FILE

INTERNAL DOCUMENT

129

I.O.S.

THE DISTRIBUTION OF GLACIAL ERRATICS IN THE NORTHEAST ATLANTIC

A Report on the Study of Dredged Material a Present Available in the UK, France and USA

Q.J. Huggett

Internal Document No. 129

NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF OCEANOGRAPHIC SCIENCES

INSTITUTE OF OCEANOGRAPHIC SCIENCES

Wormley, Godalming,
Surrey GU8 5UB
(042-879-4141)

(Director: Dr. A. S. Laughton)

Bidston Observatory,
Birkenhead,
Merseyside L43 7RA
(051-653-8633)
(Assistant Director: Dr. D. E. Cartwright)

Crossway,
Taunton,
Somerset TA1 2DW
(0823-86211)
(Assistant Director: M. J. Tucker)

THE DISTRIBUTION OF GLACIAL ERRATICS IN THE NORTHEAST ATLANTIC

A Report on the Study of Dredged Material at Present Available in the UK, France and USA

Q.J. Huggett

Internal Document No. 129

Work carried out under contract to the Department of the Environment

This document should not be cited in a published bibliography except as 'personal communication' and is supplied for the use of the recipient only.

Institute of Oceanographic Sciences,
Brook Road,
Wormley,
Godalming,
Surrey,
GU8 5UB

ABSTRACT

This study of dredge hauls, held in repositories in the UK, France and USA, considerably extends the database on the distribution of ice-rafted material on seamounts and ridges in the North East Atlantic Ocean.

Material collected from seamounts indicates that Pleistocene ice-rafting has occurred to at least 30°N in the North Atlantic. It has been concluded that boulders, which could present a hazard to HLRW canister emplacement, and pebble material which could impart a heterogeneity to the sedimentary medium, could be present in study areas near, or to the north of, this latitude.

The analysis of rock type data has produced preliminary estimates of the size and spatial distribution of glacial erratics for latitudes 45-57°N. These estimates have shown that, at latitude 50°N, recently deposited, boulder-sized glacial erratics occur on the surface of abyssal plains at frequencies of less than 1 per 1000 m^2.

INTRODUCTION

This report outlines some of the findings of a project to examine the distribution of ice-rafted material on the sea bed of the North East Atlantic Ocean. The overall aims of this project are (1) to define more clearly the latitudinal distribution of ice rafting and (2) to define the size distribution of glacial erratics on and within the deep sea sediments. (Institute of Oceanographic Sciences, 1979).

The compaction of snow produces ice to form a glacier. The scouring action of the glacier as it flows downhill scrapes rock from the floor and walls of the enclosing valley. This debris becomes frozen into the ice and protrudes in places, so increasing the scouring action of the glacier. Thus, the action of glaciers erodes bedrock to produce a sediment called glacial drift which is characteristically unsorted: it is composed of particles of rock which vary in size from rock flour to large boulders.

Depending upon climatic and geographic conditions, a glacier may terminate on land or at sea. If the termination occurs on land, rock material trapped in the ice is released at the toe of the glacier to produce thick deposits of glacial drift called terminal moraines. When a glacier terminates in the sea, the toe moves away from land and is repeatedly broken off to form icebergs. These float oceanwards carrying glacial drift frozen into them: the process known to geologists as "ice rafting". Calculations based upon the densities of rock and ice indicate that icebergs may carry up to 7.5% by volume of rock before sinking. The glacial drift is released both continuously through slow melting on the undersurfaces, and in batches as the iceberg turns over and drops material lying on the upper surfaces.

For at least the past three million years glaciers have been active in many areas around the North Atlantic Ocean. An estimated 200,000 km^3 of glacial drift has been moved from the continents by ice rafting alone (Ruddiman, 1977). During interglacial periods like the present, glacial activity is much reduced. Small icebergs (up to 10m thick) have, however, been observed as far south as 31°N in the North Atlantic (U.S.N.O.O., 1968).

It is therefore possible that, in any region where it can be shown that ice rafting has taken place, large boulders may be encountered. Ice rafted detritus on the sea bed may make hazardous the emplacement of waste canisters into deep sea sediment sequences. Also, the variability of sediment characteristics in a sediment sequence deposited partly through ice rafting, may be so great that the predictability of the waste disposal system would be poor.

Recently deposited material may be identified in bottom photographs in high latitudes (Kidd and Huggett, 1981) but further south, Pleistocene rock accumulations are normally obscured by a thin veneer of sediment. Layers of ice rafted sands in sediment cores have been used to outline the changes in the distribution of Pleistocene glacial debris (Ruddiman, 1977). However, that study was based on only 32 cores covering the whole of the North Atlantic and the maps produced are generalised. Other tentative suggestions have been made as to the nature of ice rafting (Il'In and Shurko, 1968). The southern limits of glaciation have also been inferred from findings of debris reported on seamounts and ridges, and in isolated sediment cores (Davies and Laughton, 1972; Rawson et al., 1978; Figure 1), but no quantitative estimates of erratic distribution were made.

Prior to this project, therefore no quantitative work on ice-rafting had been done and little was known about the distribution of ice-rafted material on open abyssal plains, which had only been dredged for the purposes of research into benthic biology. Residues from such sampling have already been examined within the scope of this project and the results reported in Kidd et al., (1980).

Reported here is the phase of the I.O.S. project which has concentrated on a study of all the available material dredged from seamounts and ridges in the North East Atlantic. The samples were obtained from collections in the U.K. (University of Newcastle-upon-Tyne; University College, Swansea; I.O.S. Wormley) the U.S.A., (Woods Hole Oceanographic Institution (WHOI); and Lamont Doherty Geological Observatory (LDGO)), and France (Centre Oceanologique de Bretagne (COB)). Some extra material collected by the Scottish Marine Biological Association (SMBA) was also examined. A total of 137 stations have been examined, 46 of which have yielded glacial erratics (Tables 1 and 2). Additionally, sufficiently documented material from elsewhere in the Atlantic is being examined in order to extend the database (Stanley and Cok, 1968; Aumento, 1970; Von Rad, 1974).

METHODS

1. Sampling

Samples studied for this report were collected using four different devices that may be grouped into two basic types (Fig. 2 and 3):

(a) Geological sampling dredges (Fig. 2)

(i) Pipe Dredge (PD) (Figure 2i): this has a mouth size of 15 cm diameter and length of 45 cm; it was designed for use over rock outcrops.

(ii) Rock Dredge (RD) (Figure 2ii): many rock dredges approximate to the design of the WHOI dredge (Nalwalk *et al.*, 1961), which was constructed for dredging rock outcrops. This type of dredge, as used by Nalwalk and others, rides over larger boulders and collects only smaller, pebble-sized material. The I.O.S. version of this dredge is less selective and samples the full range of rock sizes that it can gather. Dredges of this kind are normally used in conjunction with nylon mesh liners in order to set the lower limit of grain sizes collected.

(b) Biological sampling sledges (Fig. 3)

(i) I.O.S. Epibenthic sledge (BS) (Fig. 3i): this is used for sampling sedimented sea-floors. The skids (40 cm wide) are designed to prevent the sledge from sinking into the sediment The sledge also supports a 35 mm camera which photographs the sea bed immediately in front of the sledge mouth and is monitored with a precision pinger which relays information to the ship on the depth, attitude and speed along the sea bed, and indicates that the camera is functioning. The mouth is 1.2 m wide by 0.7 m high with mesh sizes usually less than 1 cm.

(ii) W.H.O.I. Epibenthic sledge (WS) (Fig. 3ii): this is similar to the I.O.S. sledge, except that it has no camera or odometer wheel and is designed to operate either way up. It has a mouth size of 81 cm x 30 cm, with mesh sizes usually less than 1 cm (Hessler & Sanders, 1967).

(iii) Otter Trawl (OT) (not illustrated): this is a modified fisherman's trawl collecting samples for qualitative work only.

2. Sources of sampling bias

A number of geological factors have come to light which affect the observed distribution of ice rafted material. The more fundamental problems of interpretation arise, however, from the sampling methods used.

(a) Dredge design

In most cases, rock dredges with chain bags were used in conjunction with fine mesh liners, the precise mesh sizes of which were never recorded. The mouth sizes of the dredges were not always recorded either. However, in all cases except RD 9564, in-situ material larger than the largest erratic collected was always seen in the dredge hauls. Thus the upper grain size limit seen in those hauls was probably defined by the natural distribution of erratics on the sea bed rather than the ability of the dredges to collect large erratics.

(b) Dredging operations

In estimating grain size distributions, it is assumed that the dredge collects all the material in its path that is small enough to enter it. The populations that we observe from the material collected may be biased because the dredge rides over large boulders (as some dredges are designed to do; Nalwalk *et al*., 1961). Other errors can be introduced by the dredge lifting off or even, in the case of exceptionally large hauls, spilling some of its load.

(c) Ship's track

In areas of rock outcrop scientists have used their knowledge of the structure of the sea-floor to improve the quality of dredge hauls. Scree-like accumulations of material at the foot of submarine slopes commonly produce high proportions of glacial erratics in dredge hauls (up to 45% in D9561). Precise dredging around acoustic beacons in the Kings Trough area during Discovery Cruise 64 (Kidd *et al*., 1981) has highlighted the importance of ships track during dredging operations. Hauls taken along and across strike were seen to produce different yields of glacial erratics.

(d) Sample treatment

Once identified, each ice rafted specimen was examined to determine grain size (maximum diameter), volume and rock type. Volume, rather than weight, was measured in order to eliminate bias introduced by the differing densities of the lithological groups identified. The lower size limit for material to be included was set at 1.5 cm; below this size little confidence was placed in the criteria for identifying the ice-rafted proportions of dredge hauls (see para. 3, p.5).

Data quality varied considerably because of differing methods of sample storage and treatment used by the various institutions and repositories. Until this project, rock-dredging operations have been carried out solely to collect in-situ bedrock. Grain-size data were not always required, and so material was often broken down for identification purposes; an example being D9564 which was one of the largest hauls examined. This, with the lack of data on mesh sizes, has meant that the control for producing grain size distribution curves for most dredge hauls is poor. At only two rock dredge stations (RD9825 and V27, RD8, Fig. 5) was control good enough for grain-size distribution work to be done. The addition of data from benthic sledge stations has assisted in the generation of grain-size statistics.

