PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Oceanic Sediment Barrier [and Discussion]

T. J. G. Francis, R. C. Searle, T. R. S. Wilson, S. H. U. Bowie, A. S. Laughton and J. Rae

Phil. Trans. R. Soc. Lond. A 1986 **319**, 115-137
doi: 10.1098/rsta.1986.0090

Phil. Trans. R. Soc. Lond. A **319**, 115–137 (1986) [115]
Printed in Great Britain

The oceanic sediment barrier

By T. J. G. Francis, R. C. Searle and T. R. S. Wilson
Institute of Oceanographic Sciences, Brook Road, Wormley, Godalming, Surrey GU8 5UB, U.K.

[Plate 1]

Burial within the sediments of the deep ocean floor is one of the options that have been proposed for the disposal of high-level radioactive waste. An international research programme is in progress to determine whether oceanic sediments have the requisite properties for this purpose. After summarizing the salient features of this programme, the paper focuses on the Great Meteor East study area in the Northeast Atlantic, where most oceanographic effort has been concentrated. The geological, geochemical and geotechnical properties of the sediments in the area are discussed. Measurements designed to determine the rate of pore water movement through the sediment column are described. Our understanding of the chemistry of both the solid and pore-water phases of the sediment are outlined, emphasizing the control that redox conditions have on the mobility of, for example, naturally occurring manganese and uranium. The burial of instrumented free-fall penetrators to depths of 30 m beneath the ocean floor is described, modelling one of the methods by which waste might be emplaced. Finally, the nature of this oceanic environment is compared with geological environments on land and attention is drawn to the gaps in our knowledge that must be filled before oceanic burial can be regarded as an acceptable disposal option.

Introduction

Research into the disposal of high-level radioactive waste in the sediments of the ocean floor began in the U.S.A. in 1974 with the start of the 'Subseabed Disposal Program' (Bishop & Hollister 1974; Schneider & Platt (eds) 1974; Bishop 1975). Other countries joined in the research in the late 1970s and since then the work has been coordinated internationally through the Seabed Working Group (SWG) of the Nuclear Energy Agency of the OECD. Proceedings of the annual SWG meetings and of its various task groups are published by Sandia National Laboratories, U.S.A., on behalf of the NEA; significant new results of the research are published regularly in the scientific literature. At the present time ten countries (Belgium, Canada, Federal Republic of Germany, France, Italy, Japan, The Netherlands, Switzerland, United Kingdom, United States of America) and the Commission of the European Communities are involved in this endeavour (OECD 1984).

After preliminary desk studies, research in the U.K. began in 1979 when the Institute of Oceanographic Sciences (IOS) of the Natural Environment Research Council was awarded a 5 year contract by the Department of the Environment to carry out research into the feasibility of high-level radioactive waste disposal both on and beneath the seabed. The results of this first 5 years of activity have been reviewed by Francis (1984). The contract to IOS was extended for a further 3 years in 1984 and the U.K. ocean disposal research programme now involves other Government-funded laboratories and a number of University departments.

Concepts

Essentially four methods of oceanic waste disposal are available if we are to rely on existing or only small extensions of existing technology (figure 1).

(*a*) Solidified waste could be packaged into a streamlined projectile, freely dropped to the ocean floor and finish up buried to a depth of a few tens of metres within the unlithified sediments. Model penetrator experiments designed to test this technique are described later in the paper. Full-scale penetrators would need to be perhaps 10 m long and weigh 20 t to accommodate the blocks of waste.

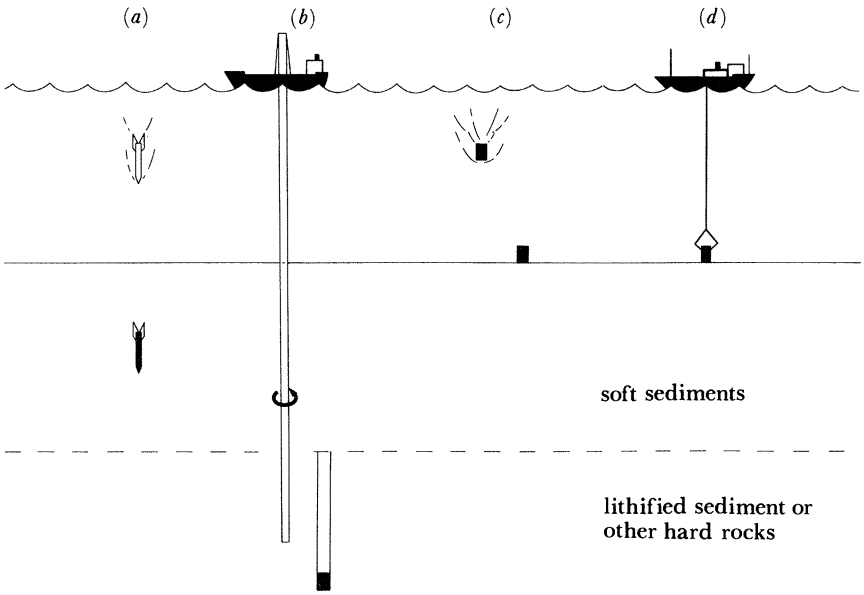

Figure 1. Possible methods of oceanic waste disposal.

(*b*) Alternatively, a hole might be drilled into the lithified sediment or basement of the ocean floor, waste canisters stacked within it and the hole sealed by grouting or other backfilling. Although holes have been drilled in oceanic depths for scientific purposes since the late 1960s as part of the Deep Sea Drilling Project and currently of the Ocean Drilling Program, these holes were all drilled without a riser. The maximum water depth in which riser drilling has been achieved to date is just over 2 km, and the viability of riser drilling in full oceanic depths has yet to be proved. Nevertheless drilling, emplacement of canisters and re-sealing of the hole are all believed to be technically-feasible in the riserless mode.

(*c*) The third concept is simply to dump suitably packaged canisters so that they lie on the seabed. Clearly this is the cheapest method that can be conceived and is that which was adopted for the disposal of low-level waste in the Northeast Atlantic within the framework of the London Convention until that practice was suspended in 1983 (Holliday 1984). However, the London Convention prohibits such a method for high-level radioactive waste.

(*d*) Finally, the canisters might be placed in a more controlled way than (*c*) so that they rest, possibly in some structure, on the seabed.

Research into the feasibility of disposal in the oceans, so long as it does not involve the actual

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

disposal of any nuclear waste, does not contravene existing international law. But movement towards an actual disposal operation using any of the above techniques could not take place without substantial international discussion and agreement, probably within the framework of the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (the London Dumping Convention) or of the proposed U.N. Convention on the Law of the Sea (OECD 1984).

