigenous fine materials, from North to South, in three sedimentary North Atlantic basins. For example, the distribution of smectite/illite ratio in the Icelandic Basin (Fig. 5) indicates a detrital volcaniç effusion from Iceland or the Faeroe Islands. Conversely, the distribution of rubidium (Fig. 6) indicates that it occurs in regularly increasing amounts from North to South; the implication is that rich, fine Rb deposits may be found in the southern part of the Icelandic Basin.

This sorting, which exceeds 20% in the Rockall Channel and 50 % in the Icelandic Basin, indicates material transport on a large scale close to the bottom as a result of deep-sea hydrodynamic processes, with consequent communication between the northen and southern parts of these basins. In the Icelandic Basin, terrigenous acidic materials, accounting for 50% of the detrital sedimentation, are largely deposited in the South, near the Gardar Drift; they have also been trapped in the Gibbs Fracture with a sedimentation rate of 15 cm/1 000 yrs. In the Rockall Channel, fine sediments are mainly deposited near the Feni Ridge. In the Northwest Atlantic Mid-Ocean Canyon terrigenous volcanic and basic materials are always present in the Eirik and Newfoundland Ridges. Terrigenous acidic materials originate in the continental platforms of Scandinavia, Greenland, north Canada and Newfoundland, while volcanogenic materials come from the Faeroe Islands or Rockall. These deposit zones are thus situated at a considerable distance from their transmitting continental or insular sources, sometimes more than 4 000 km. For example, in the south of the Icelandic Basin (more precisely in the Gibbs Fracture), the contribution of terrigenous acidic materials from Greenland and Scandinavia is of the order of 15 cm/1 000 yrs. This proves

Figure 7

Relationship between detrital material distribution and hydrodynamic processes in the North Atlantic Ocean during interglacial and postglacial periods.
1. *Norwegian Deep Sea Water (NDSW);*
2. *sedimentary ridge deposits from NDSW;*
3. *detrital deposits through turbidity currents;*
4. *non or little postglacial deposits.*

Relation entre la distribution de matériaux détritiques et les processus hydrodynamiques dans l'Océan Nord Atlantique pendant les périodes interglaciaires et postglaciaires.
1. Eaux profondes norvégiennes (EPN);
2. rides sédimentaires formées à partir de EPN;
3. dépôts détritiques à partir des courants de turbidité;
4. peu ou pas de dépôts post/interglaciaires.



that Norwegian Deep-Sea Water (NDSW) has played a major role in the transport and deposit of sedimentary materials in the North Atlantic (Fig. 7). The lack of quasi-systematic postglacial deposits near the Faeroe-Shetland and Faeroe-Iceland ridges is indeed due to the presence of Norwegian Deep-Sea Water, attaining high velocities which inhibit particle sedimentation and cause erosion. Finally, the diminishing sedimentation rate near the ridges may be attributed to a higher velocity of Norwegian Deep-Sea Water overflow. In this respect, our findings are in agreement with the conclusions of hydrological studies conducted in this field. Crease (1965), Lee and Ellet (1965), Ellet and Martin (1973), Hollister *et al.* (1976), and Lonsdale and Hollister (1979) have studied *in situ*, and close to the sea floor, high current velocities, with a maximum of 10-30 cm/sec. Furthermore, nephelometric measures (Thorndike, Ewing, 1967; Jones *et al.*, 1970 and Eittreim *et al.*, 1976) have revealed the displacement of fine particles near the bottom in the nepheloid layer (Brewer *et al.*, 1976; Chesselet *et al.*, 1976; Biscaye, Eittreim, (1977).

In the zones situated below the slope of the large Britannic, Scandinavian, Greenland, Canadian, Icelandic, Ferroannian and Rockall platforms, and in the Maury Fan and the Bay of Biscay, interglacial and postglacial sediments display mineralogical and geochemical characteristics identical to those of detrital materials in the closest platforms (Fig. 4). In these zones, however, sedimentation rates are relatively slow. The autochtonous nature of these deposits may be contrasted with the generalized sedimentation found in the central zones of the basins. This leads us to suppose that sediments were directly deposited from the platforms of origin by turbidity currents (Fig. 7). Such a hypothesis is frequently confirmed by the granulometric and faciologic characteristics of turbidites (Gonthier *et al.*, 1977; Faugères *et al.* 1978). Furthermore, the presence of altered benthic microorganism tests (Berthois *et al.*, 1973; Pujol *el al.*, 1974: Grousset *et al.*, 1978) proves that these sediments are essentially composed of terrigenous materials redistributed by turbidity currents from the continental and insular slope.