3. Separation of Ice-Rafted Material

For each station the total haul was first examined to sort glacially derived material from in-situ and other rock. The identification of material as having ice-rafted origins is based upon a set of criteria established by marine geologists studying the oceanic crust and bedrock. The criteria have been applied more extensively for this project by the addition of criteria based upon groups of rocks. While it is recognised that exotic material may also be transported by kelp and mammals (Emery 1941; Emery & Tschundy, 1941), it is felt that these processes produce coarse clastic sediments at such slow rates that they may be ignored for the purposes of this study. Recently deposited clinker from coal-burning ships, although significant as a sediment, is not easily confused with ice-rafted material. Ballast dropped from ships of all kinds may, in some cases, be mistaken for recently-deposited glacial erratics. No accurate data can be found on the volume or distribution of ballast deposited; however, it is considered that such material is likely to be restricted to coastal areas near sea ports rather than the deeper, open waters considered here.

(a) Criteria based upon individual specimens (Fig. 4)

Through the actions of polishing in subglacial streams and the grinding of rock trapped in the ice, glaciers modify the shape of rock fragments from being angular and freshly broken to faceted, striated and polished forms. Fragments trapped in the undersurfaces of the glacier will be ground and scratched to produce faces and striations parallel with the ground and direction of motion. Similarly, bedrock may be faceted and striated prior to being picked up by the ice. Material dropped into streams running under the ice will become rounded and polished by the action of water, later to be caught in the ice and carried out to sea. Thus the presence of polishing, striations or faceting is an indication that dredged specimens have been supplied by glacial processes and may be included in the ice rafted category.

The ice rafted material examined for this project has been collected in regions where the ocean crust and bedrock is considerably older than the earliest (Pleistocene) erratics deposited. One would, therefore, expect the manganese coating, which gradually accumulates on all sea-bed rocks, to have accumulated into greater thicknesses on bedrock than on ice rafted material. In places like King's Trough, differences as great as 2 cm of manganese crust on in-situ material against 0.5 mm on glacial erratics were recorded. Conversely, a thin manganese coating is a good indication that the material is not ballast dropped from ships, as such material would not have rested on the sea-floor long enough to accrete any noticeable thickness of manganese (Bender et al., 1969).

Fragile rocks such as shales are less resistant to mechanical abrasion during ice transport and are usually reduced to a fine-grained rock flour quicker than harder rocks such as gneiss. One would not, therefore, expect to find large fragments (> 1.5 cm) of fragile rocks surviving ice transport and any such rocks found are normally regarded as not being glacially-derived.

(b) Criteria based upon complete collections

The dredging of lithified oceanic crust and bedrock will rarely yield more than two or three types of rock, as the petrology of in-situ material is relatively uniform over large areas. Thus, if a haul yields a great variety of rock types it may be assumed that some of them are exotic (probably having been ice rafted). Furthermore, once the complete collection (from one haul) has been grouped into rock type categories, the specimens are examined for any positive features of glaciation (faceting, striations, etc.). If any one piece within a group of specimens shows positive features of glaciation, then the whole group is placed in the ice-rafted category.

4. Grain-size analysis

Both rock dredge and benthic sledge data were used to establish a model for the size distribution of glacial erratics. The data have been collected from both rock outcrops (representing accumulations from the whole of the Pleistocene) and sedimented sea-floors (possibly representing only recently-deposited erratics).

The first step was to examine the distribution of grain-size from all the samples (Fig. 6; Table 3) to see if they were all derived from the same population, for this a χ^2 test was used. This test revealed that of the seven stations examined three should be rejected as not having samples from the same population; these were SMBA 26 and 144 and V27RD8. On further examination of information on the rejected stations, it appeared that loss of smaller grain sizes through the use of coarse meshes and unrecorded sub-sampling (i.e. removal of specimens) had taken place.

The samples accepted for further statistical analysis were then examined to produce distribution curves. These approximated to straight lines when cumulative frequency against grain size was plotted on log-normal graph paper (Fig. 7). The straight lines were drawn by least squares fit. At D9825, two lines were drawn with the least variance on each line as it was felt that material with grain sizes larger than 6 cm followed a different gradient, implying that two populations had been observed.

At stations D9756$^{\#9}$ and D9756$^{\#14}$ the benthic sledge had been used with an odometer wheel which gave a good indication of the distance run. From this an area sampled could be calculated and so a distribution of material per unit area could be produced.

Thus a normalised plot of cumulative frequency of particles/sq. km. has been drawn (Fig. 8).

5. Rock type analysis

Selected specimens were examined in detail to extract any mineralogical or palaentological data relating to their possible source areas. This has been done to see if iceberg "pathways" may be identified which would lead to a longitudinal variation in the amount of ice rafted material deposited. These more detailed studies will be continued in phase 3 of the project. For the purposes of this phase of the project, the rock type data have been presented on pie charts to give a view of overall rock type distribution (Fig. 9). In some areas the density of dredge stations is relatively great and so they have been grouped. This has been done on the assumption that variations in rock type percentages will occur over greater areas than those over which grouping has been done. Included in Figure 9 are some stations run by benthic biology groups; this has been done as the stations in Rockall Trough are good examples with which to illustrate some of the local provenance tendancies. The benthic biology stations further south have been included for completeness (from Kidd et al., 1980).

RESULTS

(1) Size distribution

The southernmost rock dredge haul to yield glacial erratics is from Great Meteor Seamount. Here, material up to 16 cm in size was found. Other coarse-grained clastic material tentatively identified as glacial erratics have been found in benthic sledge hauls at 25°N. The largest boulder recovered was from King's Trough (D 9561). Significantly, this is the largest boulder that the I.O.S. dredge can collect (25 x 15 x 10 cm).

A plot of cumulative frequency against grain size on log-normal graph paper can be fitted by straight lines drawn through the data points. This property indicates that the grain sizes are distributed exponentially. For the straight lines in Figures 7 and 8 the general equation is:

$$\mathrm{Log}_{10}\, X = \mathrm{Log}_{10}\, M - aD$$

where: M is the intercept of the line on the y axis
a is the gradient of the line
D is the grain size (maximum diameter)
X is either: cumulative frequency (N)
or: cumulative frequency of particles/sq km (P)

Application of this equation is based on the assumption that the data are derived from a continuous population even though they are grouped for the purposes of this study. The cumulative value decreases exponentially as the grain size increases; thus the distribution is a negative exponential function. Exponential functions may be found to occur rather commonly in sedimentary situations, and Krumbein (1973) has described several examples of negative exponential functions. Figure 7 shows that the gradient of lines for stations at which control was good varies from 0.11 to 0.49. This figure also shows that for station D9825 at least, there may be two populations being examined, as the data clearly fall into two groups for which two distinct lines can be drawn, intersecting at 6 cms.

The normalised plot of data on grain sizes less than 6 cm from benthic sledge stations can be used to calculate the frequency of occurrence of large boulders on the sedimented sea-floor. This may be done assuming that grain sizes are distributed exponentially and are from one population only, an assumption which is clearly questionable. Bearing this in mind and if one also assumes that there is no longitudinal variation in bulk quantity the results from this graph may be applied for the whole of latitude 50°N. Two lines have been drawn on Figure 8. Line A was derived directly from the data collected at the two stations. Line B is inferred using the distribution curve seen in Figure 7 for material greater than 6 cm at station D9825, but normalised by the same factor used for station D9756. Taking boulders to be rocks greater than 25.6 cm (maximum diameter) (Wentworth, 1922) the frequency of their occurrence per sq km can be calculated:

Line A:

$$a = 0.49$$

$$\mathrm{Log}_{10} M = 5.68$$

$$\mathrm{Log}_{10} P = 5.68 - (0.49 \times 25.6)$$

$$\therefore \mathrm{Log}_{10} P = -6.86$$

$\therefore$ frequency is $10^{-6.9}$/sq km

Line B:

$$a = 0.10$$

$$\mathrm{Log}_{10} M = 3.64$$

$$\mathrm{Log}_{10} P = 3.64 - (0.1 \times 25.6)$$

$$\therefore \mathrm{Log}_{10} P = 1.08$$

$\therefore$ frequency is 12/sq km

From the graph (Fig. 8) and these calculations one can see that, over an area of 1 sq km at latitude 50°N, there is a significant occurrence of glacial erratics (i.e. more than 10/sq km) in size ranges of 9.4 cm and less for Line A and 25.6 cm and less for Line B. This discrepancy between the two lines is discussed below.

2. Rock type distribution

From figure 9 it can be seen that there is no significant change in rock type distributions over the area studied. Specific lithologies, however, do show some provinciality at the margins of the N.E. Atlantic ocean (e.g. Rockall Trough). For example, stations in Rockall Trough show a large proportion of material tentatively identified as Torridonian sandstone which may have come from the Scottish Highlands. Also, Porcellaneous limestones occur in greater abundance in stations to the west of 15°W, reflecting perhaps a Western Atlantic source area.

Some specimens (e.g. porcellaneous limestones) may be useful in establishing the provenance of some of the erratics found.

DISCUSSION

Recent ice observations have shown that, even in more northerly latitudes icebergs greater than 150 m in thickness are rare (Sukhov, 1977). Other estimates have suggested that iceburgs up to 300 m draft are not uncommon (Belderson et al., 1973). Assuming that icebergs up to this size would have been able to reach further south during glacial maxima, the largest boulder that could have been dropped would have a diameter of 78 m (calculated on the basis that rock constitutes 7.5% by volume of an iceberg).

It is often observed that greater recoveries of ice rafted material are achieved over topographic highs than on abyssal plains. From a comparison of benthic sledge and rock dredge hauls this appears to be true even accounting for errors introduced by sampling. It is not clear whether this effect is due to greater accumulation rates of glacial erratics over topographic highs or entirely to higher sedimentation rates over abyssal plains obscuring erratic material. If one takes a relatively low pelagic sedimentation rate for the N.E. Atlantic of 2.4 cm/10^3 years (Ruddiman & Glover, 1972) boulders would become buried after resting on the sea-floor for 10^4 years, a span of time well within the present interglacial. Thus material deposited during the last glacial maximum may be completely obscured on abyssal plains. The occurrence of 500,000 year old manganese nodules on the sediment surface suggests that mechanisms exist which may prevent manganese nodules from being buried. Piper & Fowler (1980), have suggested that the action of sediment in fauna may be responsible for this effect, which may also be applied to glacial erratics. Clearly the question of pebble burial is of great importance as it affects any estimates of the occurrence of ice-rafted detritus on, or within, pelagic sediments.

Some of the stations containing large amounts of ice-rafted material are near the edge of the continental shelf. It has been shown for the outer U.K. shelf edge that iceberg grounding has taken place (Belderson et al., 1973) and this effect would be expected to cause greater accumulations of glacial erratics, due to icebergs being forced to melt and deposit their loads within a restricted area. This process may be extended to include other parts of the Atlantic with water depths less than 400 m (reducing to 300 m at times during the Pleistocene (Bloom et al., 1974). Seamounts in the N.E. Atlantic including Gt. Meteor, Cruiser and Josephine Seamounts (30°N, 32°N, 37°N respectively) may therefore have experienced iceberg grounding.