When a waste canister is buried within the sediments of the ocean floor the transport of radionuclides back to man is restricted first by containment, then by dispersal within the ocean. The complete process is summarized in the flow diagram shown in figure 2. A series of barriers

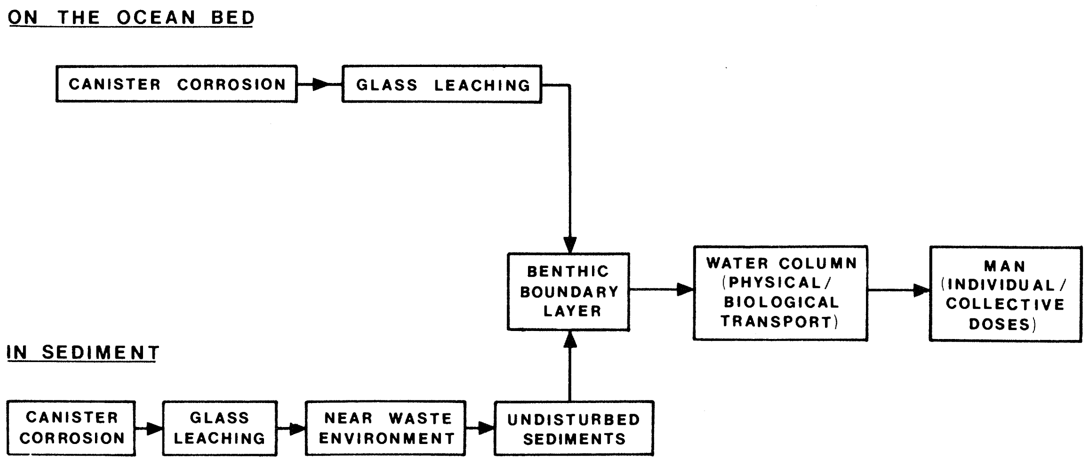

FIGURE 2. System model of transfer processes from emplaced waste back to man.

exist to contain the waste within the sediment. This 'belt and braces' approach is known as the multiple barrier concept. Each barrier has characteristic time constants in its ability to retard the transport of radionuclides. The barriers created by the canister itself and by the leaching resistance of the waste form are discussed by other contributors to this symposium (Papp; Mendel; Kelly & Ringwood). Similarly the fate of radionuclides that escape from the sediments and are subject to dispersion by physical, geochemical and biological processes in the water column are discussed in this symposium by Needler. In this paper we are concerned with the box marked 'undisturbed sediments' in figure 2. What we can say about the undisturbed sediments also provides necessary input to studies of the 'near waste environment' around the canister, where the sediments are modified by its heat, radiation and corrosion products, but discussion of this environment is beyond the scope of this paper.

A few thousand years after disposal, corrosion of the canister and leaching of the solid waste form would result in the release of radionuclides into the pore water of the adjacent sediment. Once in solution in the pore water the waste must be transported many metres through the sediment before it can reach the sea itself. Studies of the physical and chemical properties of oceanic sediments indicate that this process could take a very long time. Time constants ranging from tens of thousands to hundreds of thousands of years are likely, depending on the type of radionuclide and the thickness and geochemical characteristics of the sedimentary cover. Furthermore, fine-grained sediments have the ability to adsorb many of the radioactive species found in the waste. Thus oceanic sediments have the potential to provide a most effective barrier against the escape of long-lived radionuclides. A considerable effort has therefore been directed towards establishing the integrity of this barrier: determining its physical and chemical properties, establishing that pore water movement is negligibly small and showing that in areas where waste might be disposed a régime of continuous, undisturbed sedimentation exists.

Selection and evaluation of areas

The research started with guidelines being drawn up to define the qualities desired for possible waste disposal sites (Searle 1979, 1984; Laine *et al.* 1983). The two major concerns were with the geological stability of the site and with the characteristics of the sedimentary barrier itself. Clearly areas of seismic or volcanic activity or where sediments could be disrupted by erosion or mass movement should be avoided. The sediment itself should have low permeability, good sorption characteristics and be laterally homogeneous. The underlying philosophy was that the environment in which the waste was disposed should be highly predictable.

A number of areas in the North Atlantic and North Pacific Oceans were then chosen on the basis of existing geophysical track coverage to be worthy of further study as possible disposal sites. In the Pacific, mid-plate areas of pelagic red clay sedimentation were identified. In the Atlantic, two broad categories of area were defined: (*a*) distal abyssal plain areas where turbidite flows of terrigenous sediment lose their momentum and a depositional sedimentary régime is to be expected, and (*b*) areas which because of their elevation or location receive no terrigenous input and where entirely pelagic, predominantly carbonate, sediments are deposited. Having identified these study areas, the next step was to subject them to methodical geological, geophysical and geochemical examination to understand the sedimentary environment more fully in each place and to see whether it lived up to what was considered necessary for a disposal site. It soon became clear that many of the areas were unsuitable. In some, sedimentary transport processes appeared to be too active; other areas were found to be considerably more rugged than was originally thought. In all some twenty areas have been studied to a greater or lesser extent and about three quarters of them have been downgraded. The current status of all the areas studied under the auspices of the Seabed Working Group programme have been summarized by Auffret *et al.* (1984).

The nature of the work which has been done to evaluate possible disposal areas can best be understood by concentrating on the Great Meteor East study area (GME) in the Northeast Atlantic, to which more effort has been devoted than to any other study area. Oceanographic studies in the GME area have been conducted so far by the Institute of Oceanographic Sciences and by the Rijks Geologische Dienst of the Netherlands; a French cruise with international participation is planned for summer 1985 and further research cruises are planned for 1985 and 1986 (table 1). Preliminary accounts of the Dutch work in the area have been given by Kuijpers (1982) and Duin & Kuijpers (1983). A detailed account of all the geological studies up to the end of 1983, incorporating both the British and Dutch data, has been given by Searle *et al.* (1985).

TABLE 1. OCEANOGRAPHIC ACTIVITY IN THE GREAT METEOR EAST STUDY AREA

year	ship	geology and geophysics	geochemistry	physical oceanography	marine biology
1980	*Tydeman* (Netherlands)	×	×	—	—
1981	*Discovery* 118 (U.K.)	×	—	—	—
1981	*Farnella* 3/81 (U.K.)	×	—	—	—
1982	*Tyro* (Netherlands)	×	×	—	—
1982	*Shackleton* 126 (U.K.)	×	—	—	—
1982	*Discovery* 129 (U.K.)	—	×	—	—
1983	*Discovery* 134 (U.K.)	×	—	—	—
1984	*Discovery* 144 (U.K.)	×	—	×	—
1984	*Discovery* 149 (U.K.)	—	×	—	—
1984	*Discovery* 153 (U.K.)	×	—	—	—
1985	*Charles Darwin* 1/85 (U.K.)	—	—	×	—
	planned cruises				
1985	*Marion Dufresne* (France)	×	×	—	—
1985	*Discovery* 156 (U.K.)	—	—	—	×
1985	*Charles Darwin* 9/85 (U.K.)	×	—	—	—
1986	*Charles Darwin* 1/86 (U.K.)	—	—	×	—

GEOLOGICAL SETTING OF THE GREAT METEOR EAST AREA

The Great Meteor East study area is located on the Madeira Abyssal Plain approximately 700 km WSW of Madeira and a similar distance both from the Azores and from the Canary Islands (figure 3). To the west of the area the plain dies out among the abyssal hills on the lower flank of the Mid-Atlantic Ridge. East of 24° W the continental rise climbs gradually to the foot of the slope off northwest Africa.

Building on the earlier work of Embley (1975, 1976), surveys with the long-range sidescan sonar GLORIA have established the patterns of sediment transport into the area from the northwest African margin. Slumps and slides on the continental slope in the vicinity of the Canary Islands have given rise to debris flows and turbidity currents that have transported sediment across the continental rise to its resting place on the Madeira Abyssal Plain. Debris flow deposits, strongly backscattering the acoustic energy of the sidescan sonar, are observed as far as 24° W, 1000 km from their source on the continental slope (Simm & Kidd 1984). Further west the abyssal plain is truly distal, with no indications of sediment transport on the acoustic sonographs. The morphology of the seabed within the GME area is shown in the bathymetric chart in figure 4. This chart is based not only on lines of soundings but on a comprehensive GLORIA survey of the area which allows the morphological features between the precision-echosounder profiles to be properly contoured (Searle *et al.* 1985). West of 24° W the sea floor is extremely flat with gradients of less than 1 in 2000, except where abyssal hills, typically a few kilometres across and a few hundred metres high, emerge above the level of the plain. These abyssal hills are generally elongated in a NNE–SSW direction, reflecting their origin by block faulting near the axis of the Mid-Atlantic Ridge.