During interglacial and postglacial periods, carbonates of biogenic origin are predominant in North Atlantic sedimentation. The Northwest Atlantic Mid-Ocean Canyon is the sole exception to this carbonate high content production pattern. Inputs are directly associated with the development of planktonic microfauna, more frequent in the North Atlantic Drift. Nonetheless, sedimentation rates of biogenic carbonates diminish from south to north in the Rockall Channel and in the Icelandic Basin. In the Gibbs Fracture, for example, they diminish in the order of 37 cm/1 000 yrs (total sedimentation rate = 60 cm/1 000 yrs), and 10 cm/1 000 yrs (total sedimentation rate = 13 cm/1 000 yrs) in the North Icelandic Basin, this decrease being due to dilution through terrigenous Icelandic or Ferroan inputs. The same sedimentation effect has been observed by Gorshkova (1960), Kellogg (1975-1976) and Biscaye *et al.* (1976). Materials are subsequently redistributed towards the south, via Norwegian Deep-Sea Water, and are preferably deposited in hydrodynamic quiet zones, such as the Feni Ridge, the Gardar Drift, the Gibbs Fracture, the Eirik Ridge or the Newfoundland Ridge. It would appear therefore, that the so-called "ubiquitous" sedimentation, although generally present throughout the North Atlantic, is by no means uniform at the bottom. In the Northwest Atlantic Mid-Ocean Canyon, cold currents (e.g. Irminger, Labrador currents) contribute very little to the development of carbonate planktonic microfauna, with the result that the deposit of carbonate tests at the bottom is considerably diminished.

CONCLUSIONS

The mineralogical and geochemical studies conducted in three deep-sea domains of the North Atlantic Ocean, have permitted the collection of information additional to that obtained from sedimentological and biological criteria concerning the nature, distribution and evolution of sedimentation during the Late Quaternary. The results obtained show that mineralogical and geochemical data may be considered as efficient criteria for paleogeographical, paleodynamical and paleohydrological reconstitutions in the North Atlantic Ocean. We were, in fact, able to prepare distribution maps for different terrigenous and biogenous materials during the 4 climatic periods, and subsequently to specify the role that different means of transport (turbidity, deep-sea surface currents, floating ice) may have played in each deep-sea North Atlantic basin.

Our work in the three important deep-sea basins of the North Atlantic indicates that the mineral and chemical composition of Quaternary sediments is very dependent on hydrodynamic factors. We consequently, suggest the following two hydrosedimentary patterns for the Late Quaternary.

Glacial periods (Riss and Würm)

In north Rockall, the Icelandic Basin, the Northwest Atlantic Mid-Ocean Canyon and the southern Norwegian Sea, sedimentary inputs are mainly located close to platforms where we were able to identify the materials found. Acidic terrigenous materials are particularly abundant near the Britannic, Greenland and Canadian platforms. Basic volcanic materials are stocked near the Icelandic, Ferroan platforms. Deposit by turbidity currents on this sedimentary downward slope constitutes the principal hydrodynamic process. In the southern basins, sedimentary inputs of nordic origin (acidic materials from Greenland, Canada or Scandinavia; basic materials from Iceland or the Faeroe Islands) are deposited by ice-rafting. Biogenic carbonate sedimentation which is non-existent in the northern basins and the Norwegian Sea, appear to be more frequent in the South.

These glacial sedimentation characteristics indicate the existence of two important phenomena:

a) pack-ice and permanent banquise in the North Atlantic. This leads to the isolation of the Norwegian Sea from the remainder of the Atlantic;

b) the transfer of water masses towards the south. This explains why North Atlantic circulations were to such an extent reduced and even ceased entirely. Deep-sea waters were probably formed in the west of the Bay of Biscay.

Postglacial and interglacial periods (Riss-Würm)

The mineralogical and geochemical characteristics of postglacial/interglacial deposits are good indicators of biogenic/detrital and fine-grained material transport and deposit towards the sedimentary ridges; this transport was provoked by deep-sea currents (Norwegian Deep-Sea Water). Materials carried so frequently by turbidity currents are located near the continental slopes. During warm periods, biogenic carbonate sedimentation is important in the North Atlantic, as a direct consequence of the presence of surface warm currents (North Atlantic Drift) — extension of the Gulf Stream.

Acknowledgements

I am indebted to the Centre National de la Recherche Scientifique (CNRS) for having financed the oceanological Faegas 1 and 2 cruises. I would also like to thank Drs. M. Caralp and C. Latouche for reading the manuscript and discussing its contents.

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