In addition to localised variations of ice-rafted material (e.g. scree slopes, etc.) there is probably an overall change in the bulk quantity per unit area in the N.E. Atlantic as one moves south. It has also been suggested that a high concentration of erratic material may be expected at the confluence of the Gulf Stream and the major iceberg-carrying current of the Arctic (Ruddiman, 1977).

The analysis of grain size data has revealed that for grain sizes up to 6 cm there is no latitudinal change in the relative frequencies of different grain sizes between 45° and 57°N. Statistical control of the data is not good enough to extend this result into the larger grain sizes or to regions further south. From the tests performed it is also apparent that some of the different sampling techniques (benthic sledges and rock dredges) which would be expected to sample rocks deposited over a range of times, have still sampled from the same population. Thus one can say that present-day ice rafting is producing material of the same nature as Pleistocene activity, the only difference being in bulk quantity. The change in gradient observed at station D9825 suggests the existence in the same area of two different populations. This change may cast serious doubts on the validity of the normalised data. The lines drawn for SMBA 26 might suggest a similar effect; however, the points are well scattered and not much confidence may be placed in this.

The normalised data, despite the problems of changing gradients at 6 cm, do provide estimates of the amounts of boulder material lying on the surface. It must be noted, however, that these results reflect only the surface distribution which probably represents a small fraction of the total volume of ice-rafted material that may be found within the sediment.

CONCLUSIONS

1. This study considerably extends the data base available on ice-rafted material found in existing collections of rock dredge hauls. Material in collections at British, French

and American repositories has been sorted using an improved set of identification criteria. Data quality varies considerably because of differing sampling methods used and the treatment of the material afterwards.

2. The southernmost occurrence of glacial erratics in rock dredge hauls was from Great Meteor Seamount (at around 30°N); here material ranging from 3 to 15 cm in size was found. Other coarse-grained clastics found in benthic sledge hauls at 25°N have not been positively identified as glacial erratics.

   The largest boulder recovered was from the King's Trough (station D9561); this measured 25 x 15 x 10 cm.

3. The grain sizes of glacial erratics are distributed exponentially. Grain size data have revealed the existence of two populations, whereby material smaller than 6 cm (maximum diameter) is distributed differently than that larger than 6 cm. A clarification of these anomalies is needed before accurate predictions on the distribution of boulders on sedimented sea-floors can be produced. More sampling of study areas would be important in the production of these statistics.

   Between latitudes 45°N and 57°N glacially derived pebbles with sizes ranging from 1.5 to 6 cm are distributed along a curve denoted by:

$$\mathrm{Log}_{10} P = \mathrm{Log}_{10} M - 0.49D$$

   where: P is the number of pebbles
   M is the intercept of the line

   The value M is considerably higher for seamounts than for sedimented sea-floors and for northern than for southern areas.

4. Work so far carried out on the processes that bury material on sedimented sea-floors is inconclusive. It is not known whether current estimates of the spatial distribution of glacial erratics represent the whole or part of the total volume of glacial erratics deposited over the past 3 million years.

5. Provenance studies which examine the source areas of erratic material are still in progress. No specific provenances have been found; however, near some shelf areas (i.e. Rockall Trough) the erratics do show some provinciality which reflects their proximity to source areas.

REFERENCES

Aumento, J., 1970. Petrological, geophysical and geochemical studies of rocks dredged from the Mid-Atlantic Ridge at 45°N. Bedford Institute of Oceanography; Atlantic Oceanographic Laboratory Data Series 5D, Volumes 1 and 2.

Belderson, R.H., Kenyon, N.H. & Wilson, J.B., 1973. Iceberg plough marks in the Northeast Atlantic. Palaeogeography, Palaeoclimatology, Palaeoecology, 13, 215-254.

Bender, M.L., Ku, T.L., & Broecker, W.S., 1969. Accumulation rates of Manganese in Pelagic Sediments and Nodules. Earth Planet. Sci. Lett., 8, 143-148.

Bloom, A.L., Broecker, W.S., Chappel, M.A., Matthews, R.K., Mesdella, K.J., 1974. Quarternary sea level fluctuations on a tectonic coast, new ^{230}Th/^{234}U Dates from the Huon Peninsular, New Guinea, Quart. Research 4,(2) 185-205.

Davies, T.A. & Laughton, A.S., 1972. Sedimentary Processes in the North Atlantic in Laughton, A.S. & W.A. Perggren et al., Initial Reports Deep Sea Drilling Project, 12, 905-934, U.S. Govt. Printing Office, Washington, D.C.

Emery, K.O., 1941. Transportation of rock particles by sea mammals. J. Sediment Petrol., 11, 92-93.

Emery, K.O. & Tschudy, R.H., 1941. Transportation of rock by kelp. Bull. Geol. Soc. Am., 52, 855-862.

Hessler, R.R. & Sanders, H.L., 1967. Faunal diversity in the deep sea. Deep-Sea Res., 14, 65-78.

Il'In, A.V. & Shurko, I.I., 1968. Petrographic regionalisation of the coarse clastic deposits of the north east Atlantic. Izvestiya Akademii Navk SSR, Seriya Geologicheskaya, 9, 126-129. Translated by N.C.P. Holland, I.O.S. Translation/A3.

Institute of Oceanographic Sciences, 1979. Oceanography related to deep-sea waste disposal. IOS Report No. 77, 264pp (unpublished manuscript).

Kidd, R.B. & Huggett, Q.J., 1981. Rock debris on abyssal plains in the Northeast Atlantic: A comparison of epibenthic sledge hauls and photographic surveys. Oceanologica Acta, 4, 99-104.

Kidd, R.B., Huggett, Q.J. & Crease, S., 1980. The Distribution of Pebble material on the Northeast Atlantic Seabed: Preliminary Results. IOS internal Document 84, 11 pp., (unpublished manuscript).

Kidd., R.B., Searle, R.C., Ramsay, A.T.S., Prichard, H., Mitchell, J. 1981 The Geology and Formation of King's Trough, Northeast Atlantic Ocean. Marine Geology, in press.

Krumbein, W.C., 1937. Sediments and exponential curves. J. Geol. 86, 577-601.

Nalwalk, A.J., Hersey, J.B., Reitzel, J.S. and Edgerton, H.E. 1961. Improved techniques of deep sea dredging. Deep-Sea Res., 8, 301-302.

Piper, D.Z. & Fowler, B., 1980. New constraint on the maintenance of manganese nodules at the sediment surface. Nature, 286, 880-883.

Rawson, M.D., Ryan, W.B.F., et al., 1978. Ocean floor sediment and polymetallic nodules. Office of the Geographer, Washington D.C. (Map at scale 1:23,230,300).

Ruddiman, W.F., 1977. Late Quaternary deposition of ice-rafted sand in the Sub Polar North Atlantic (Lat. 40°N to 65°N). Bull. Geol. Soc. Am., 88, 1813-1827.

Ruddiman, W.F. & Glover, L.K., 1971. Vertical mixing of ice-rafted volcanic ash in North Atlantic Sediments, Bull. Geol. Soc. Am., 83, 2817-2836.

Searle, R.C., 1979. Guidelines for the selection of sites for disposal of Radioactive Waste on or beneath the Ocean Floor. IOS Report 91.

Stanley, D.J. & Cok, A.E., 1968. Sediment transport by ice on the Nova Scotia Shelf, in: Stewart, H.B., Jr. (Editor), Transactions of the national symposium on ocean sciences and engineering of the Atlantic shelf. Marine Technology Society, Philadelphia, pp. 109-114.

Sukhov, B.P., 1977. Measurement of Iceberg Draft. In: A.A. Husseing (Editor), Iceberg Utilisation, Pergamon, London, pp. 265-275.

U.S. Navy Oceanographic Office, 1968. Ice, Publ. No. 700, 111.

Von Rad, U., 1974. Great Meteor and Josephone Seamounts (Eastern North Atlantic): Composition and origin of bioclastic sands, carbonate and pyroclastic rocks. Meteor Forschungsergebuisse Reihe C, (19), 1-61.

Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. J. Geol., 30, 377-392.

TABLE LIST

1. Table of all the rock dredge stations examined for this report. The stations are arranged latitudinally with those containing ice-rafted material greater in size than 1.5 cm marked thus *. The two letter prefix to the station number refers to equipment described in the text.

2. Table of all the benthic biology sampling stations examined for this project. The stations are arranged latitudinally with those containing ice-rafted material marked thus *. The two letter prefix to the station number refers to equipment described in the text. All except the SMBA stations in this table have been reported upon in Kidd et al., 1980 and Kidd & Huggett, 1980.

3. Table of the size data used in this report.

FIGURE CAPTIONS

Fig. 1. Occurrence of ice-rafted material in the North Atlantic, from dredge hauls and DSDP cores. Black squares indicate erratics in dredges and dots and triangles indicate erratics in DSDP and Lamont cores respectively. Contours; maximum rate of deposition of glacial sands in milligrams per square centimetre per thousand years (from Ruddiman, 1977); also shown are inferred limits of rafted ice (Davies & Laughton, 1971). Reproduced from Searle (1979).

Fig. 2. (i) Pipe dredge. A type of rock dredge used up until the early 1960s by many institutions. The mouth opening is 15 cm in diameter.

(ii) Rock dredge. A generalised picture of rock dredge for use on outcrops. These in various modifed forms are used by most institutes and universities of the world. The mouth openings are usually around 1 m width.

Fig. 3. (i) I.O.S. Epibenthic Sledge. A sampling device used up until 1978 by the I.O.S. Benthic Biology group for sampling sedimented sea-floors. It is an acoustically monitored device with a camera and relay information on camera operation, sledge attitude, speed along the sea-floor and absolute water depth. The mouth opening is 1.2 m wide.

(ii) W.H.O.I. sampling sledge. Also used by marine biologists for sampling sedimented surfaces, this device is not monitored so precisely and may be used either way up. It has a mouth opening of 81 x 30 cm.

Fig. 4. Three examples of positive features used in the identification of ice-rafted material.

Fig. 5. Locations of rock dredge stations found to contain ice-rafted material. The two areas at which grouping was carried out are identified by the prefix symbols Δ and □.

Fig. 6. Histograms of the particle size data at the seven stations examined.