Seismic reflection profiling with airgun and water gun sources has provided information about the thickness of the sediments and the basement morphology. By using an appropriate velocity–depth relation for the sediments, acoustic travel times observed on the seismic profiles have been converted to thicknesses (Duin & Kuijpers 1983; Searle *et al.* 1985). A contour map of total sediment thickness in the area is shown in figure 5. The sediment thickness varies

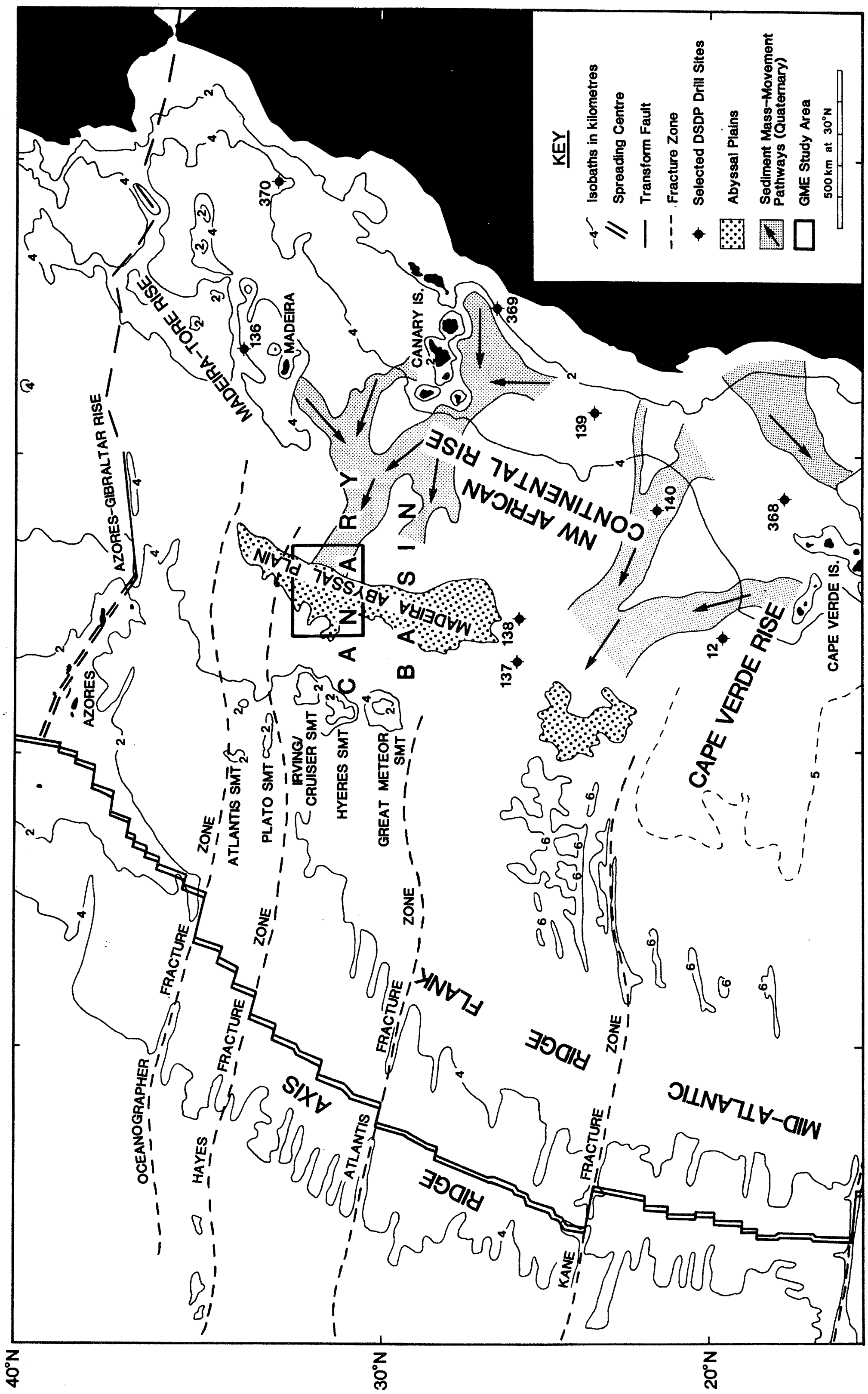

FIGURE 3. Regional setting of the Great Meteor East radioactive waste disposal study area. (After Searle *et al.* 1985.) Outline bathymetry in kilometres.

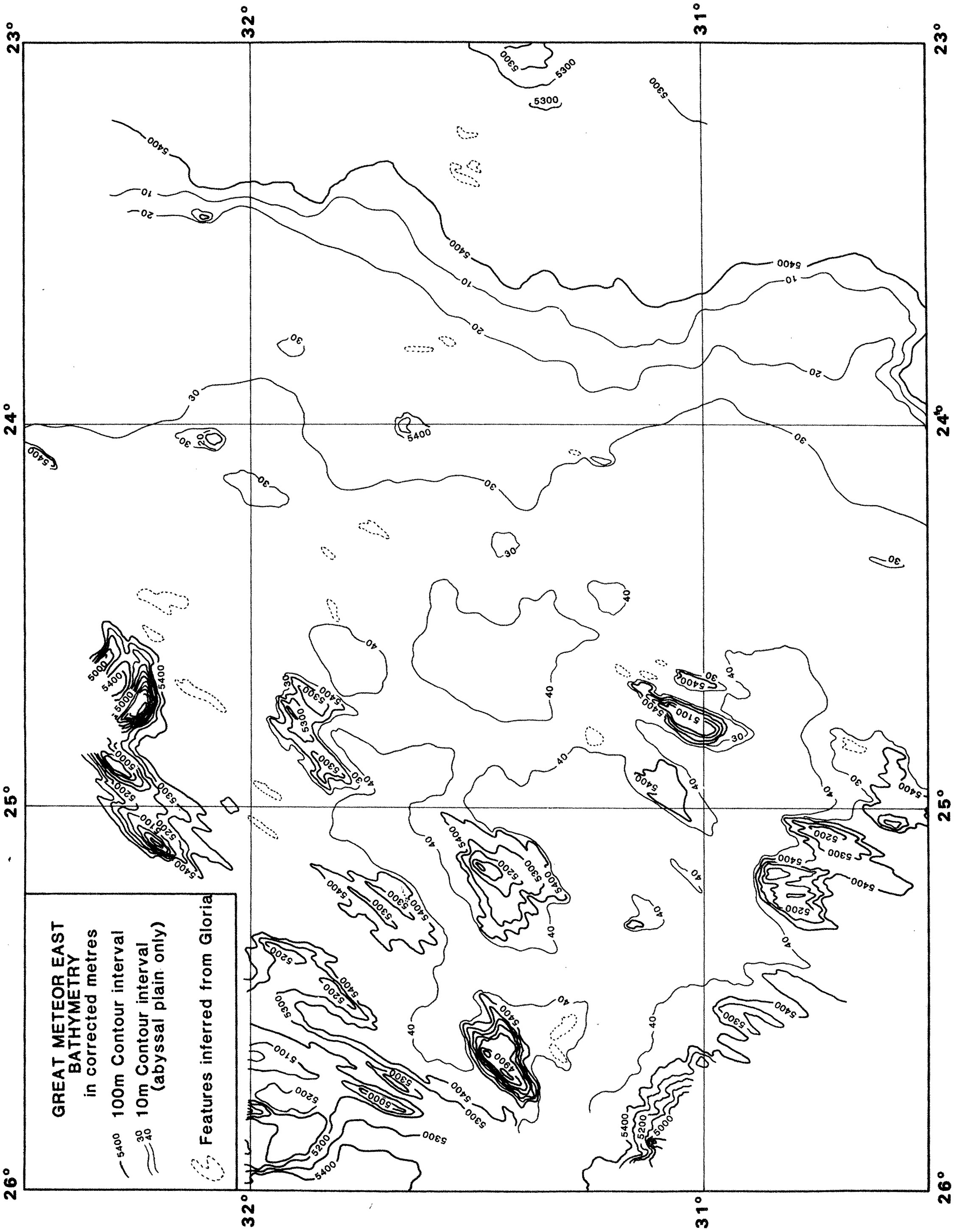

FIGURE 4. Bathymetric chart of the Great Meteor East study area.

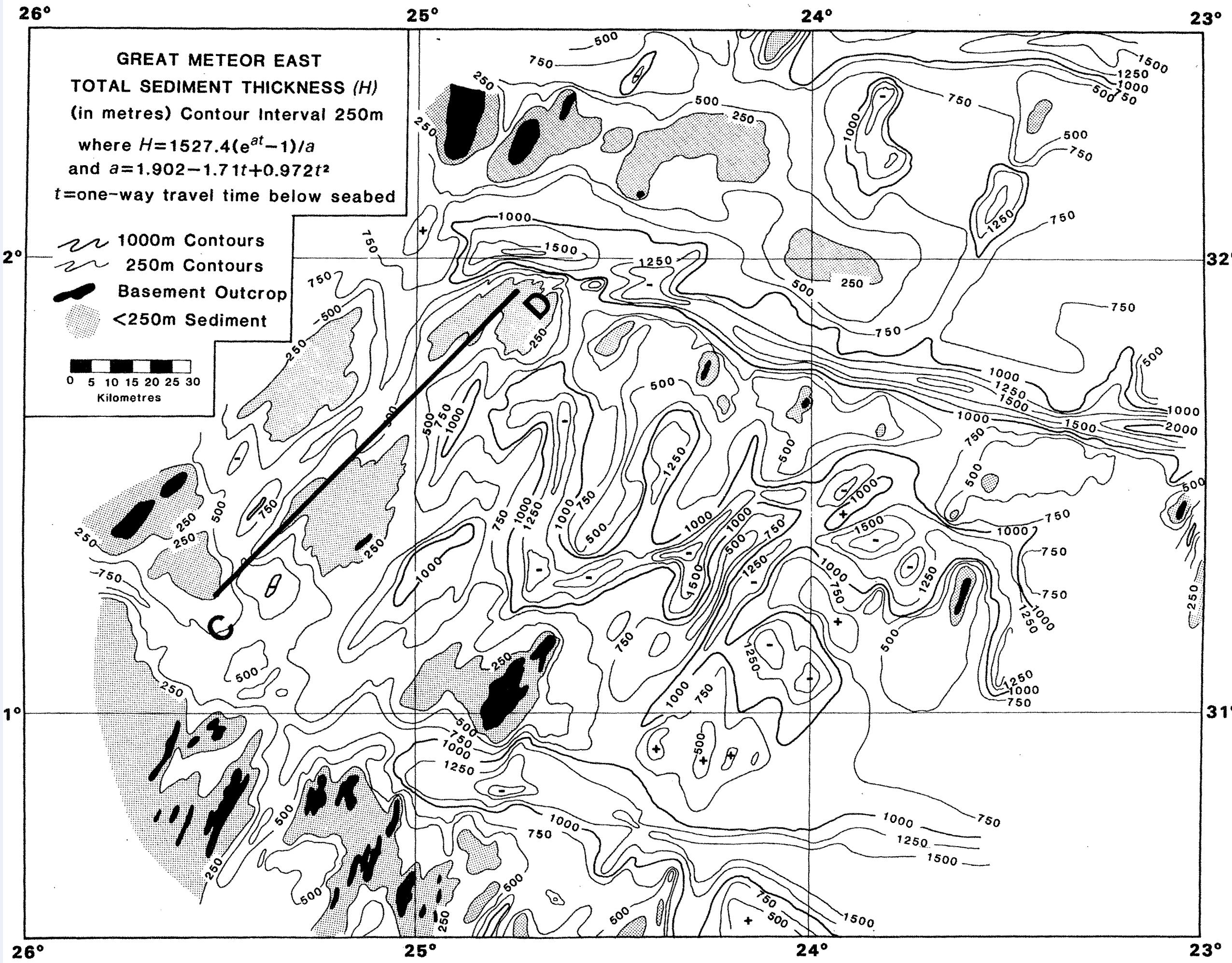

FIGURE 5. Map of total sediment thickness in the Great Meteor East study area from seismic reflection profiling. Institute of Oceanographic Sciences data combined with that of Duin & Kuijpers (1983). The line CD shows the location of the profile in figure 6.

considerably over the area but is generally in excess of 250 m. The basement topography has a pronounced NNE–SSW grain, reflecting the same tectonic origin as already discussed for the exposed abyssal hills. Two prominent valleys cutting across the area in a WNW–ESE direction represent the traces of inactive fracture zones. The seismic reflection profile obtained along line CD in figure 5 is shown in figure 6, plate 1. Two major regional reflectors, marked 2 and 4 on the figure, are recognized in the area. Reflector 4, generally lying between 200 and 400 m below the seabed, is interpreted as marking the base of the turbidites that are believed to compose the bulk of units A and B. The first major turbidites may have been emplaced at about 6.2 Ma ago in the late Miocene or as recently as 2.4 Ma ago at the onset of the Northern Hemisphere glaciation (Weaver *et al.* 1985). Below reflector 4, units C and D are interpreted as being pelagic in origin and composed predominantly of clay. The oldest sediments along this profile are likely to be Turonian in age (92 Ma old) in keeping with the age of the underlying basement.

An extensive coring programme has been carried out in the GME area, including over 50