Fig. 7. Grain size data. A plot of cumulative number of particles against grain size on log-normal graph paper enables straight lines to be drawn through the data points. The cumulative value decreases exponentially as grain size increases thus the distribution is a negative exponential function. The straight lines have been drawn by least squares fit. The change in gradient of the lines at 6 cm indicates that there may be two populations being sampled. This reflects the existence in the same area of two different populations. These data have shown that, for the latitudes so far examined (45°-57°N) there is no change in the relative frequency of different grain sizes, however, the bulk quantity does vary. The two heavier lines denote the stations for which statistical control was good and at which comparisons could be made.

Fig. 8. Normalised grain size data. Using the data from D9756#9 and D9756#14, a normalised curve giving the cumulative frequency of particles/sq km can be drawn. From this graph (heavy line, A) one can estimate the number of particles (greater than any given size over 1.5 cm) per 1 sq km. This estimate, however only applies to material with grain sizes from 1.5-6 cm. To predict the distribution of material >6 cm in diameter, the dotted line (B) should be used.

Fig. 9. Rock-type data. The rock types of glacial erratics have been examined to see if there are any overall changes in their distributions across the Atlantic. The 'pie' diagrams show the proportion of rock types by volume at each station. From this figure, one can see that there is no significant change. Specific lithologies, however, do show some provinciality at the margins of the Atlantic (e.g. Rockall Trough). Other specimens (e.g. Porcellaneous limestones) may be useful in establishing the provenance of some of the erratics found.

TABLE 1 - LIST OF GEOLOGICAL SAMPLING STATIONS EXAMINED FROM NE ATLANTIC: STATIONS ARE ARRANGED LATITUDINALLY

Cruise	Station# (equipment)	Position		Depth m	Erratics found *	Present Repository
		Latitude	Longitude			
45°N - 50°N						
Geomanche 2	RD 07	47°59.8'N	12°08.4'W	3320	*	COB, France
"	RD 08	47°59.8'N	12°07.7'W	3365	*	"
"	RD 09	47°58.9'N	12°06.1'W	3500	*	"
"	RD 10	47°59.2'N	12°07.1'W	3411	*	"
"	RD 12	47°47.5'N	12°16.2'W	4141	*	"
"	RD 13	47°46.0'N	12°19.6'W	4152	*	"
"	RD 18	48°34.8'N	12°34.3'W	2050	*	"
"	RD 20	48°26.6'N	11°19.9'W	2344	*	"
"	RD 21	48°36.3'N	11°10.1'W	2738	*	"
Vema 27	RD 6	48°09.1'N	15°55.9'W	4333		LDGO, USA
Vema 28	RD 8	48°20.0'N	11°00.0'W	No depth marked		"
Chain 13	RD 08	48°46.0'N	10°02.0'W	334		WHOI, USA
"	RD 09	48°47.0'N	10°01.5'W	815		"
Chain 43	RD 37	45°11.0'N	27°58.0'W	2612	*	"
40°N - 45°N						
Discovery	RD 9560	43°50.7'N	21°56.7'W	4500		IOS, UK
"	RD 9561	43°50.2'N	21°52.9'W	3700	*	"
"	RD 9562	43°54.8'N	21°56.5'W	3200	*	"
"	RD 9563	43°53.7'N	21°57.6'W	3850	*	"
"	RD 9564	43°59.1'N	21°54.0'W	2550	*	"
"	RD 9565	43°52.9'N	21°57.9'W	4100	*	"
"	RD 9566	44°02.6'N	21°48.7'W	1857		"
"	RD 9572	43°53.9'N	22°07.2'W	4540		"
"	RD 5610	42°51.0'N	20°16.5'W	4645	*	"
"	RD 5614	42°53.5'N	20°16.0'W	3809	*	"
"	RD 5623	43°07.5'N	19°39.5'W	3869		"
"	RD 5626	42°50.8'N	19°59.5'W	2646	*	"
"	RD 5627	42°51.5'N	19°56.0'W	2692	*	"
"	RD 5636	42°42.5'N	20°14.9'W	4939		"
"	RD 5951	42°35.8'N	11°57.5'W	1030	*	"
"	RD 5975	42°54.2'N	20°12.8'W	3200		"

Table 1 cont.

		Position				
Cruise	Station# (equipment)	Latitude	Longitude	Depth m	Erratics found *	Present Repository
Discovery	RD 5976	42°53.6'N	20°15.7'W	3400		IOS, UK
"	RD 5978	42°54.6'N	20°11.2'W	3486	*	"
"	RD 5979	42°50.7'N	20°16.2'W	4900	*	"
"	RD 5981	42°51.5'N	20°16.5'W	4800		"
"	RD 5983	42°54.4'N	20°13.4'W	3280		"
"	RD 5607	42°54.0'N	20°08.5'W	3288	*	"
Vema 27	RD 7	43°36.8'N	15°41.4'W	5606		LDGO, USA
"	RD 8	43°44.7'N	21°51.6'W	3542	*	"
"	RD 9	43°59.6'N	22°12.5'W	3086		"
"	RD 10	42°29.5'N	29°00.5'W	No depth marked		"
"	RD 11	42°19.9'N	27°9.3'W	3193		"
"	RD 12	42°20.5'N	25°52.6'W	2861		"
"	RD 17	40°35.0'N	13°55.0'W	No depth marked		"
Chain 43	RD 38	44°34.0'N	28°09.2'W	3264	*	WHOI, USA
"	RD 40	42°39.3'N	28°59.1'W	1628		"
"	RD 41	42°42.4'N	29°01.5'W	1756	*	"
Chain 82	RD 06	42°55.4'N	28°55.0'W	1395		"
"	RD 01	41°55.0'N	29°13.0'W	3085		"
AII 13	DR 01(75)	42°29.0'N	28°56.0'W	1159	*	"
Albatlante	DR 05	44°37.6'N	13°27.7'W	3996		COB, France
"	DR 07	43°11.0'N	12°00.0'W	1913	*	"
"	DR 08	40°57.0'N	11°34.4'W	3950		"
35°N - 40°N						
Gibraco	RD 02	35°01.1'N	12°55.6'W	1300		COB, France
"	RD 04	36°35.5'N	11°43.0'W	2600		"
"	RD 05	36°48.6'N	11°12.4'W	1847		"
"	RD 06	36°43.2'N	11°21.5'W	1600		"
"	RD 07	37°30.5'N	13°50.4'W	2048		"
"	RD 08	36°40.5'N	15°42.1'W	3749		"
"	RD 10	36°56.4'N	18°46.8'W	5340		"
"	RD 11	37°30.6'N	18°49.9'W	5103		"
"	RD 12	37°02.5'N	20°05.3'W	3475		"
"	RD 14	36°33.1'N	26°52.3'W	2800		"
"	RD 25	38°09.5'N	27°07.9'W	1480		"

Table 1 cont.

Cruise	Station# (equipment)	Position Latitude	Position Longitude	Depth m	Erratics found *	Present Repository
Cyagor	RD 02	36°25.0'N	11°29.0'W	1725		COB, France
"	RD 04	36°25.7'N	11°36.7'W	1093		"
"	RD 05	36°31.7'N	11°23.1'W	935	*	"
"	RD 06	36°34.2'N	11°25.3'W	452		"
"	RD 07	36°32.5'N	11°05.6'W	2070		"
"	RD 08	36°38.4'N	11°09.9'W	1842		"
"	RD 09	36°36.8'N	11°40.7'W	1900		"
"	RD 10	36°37.2'N	11°42.6'W	2520		"
"	RD 11	36°33.5'N	11°35.7'W	No depth marked		"
"	RD 12	36°36.5'N	11°40.2'W	1690		"
"	RD 13	36°40.8'N	11°03.2'W	1250		"
"	RD 14	36°42.1'N	11°05.2'W	190		"
"	RD 15	36°40.9'N	11°06.9'W	380		"
Gorgetti	RD 14	36°44.2'N	11°03.7'W	108		"
Noratlante	RD 06	36°36.5'N	26°38.1'W	3640		"
Nestlante	RD 15	36°45.0'N	11°24.0'W	2150		"
Vema 27	RD 13	38°43.7'N	18°06.3'W	4381		"
"	RD 14	36°37.1'N	14°09.8'W	1098		"
"	RD 15	36°47.0'N	14°15.6'W	546		"
"	RD 16	36°45.8'N	14°15.7'W	343		"
Vema 30	RD 12	35°08.0'N	35°36.0'W	4032	*	LDGO, USA
AII 13	RD 02	37°51.0'N	25°52.0'W	No depth marked		WHOI, USA
"	RD 03	39°35.0'N	31°12.0'W	No depth marked		"
AII 77	RD 10(55)	36°35.0'N	33°31.5'W	2437	*	"
AII 73	RD 12	36°29.3'N	33°39.0'W	2589		"
KNR 42	RD 24	36°36.4'N	33°28.5'W	2075		"
"	RD 27	36°50.9'N	33°32.5'W	1323		"
"	RD 30	36°31.9'N	33°29.4'W	1950		"
Chain 7	RD 19	35°05.0'N	12°13.0'W	169		"
"	RD 20	35°05.0'N	12°13.0'W	208		"

30°N - 35°N

Cruise	Station# (equipment)	Position Latitude	Position Longitude	Depth m	Erratics found *	Present Repository
Gibraco	RD 01	34°59.3'N	12°57.2'W	2006		COB, France
KNR 42	RD 33	34°48.6'N	57°13.4'W	3170		WHOI, USA
Chain 7	PD 1	30°02.0'N	28'34.0'W	640	*	"

Table 1 cont.