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

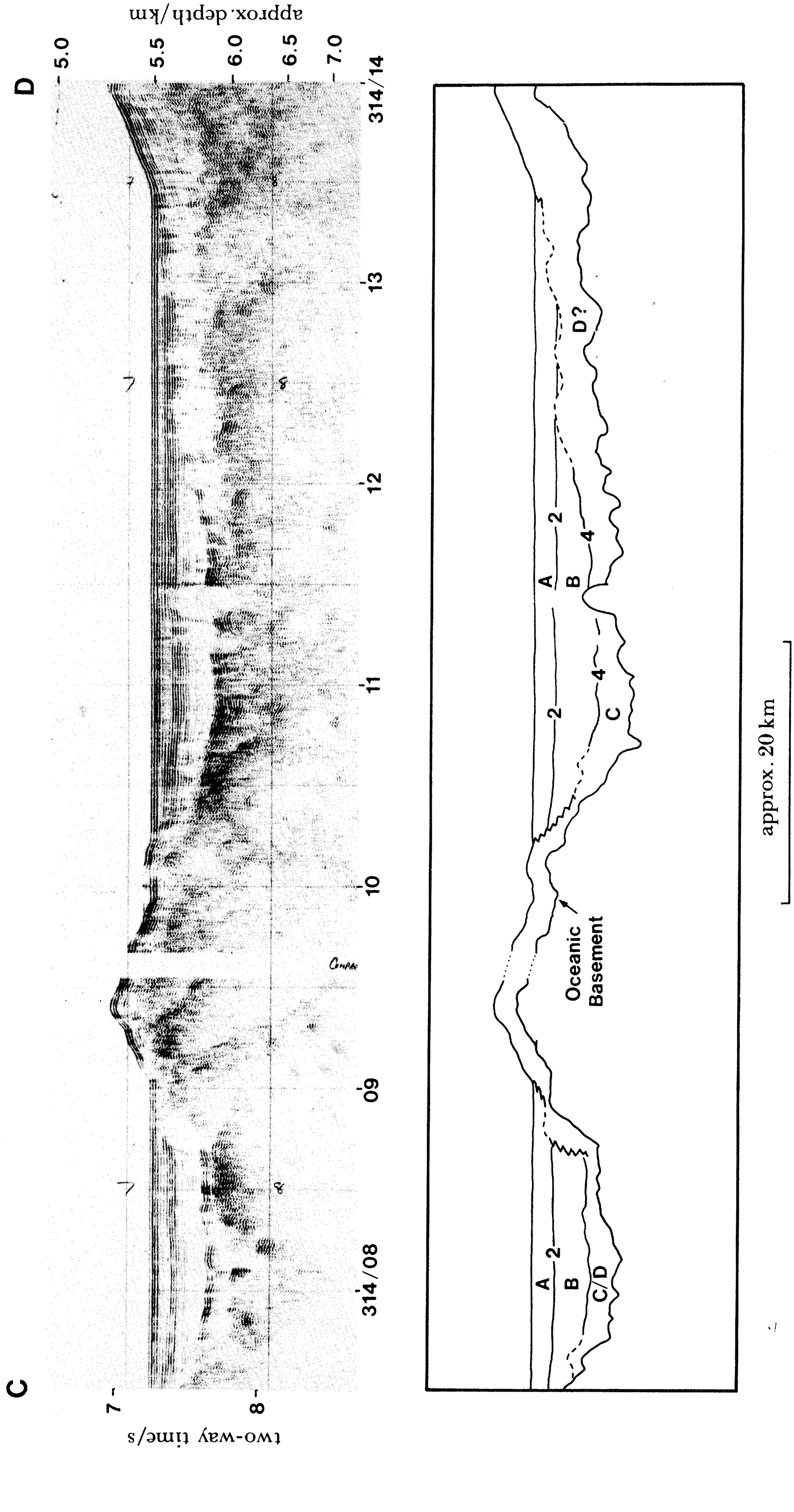

FIGURE 6. Seismic reflection profile obtained along line CD in figure 5, with interpretation. See text for details of interpretation.

(*Facing p.* 122)

piston cores and a smaller number of large cross section Kastenlot and box cores. The cores obtained have allowed the sedimentology and stratigraphy of the sediments to be studied down to a depth of 22 m. The sediments of the abyssal plain are composed predominantly of fine-grained turbidites of calcareous marl, typically a couple of metres thick, interbedded with much thinner pelagic units of ooze and clay. Some of the turbidites have thin basal layers of fine sand to silt, the proportion of sand increasing towards the east of the area (Duin & Kuijpers 1983). Detailed micropalaeontological analyses of the cores to determine the abundances of five different coccolith species have allowed their stratigraphy to be resolved in considerable detail (Weaver & Kuijpers 1983). Individual turbidites can be correlated across the whole area (figure 7) and it is clear that by the time they reach GME they have lost their erosive power and that the environment is depositional.

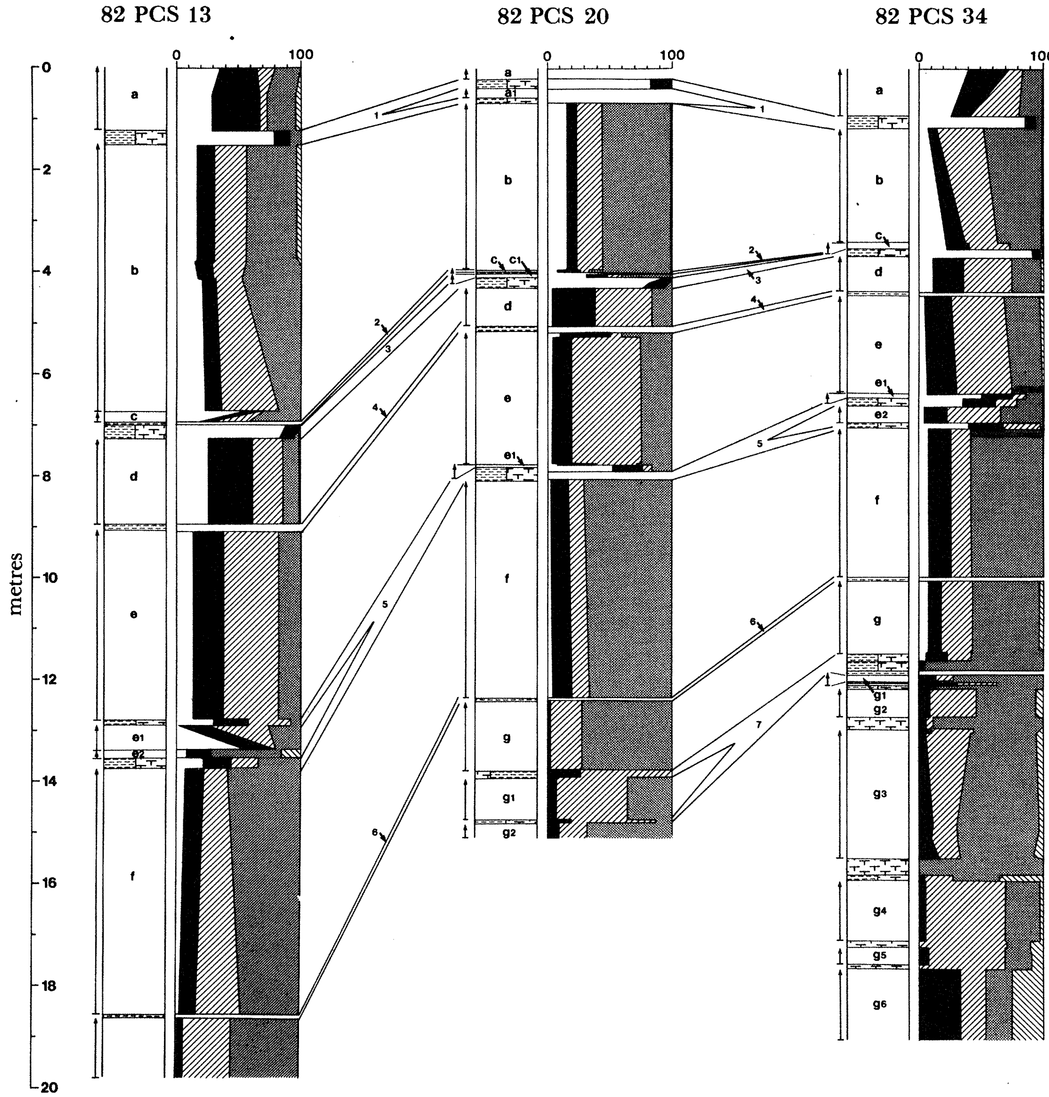

FIGURE 7. Correlation of three turbidite cores from the Madeira Abyssal Plain. Turbidites present in all three cores are lettered consecutively from the top. Numbers between core sections give oxygen isotope stages. The three cores are separated by more than 100 km from each other. Core 82 PCS 13 was located in the western part of the area shown in figure 4. (After Weaver & Kuijpers 1983.)