Cruise	Station# (equipment)	Position Latitude	Position Longitude	Depth m	Erratics found *	Present Repository
Chain 7	PD 2	30°02.0'N	28°33.0'W	4988		WHOI, USA
"	RD 21	33°44.0'N	14°20.0'W	199		"
"	RD 22	33°44.0'N	14°20.0'W	344		"
"	RD 23	33°44.0'N	14°20.0'W	636		"
"	RD 24	30°00.0'N	28°25.0'W	295		"
"	RD 25	30°00.0'N	28°23.0'W	295		"
"	RD 26	30°00.0'N	28°33.0'W	298	*	"
"	RD 27	30°00.0'N	28°30.0'W	288		"
Chain 21	RD 08	29°49.0'N	28°40.0'W	462		"
"	RD 10	29°49.0'N	28°40.0'W	349		"
"	RD 11	29°49.0'N	28°40.0'W	321		"
"	RD 13	29°47.0'N	28°19.0'W	589		"
"	RD 14	29°47.0'N	28°20.0'W	393		"
"	RD 15	29°46.3'N	28°19.0'W	850		"

TABLE 2 - LIST OF BIOLOGICAL SAMPLING STATIONS EXAMINED FROM NE ATLANTIC: STATIONS ARE ARRANGED LATITUDINALLY

Cruise	Station# (equipment)	Position		Depth m	Erratics found *	Present Repository
		Latitude	Longitude			
55° - 60°N						
SMBA	WS 6	55°03'N	12°29'W	2900		SMBA, UK
"	WS 26	56°35'N	09°08'W	573	*	"
"	OT 128	55°31'N	10°24'W	2450	*	"
"	OT 139	55°35'N	10°25'W	2450		"
"	OT 144	57°13'N	10°20'W	2240	*	"
Discovery	BS 7709$^{\#72}$	60°07'N	19°42'W	2650		IOS, UK
50° - 55°N						
SMBA	WS 27	54°40'N	12°16'W	2880 approx.	*	SMBA, UK
"	WS 55	54°40'N	12°16'W	2878		"
"	WD 56	54°40'N	12°16'W	2886		"
"	WS 59	54°40'N	12°20'W	2900 approx.		"
"	WS 111	54°40'N	12°16'W	2886		"
"	WS 118	54°39'N	12°14'W	2910		"
"	WS 129	54°39'N	12°17'W	2900 approx.		"
"	WS 135	54°39'N	12°16'W	2900 approx.		"
"	WS 137	54°34'N	12°19'W	2900 approx.		"
"	WS 140	54°40'N	12°16'W	2912	*	"
"	OT 141	54°44'N	12°14'W	2909		"
"	WS 143	54°41'N	12°14'W	2892		"
"	WS 142	54°39'N	12°16'W	-		"
"	OT 161	50°52'N to 50°53'N	12°27'W to 12°16'W	2055	*	"
"	WS 164	54°37'N	12°22'W	2925		"
Discovery	BS 9775$^{\#3}$	50°57'N	12°22'W	2016	*	IOS, UK
"	BS 9756$^{\#14}$	50°04'N	13°56'W	3690	*	"
"	OT 9640$^{\#1}$	50°03'N	13°51'W	3750	*	"
45° - 50°N						
Discovery	BS 9756$^{\#9}$	49°47'N	14°02'W	4050	*	IOS, UK
"	OT 9756$^{\#3}$	49°48'N	14°15'W	4100		"

Table 2 cont.

Cruise	Station# (equipment)	Position		Depth m	Erratics found *	Present Repository
		Latitude	Longitude			
Discovery	OT 9756$^{\#5}$	49°49'N	14°06'W	4015	*	IOS, UK
"	OT 9638$^{\#2}$	49°50'N	14°07'W	4050	*	"
35° - 40°N						
Discovery	BS 7424$^{\#1}$	37°27'N	26°52'W	2630		IOS, UK
"	BS 7423$^{\#1}$	37°51'N	27°04'W	2283		"
30° - 35°N						
Discovery	BS 9035$^{\#1}$	34°06'N	11°56'W	4454		IOS, UK
25° - 30°N						
Discovery	BS 8682$^{\#5}$	25°34'N	16°40'W	2995		IOS, UK
20° - 25°N						
Discovery	BS 8519$^{\#7}$	24°02'N	16°59'W	1000		IOS, UK
"	OT 8933$^{\#3}$	24°56'N	18°01'W	2985	*	"
"	OT 8933$^{\#4}$	24°58'N	17°57'W	2970		"
"	BS 9128$^{\#10}$	24°18'N	30°28'W	6059		"
"	BS 9129$^{\#1}$	23°06'N	27°59'W	5590		"
"	BS 9128$^{\#6}$	24°11'N	30°27'W	5726		"
"	BS 8524$^{\#1}$	20°46'N	22°43'W	4412		"
"	BS 8524$^{\#6}$	20°44'N	22°44'W	4415		"
"	BS 8521$^{\#1}$	20°47'N		3053		"
"	BS 8521$^{\#6}$	20°48'N	18°53'W	3050		"
"	BS 9131$^{\#10}$	20°15'N	21°36'W	3950		"
10° - 20°N						
Discovery	BS 8532$^{\#6}$	13°48'N	18°08'W	2956		"
"	BS 8540$^{\#1}$	11°16'N	18°23'W	3998		"

Table of grain size frequencies

Size groups cm / Station No.	1·5 – 2·49	2·5 – 3·49	3·5 – 4·49	4·5 – 5·49	5·5 – 6·49	6·5 – 7·49	7·5 – 8·49	8·5 – 9·49	9·5 – 10·49	10·5 – 11·49	11·5 – 12·49	<12·5
SMBA144	0 23	2 23	3 21	3 18	7 15	4 8	1 4	2 3	1 1			
SMBA26	69 279	109 210	51 101	16 50	14 34	12 20	0 8	2 8	3 6	0 3	0 3	3 3
SMBA 27/140	7 14	5 7	1 2	1 1								
D9756$^{\#9}$	37 56	12 19	6 7	1 1								
D9756$^{\#14}$	23 47	17 24	3 7	3 4	1 1							
D9825	451 916	289 465	96 176	35 80	13 45	7 32	5 25	5 20	4 15	2 11	2 9	7 7
V27 Dr. 8	7 32	22 25	3 3									

Table 3.

8 = frequency
19 = cumulative frequency

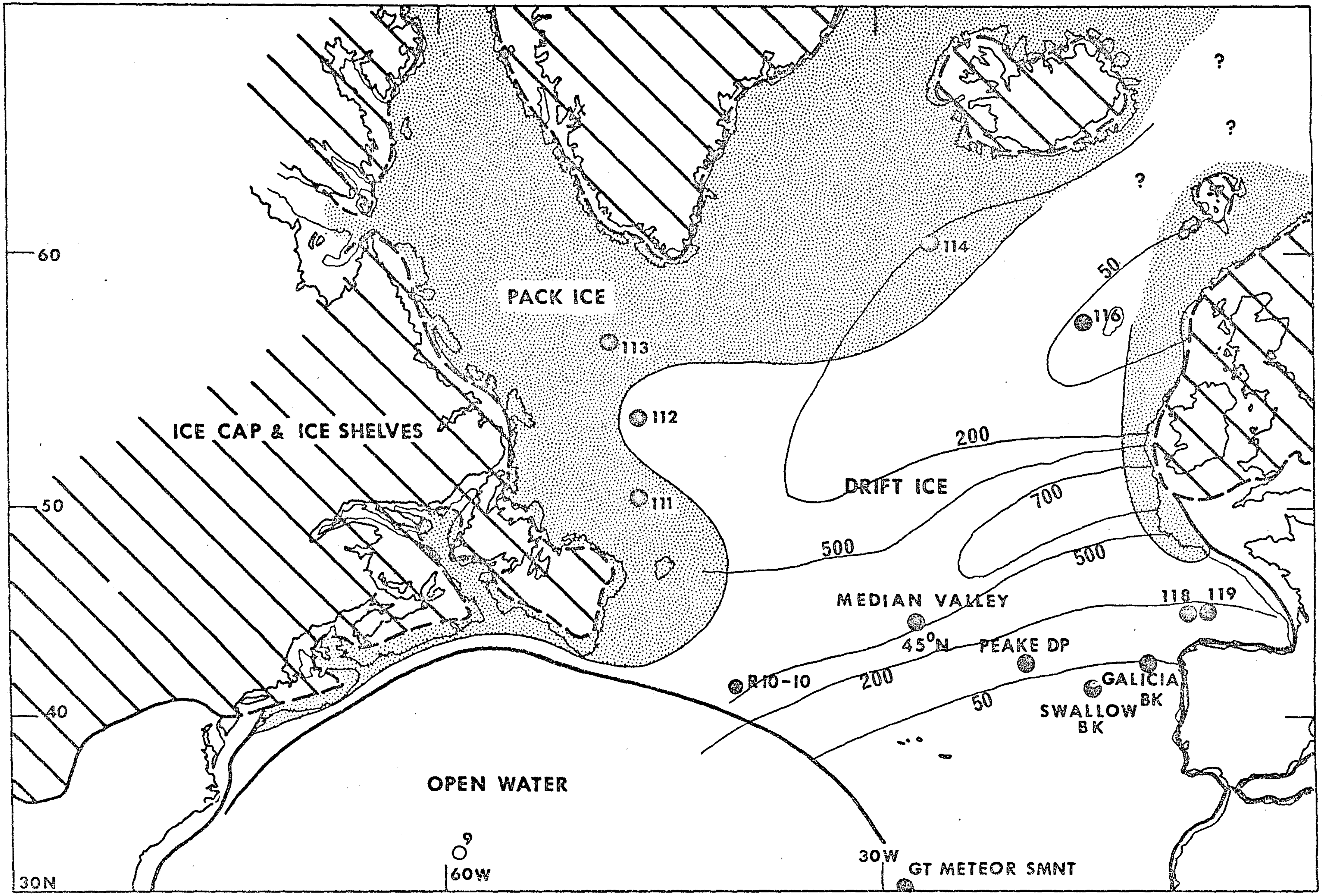

PACK ICE
ICE CAP & ICE SHELVES
DRIFT ICE
OPEN WATER
MEDIAN VALLEY
45°N
PEAKE DP
GALICIA BK
SWALLOW BK
GT METEOR SMNT
R10-10
111
112
113
114
116
118
119
9
50
500
200
700
500
200
50
?
?
?
60
50
40
30N
60W
30W

Fig.1

Fig.2

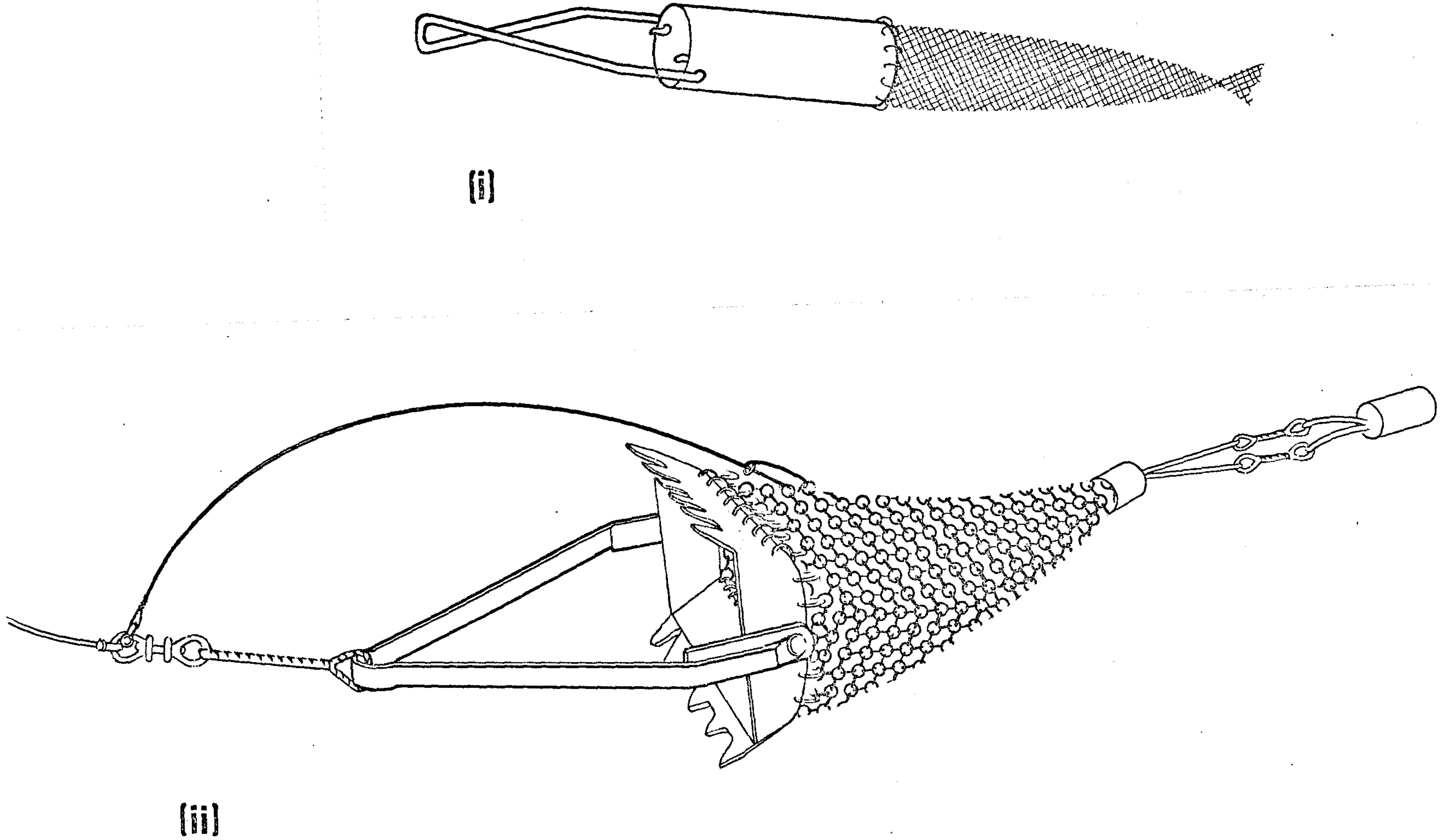
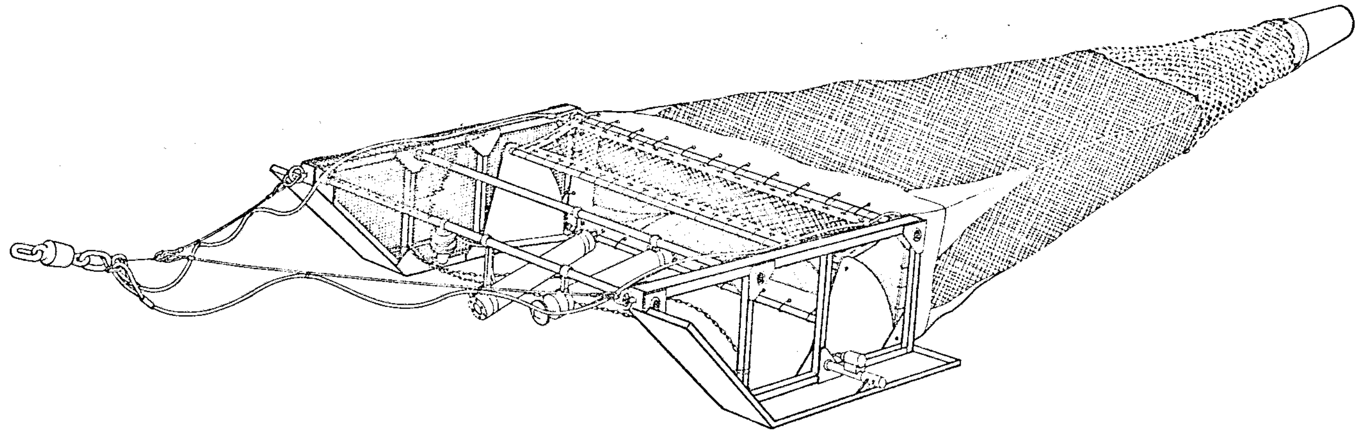
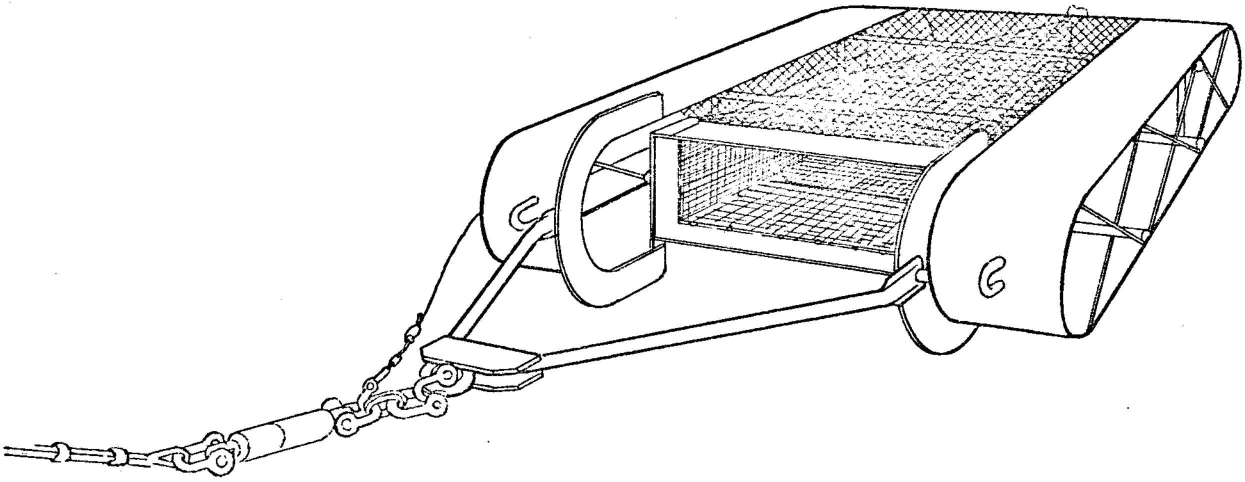


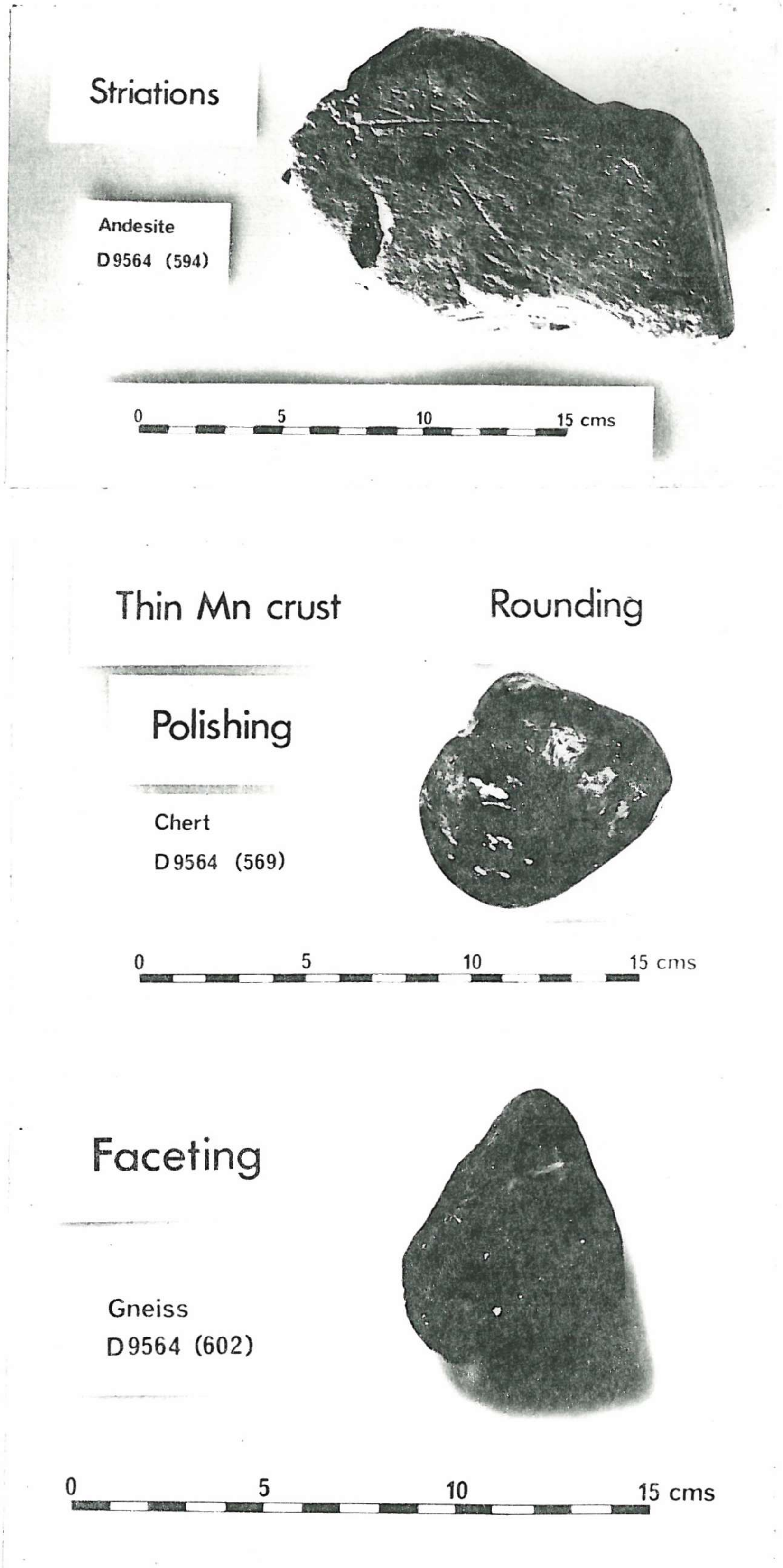
Fig.3



(i)



(ii)