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

It has been shown that the deposition of turbites correlates with the onsets and terminations of glaciations and thus are probably triggered by rises and falls of sea level (Weaver & Kuijpers 1983; Weaver *et al.* 1985). The mean sedimentation rate on the abyssal plain over the last 200000 years, determined from piston cores, varies from 10 cm/1000 years in the extreme west of the area to about 4 cm/1000 years in the northeast. The major contribution to this accumulation rate comes, of course, from the turbidites. During the pelagic intervals the sedimentation rate is approximately an order of magnitude less than its mean value (Weaver *et al.* 1985; Searle *et al.* 1985).

Although the seabed in the abyssal plain parts of the GME area is extremely flat, sub-bottom relectors are occasionally found to be interrupted by faults (figure 8). The vertical offsets along them increase with depth. These features were first observed by Duin & Kuijpers (1983) and have been discussed in more detail by Duin *et al.* (1984). Faulting so close to the sediment surface might indicate recent tectonic activity in the area, which is obviously undesirable for a disposal site. Alternatively the faults might provide pathways for increased pore water flow through the sediment. A considerable effort has therefore been devoted to mapping these features and to trying to understand their origin. The ability of surface-towed profiling equipment to resolve them is limited and only a small amount of deep-towed profiling has so far been carried out.

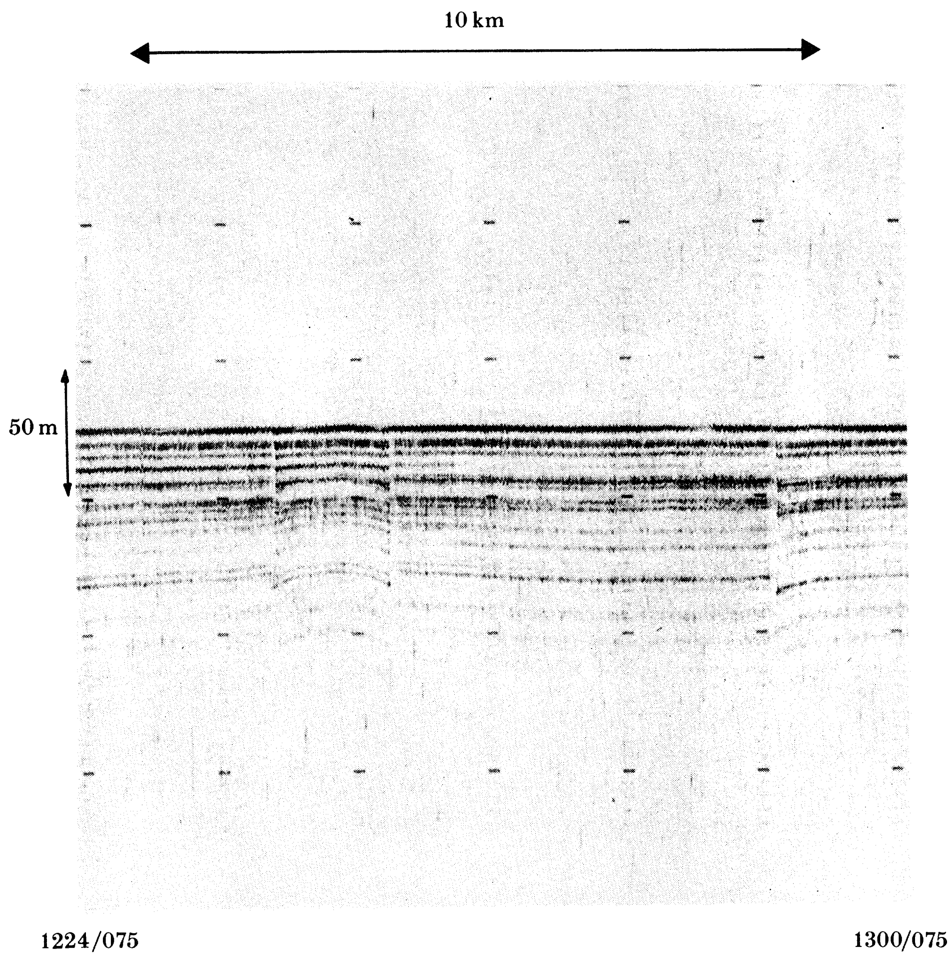

Figure 8. Examples of fault-like features observed on a 3.5 kHz profile in the Great Meteor East area.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

But it is now believed that the features are growth-faults associated with the differential compaction of the sediment over the uneven basement topography (Searle *et al.* 1985).

In parallel with the detailed geological studies of the GME area, regional studies have been conducted to increase our understanding of other natural processes relevant to the waste disposal program. For at least the last 2.4 Ma, since the onset of Northern Hemisphere glaciation, rock material has been deposited onto the North Atlantic sea floor from drifting icebergs. The material deposited ranges in size from rock flour to large boulders, some of which could interfere with the emplacement of waste into the sediment. A comprehensive study of glacial erratics in the Northeast Atlantic has therefore been done, making use of all available dredge hauls, sediment cores and camera runs to determine the size distribution and concentration of this material both on the sediment surface and where possible within the sediment (Huggett 1985). The concentration of erratic material diminishes markedly with latitude and in the GME area it has been calculated that the chance of a point protectile's encountering a glacial erratic greater than 15 mm in diameter within sediment younger than oxygen isotope stage 5 (approximately the top 12.5 m) is 0.015%.

The natural seismicity of intraplate areas of the Atlantic Ocean has also been assessed, making use of existing files of teleseismically observed earthquakes for the period 1913–79 inclusive (Lilwall 1982). The ground motions associated with earthquakes have the potential to disrupt sediments and to initiate mass movement on low angle slopes. The return period for ground accelerations in excess of 0.1 *g* is calculated to be in the range 2000–10000 years. Thus the seismicity of these intraplate areas of the Atlantic Ocean floor is somewhat less than that found in the land area of Great Britain (Lilwall 1976) and their tectonic stability correspondingly greater.

Hydrogeology of the Great Meteor East area

If its geological integrity can be established, the effectiveness of the sediment barrier depends on the physical and chemical properties of the sediments. The migration of radionuclides through the sediment will be through the medium of the pore water. Much effort has therefore been spent to determine the extent to which the pore water is moving. Evidence that deep-sea sediments might not always form an impermeable cap over the much more permeable underlying basaltic basement has come from the observation of nonlinear temperature profiles in the top few metres of the sediment column (Anderson *et al.* 1979). These have been interpreted as being the result of vertical pore water velocities of the order of a metre per year. Flow rates of this magnitude would greatly reduce the effectiveness of the sediment barrier to the migration of radionuclides. However, geochemical and geotechnical considerations have cast doubt on this interpretation and alternative explanations are possible (Noel 1984*a*).

To quantify rates of pore water movement two different physical approaches have been adopted. The first approach has been to measure the temperature and conductivity in the top few metres of the sediment. The advantage of this heat-flow method is that it is possible to acquire data rapidly, several measurements being possible on a single lowering of the heat flow probe by using a 'pogo-stick' technique. The disadvantages are that its resolution in detecting vertical pore water movement is low, velocities less than about 20 cm a^{-1} not producing detectable curvature of the temperature gradient (for constant conductivity), and the doubts about whether the interpretation of nonlinear gradients in terms of pore water movement is correct. Nevertheless, if linear gradients are observed, that is an indication that any pore water

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

movement is less than about 20 cm a^{-1}. Twenty-nine heat-flow measurements have now been made in the GME area, the great majority revealing linear gradients (Noel 1984*b*, 1985). A few nonlinear gradients have been observed but these are more likely to be the result of disturbance caused by the probe than generated by pore water movement. There is also evidence that the heat flow is influenced by the basement topography, which may indicate that some hydrothermal convection is still taking place in the basaltic basement.