Criteria used in the identification of Glacial Erratics. Fig 4

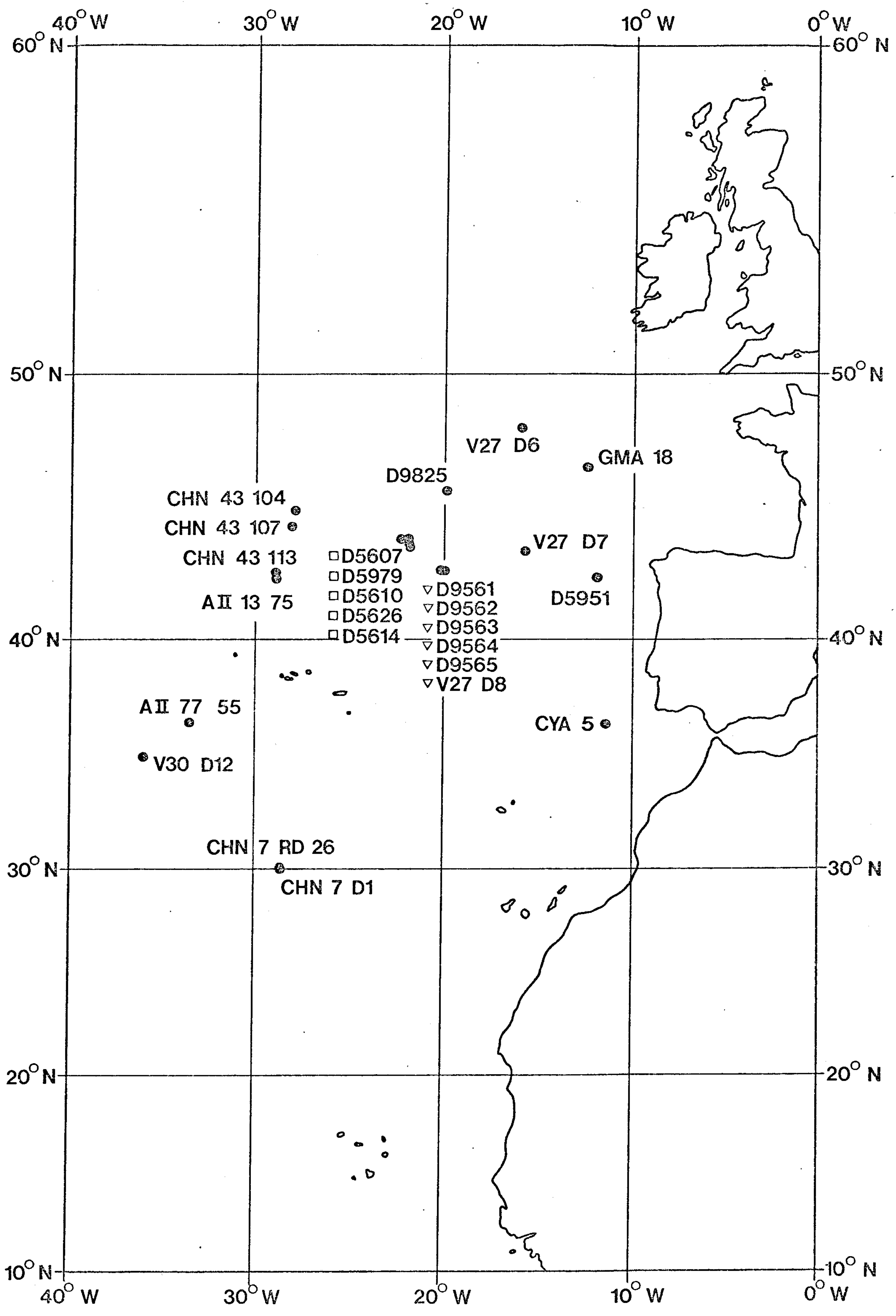


Fig.5

▽ & □: grouped stations

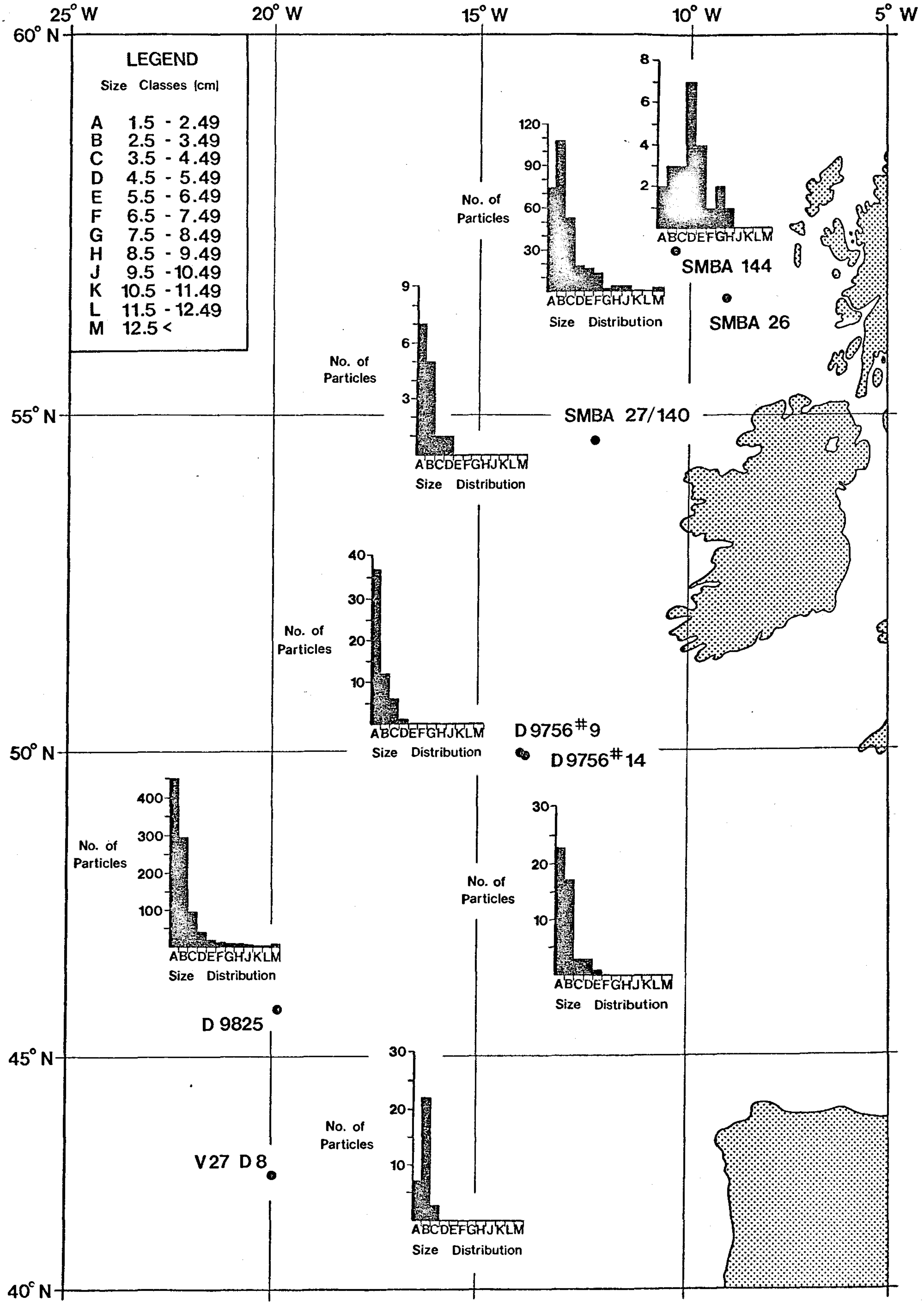
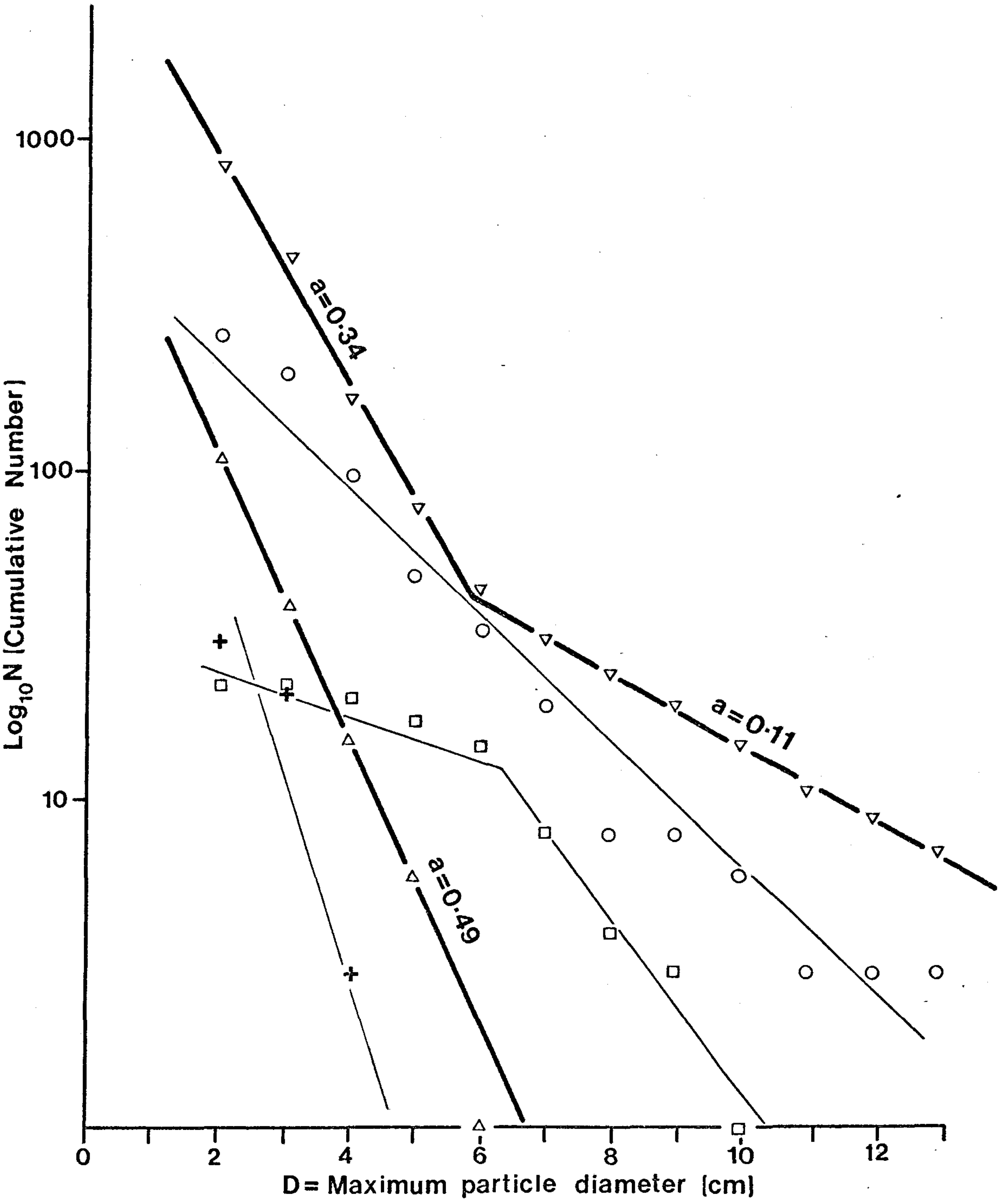

25° W
20° W
15° W
10° W
5° W
60° N
55° N
50° N
45° N
40° N
LEGEND
Size Classes (cm)
A 1.5 - 2.49
B 2.5 - 3.49
C 3.5 - 4.49
D 4.5 - 5.49
E 5.5 - 6.49
F 6.5 - 7.49
G 7.5 - 8.49
H 8.5 - 9.49
J 9.5 - 10.49
K 10.5 - 11.49
L 11.5 - 12.49
M 12.5 <
No. of Particles
Size Distribution
ABCDEFGHJKLM
SMBA 144
SMBA 26
SMBA 27/140
D 9756 #9
D 9756 #14
D 9825
V27 D8
120
90
60
30
8
6
4
2
9
6
3
40
30
20
10
400
300
200
100

Figure 6.