The second approach has been to make use of Darcy's law for the flow of water through a permeable medium (Schultheiss 1982). This is defined as

$$Q = kiA,$$

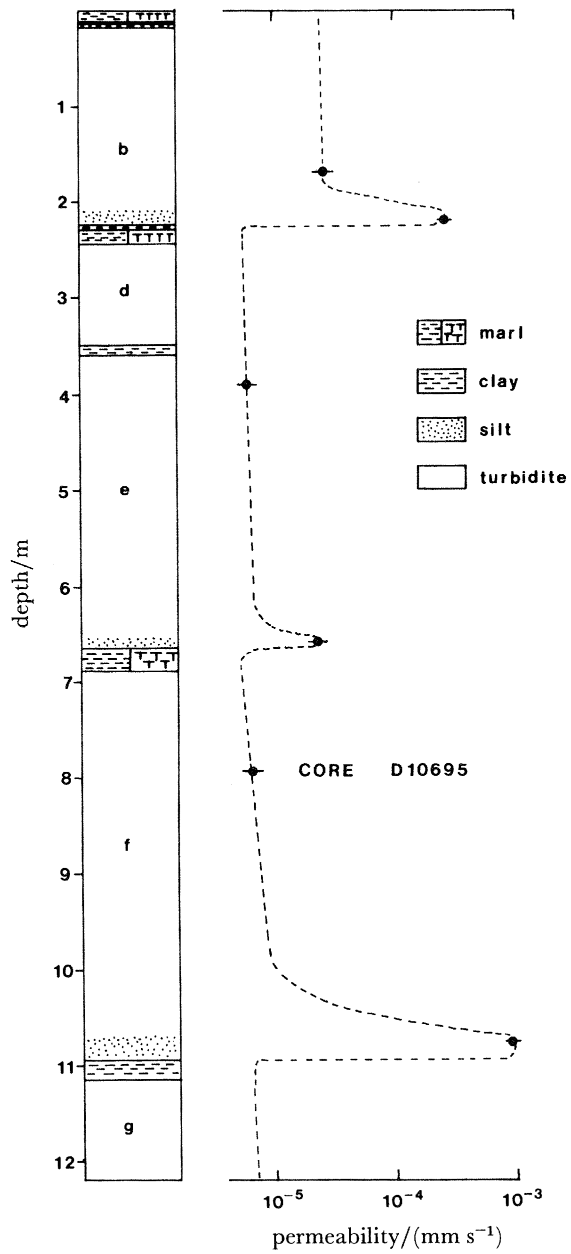

FIGURE 9. Lithology and measured permeabilities down core D10695. (After Searle *et al.* 1985.) The broken line interpolates the permeability between measured values on the basis of the sediment lithology.

where Q is the rate of flow ($m^3\ s^{-1}$), k is the permeability ($m\ s^{-1}$), A is the cross-sectional area (m^2), and i is the hydraulic gradient (dimensionless).

The hydraulic gradient, i, is the ratio of the pressure difference across a sample of sediment (expressed as a height of water) and the sample thickness. If the porosity of the sediment is n, then the seepage velocity of water through it is given by

$$V = ki/n.$$

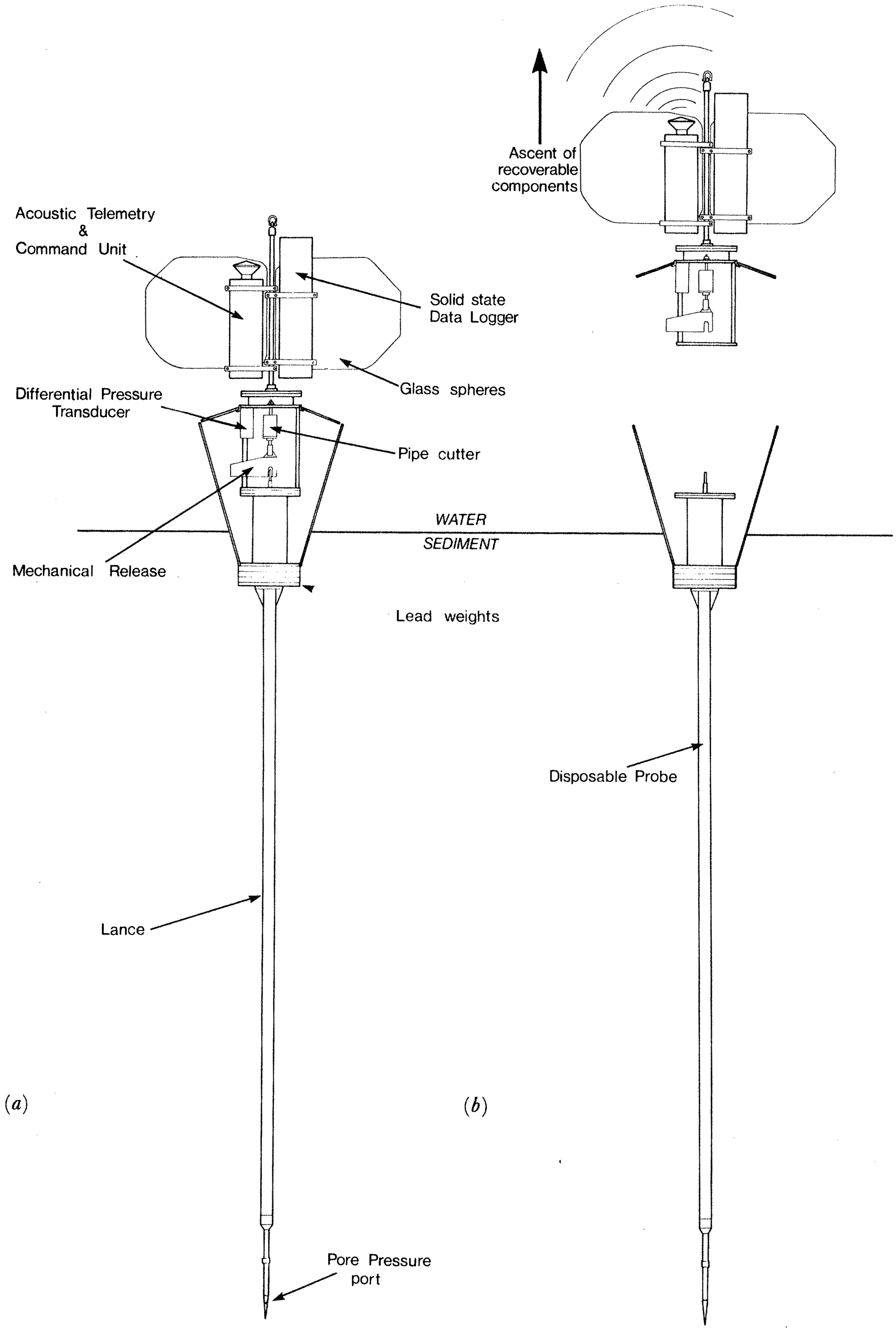

FIGURE 10. Schematic diagram of the Pop-Up-Pore Pressure Instrument (PUPPI): (*a*) after its free fall through the water column and penetration into the sediments; (*b*) after release from the sea floor showing recoverable and disposable components. (After Schultheiss & McPhail 1985.)