Fig. 7



LEGEND:

▽ D9825

△ $\text{D9756}^{\#9}$, $\text{D9756}^{\#14}$, SMBA27, SMBA14D

□ SMBA 144

○ SMBA 26

+ V27 Dr.8

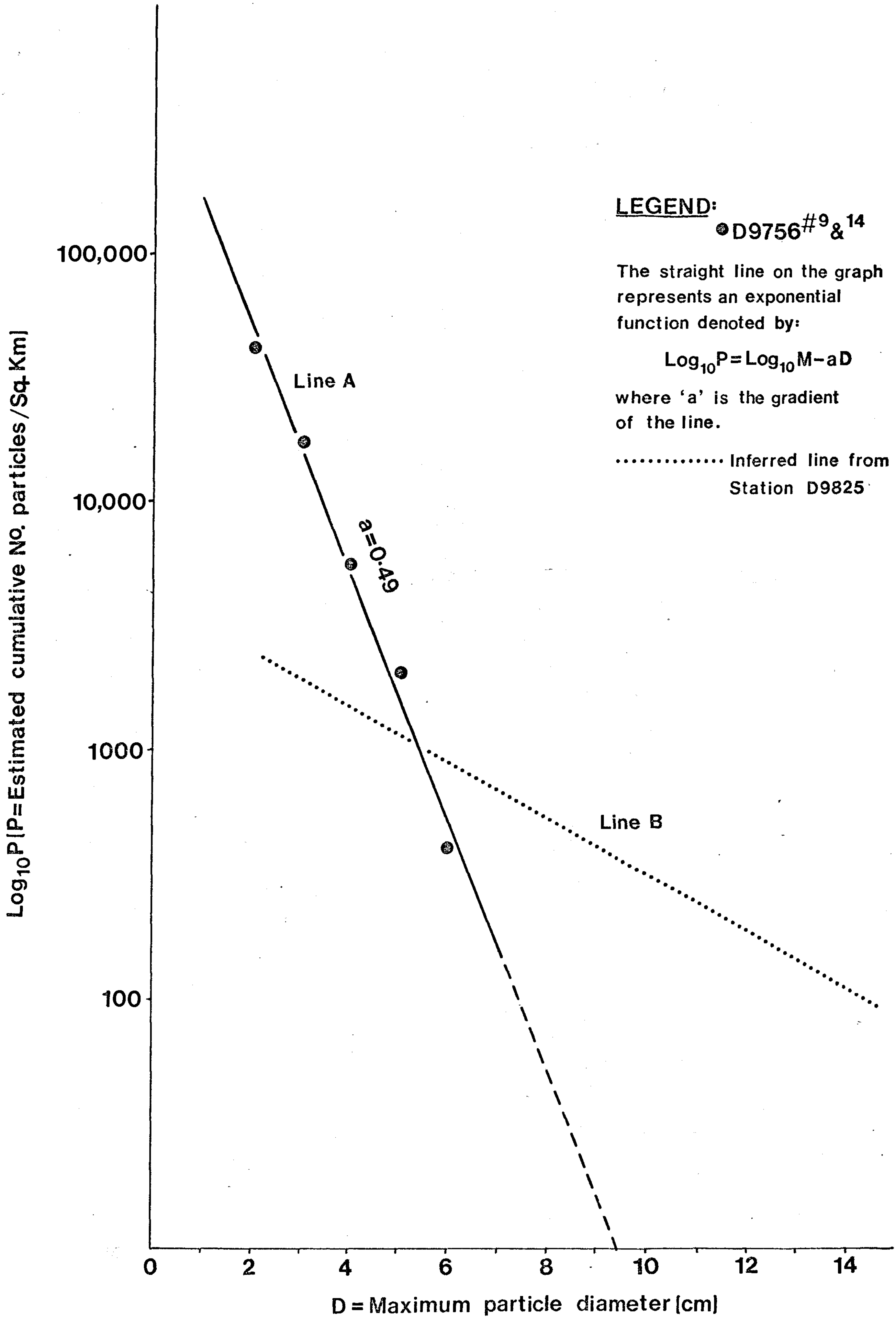
The straight lines on this graph represent exponential function denoted by:

$$\text{Log}_{10}\text{N} = \text{Log}_{10}\text{M} - \text{aD}$$

where: 'a' is the gradient of the line

'M' is the intercept on the y axis

Fig·8


LEGEND:
D9756#9&14
The straight line on the graph represents an exponential function denoted by:
$\mathrm{Log}_{10}P = \mathrm{Log}_{10}M - aD$
where 'a' is the gradient of the line.
Inferred line from Station D9825
Line A
a=0·49
Line B
$\mathrm{Log}_{10}P$ (P=Estimated cumulative No. particles/Sq.Km)
100,000
10,000
1000
100
0
2
4
6
8
10
12
14
D = Maximum particle diameter (cm)

01/15/81 1553

MERCATOR PROJECTION, SCALE=1/10000000.00 AT 40.00 DEG LAT□□□□□□□□□□□□

SUMMARY OF DATA ON GLACIAL ERRATICS (○=US, ×=FRENCH, ▽=UK DATA) QJH ● WORK IN PROGRESS

[B = MATERIAL COLLECTED BY BIOLOGICAL SAMPLING]

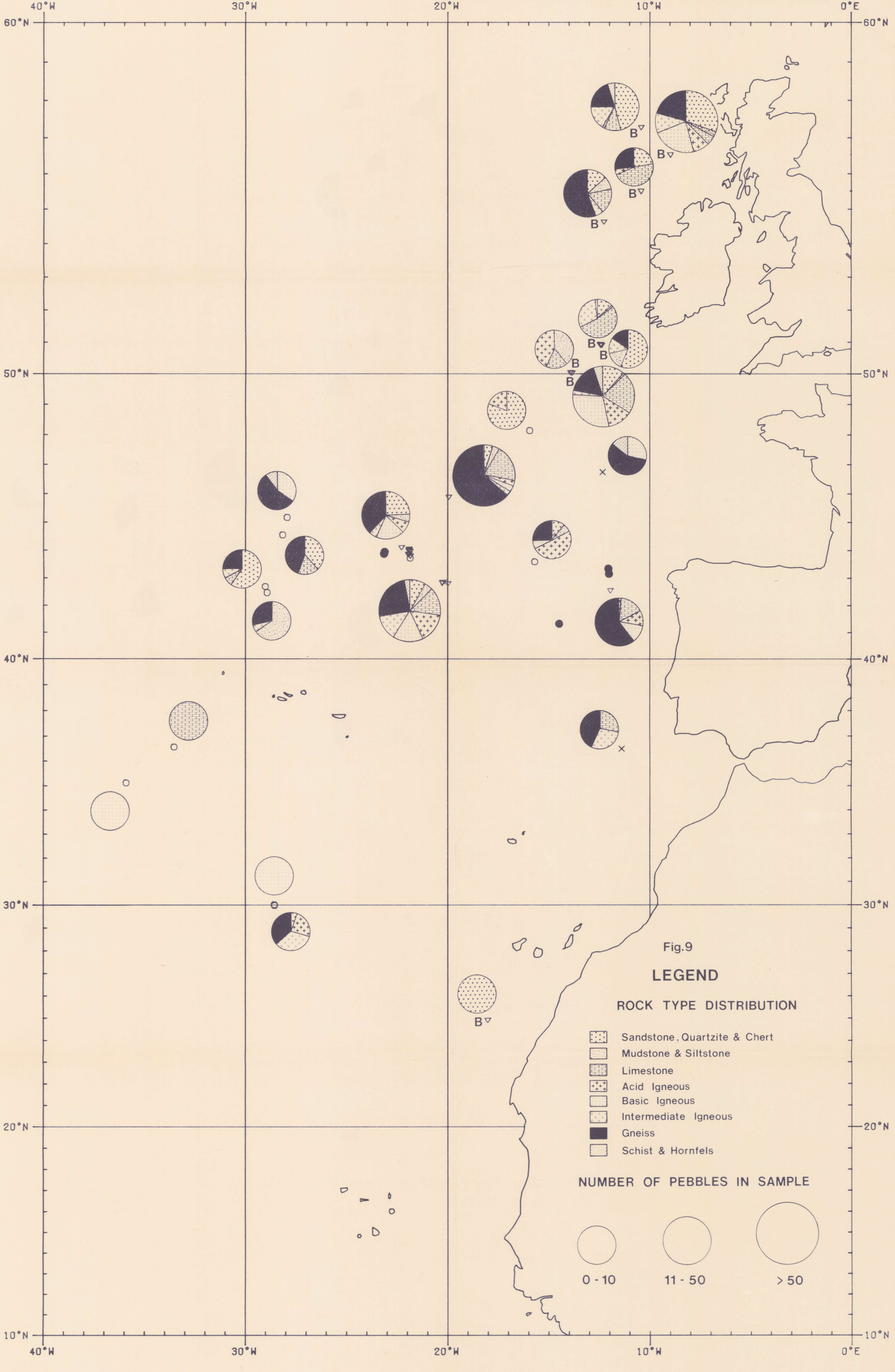


Fig.9