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

It is apparent that, if the permeabilities, porosities and pressure gradients in deep-sea sediments are measured, the pore water velocities through the sediments can be determined. Permeability and consolidation characteristics of a wide range of deep-sea sediment samples have been measured in the laboratory, providing the necessary knowledge of k and n for the above equation (Schultheiss & Gunn 1985). The variation of permeability down one particular core in the GME area is shown in figure 9. The other parameter that it is necessary to measure is the excess vertical pore pressure gradient in the sediments, which must exist if vertical advection of pore water is taking place. This must, of course, be measured *in situ*. A free-fall pop-up instrument has been developed to measure the differential pressure between the tip of a lance buried up to 4 m in the sediment and a point in the sea water (Schultheiss *et al.* 1985). A schematic diagram of this Pop-Up-Pore-Pressure-Instrument (PUPPI) is shown in figure 10. Five successful PUPPI deployments have so far been made in the GME area, each deployment lasting a few days (Schultheiss & McPhail 1985). The location of these deployments in relation to faults observed in the upper part of the sediment column on 3.5 kHz profiles, the basement topography and the total sediment thickness is shown in figure 11. The differential pore

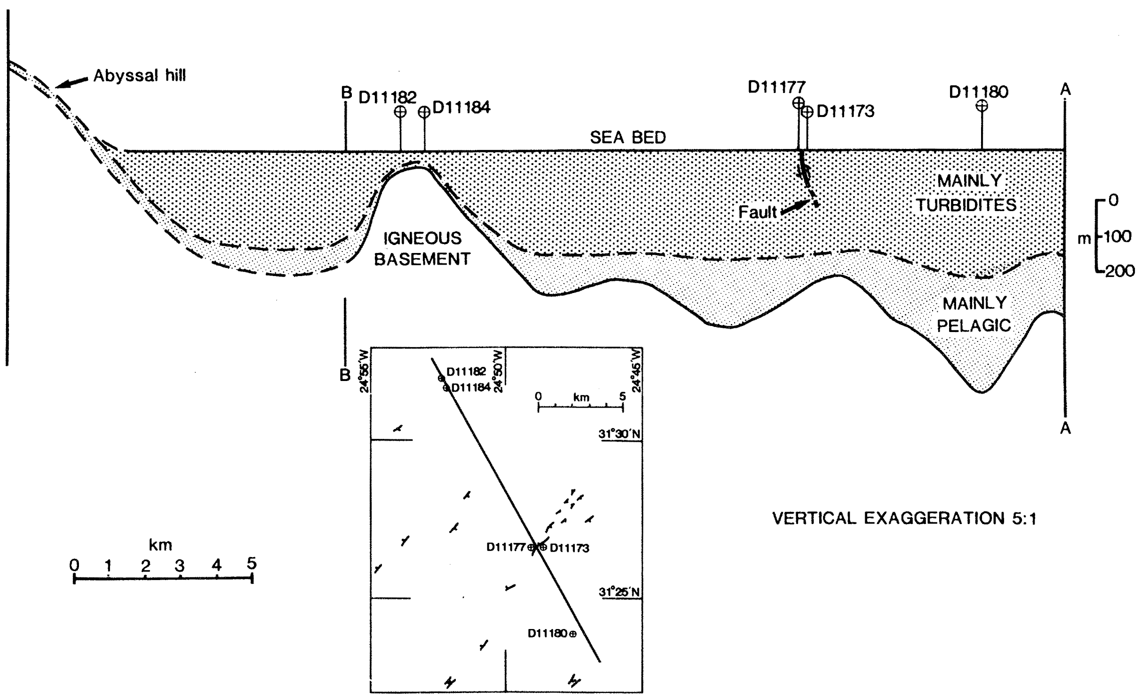

FIGURE 11. A section through the Great Meteor East study area showing the location of five PUPPI stations in relation to faults, basement topography and sediment thickness. (After Schultheiss & McPhail 1985.)

pressures observed correspond to much smaller vertical fluxes of pore water than have been suggested by some of the temperature gradients measured. Three of the sites indicated negligible pore water advection. At the other two (stations D11177 and D11184), downward movement of water was measured at rates of 0.9 and 3.6 mm a^{-1}.

More measurements are planned with both PUPPI and heat-flow probes and it is hoped that these will fully resolve the remaining uncertainties about the hydrogeological régime of the GME area.

Geochemistry of the sediments in the Great Meteor East area

If it can be shown that the rate of pore-water advection in a waste disposal area is negligibly small (i.e. less than 0.1 mm a^{-1}) the migration of a radionuclide through undisturbed sediment would be controlled by the molecular diffusion coefficient and by the sorption properties of the sediment. Even if advection is significant, the nuclides may be removed from the pore water by sorption onto particles. The extent of sorption is usually expressed by a distribution coefficient (K_D), which is the ratio of sorbed to dissolved ions in a specified volume of saturated sediment. (The term distribution ratio (R_d) is now favoured by some workers for this parameter, emphasizing its empirical nature.) Molecular diffusion coefficients for many cations in deep-sea sediments are of the order of 3×10^{-6} cm^2 s^{-1}, so that diffusion through 30 m of sediment takes about 10^5 years. A K_D of 10^3 for a particular radionuclide would increase this transit time through 30 m of sediment to 10^8 years (Heath 1979).

A considerable effort is in progress to study the sorption characteristics of deep-sea sediments from the North Atlantic, including many sediment samples from the GME area. Higgo *et al.* (1983, 1985) have reported work on the sorption of americium, neptunium and plutonium. Kershaw *et al.* (1985) have described the sorption properties of sediment in the area of the Northeast Atlantic low-level dump site. Most of this laboratory effort, however, has yet to be published. But such land-based studies on seabed samples cannot on their own provide the information needed to be able to predict the behaviour and migration of radionuclides within the sediments. It is essential that the chemical environment *in situ* is studied as well, with particular emphasis on the redox potential. This is because the chemical speciation of certain important radionuclides (e.g. plutonium, neptunium, uranium) is dependent on this factor. Variations in speciation often influence the degree to which a nuclide is adsorbed onto the solid phase and this in turn influences the rate at which it migrates. Unfortunately, in the range that is of most interest, instrumental methods of measuring redox potential are unreliable. Thus the determination of the natural redox chemistry and of the processes that determine and control redox profiles within the sediment is of primary importance. By studying the natural system, the redox potential can be characterized by reference to the redox state of naturally occurring 'marker couples'. Furthermore, by studying the processes involved in the control of the redox system it should be possible to determine the 'redox capacity' of the sedimentary system; this would be a measure of the redox buffering of the system. Such information is necessary to predict the response of the system to artificial redox disturbance.

Study of the chemistry of deep-sea sediments is further complicated by the fact that the chemical equilibria of some reactions between the liquid and the solid phase are affected by the large pressure reduction that a core experiences in being hauled to the surface. (Every 10 m of water depth represents an increase in pressure of one atmosphere (10^5 Pa), so the pressure reduction in recovery from 5400 m depth in the GME area is considerable.) To overcome this difficulty *in-situ* Pore Water Samplers (PWS) have been developed to extract pore water from the sediment on the seabed (Sayles *et al.* 1973, 1976). The effect is illustrated in figure 12, which compares alkalinity measurements obtained on squeezed sediment samples with those obtained from PWS samples. Because calcium carbonate is precipitated from the pore water within the sediment as the pressure is released, the squeezed samples underestimate the true alkalinity. A similar sampling artefact has recently been established for uranium in pore waters (Toole *et al.* 1984).

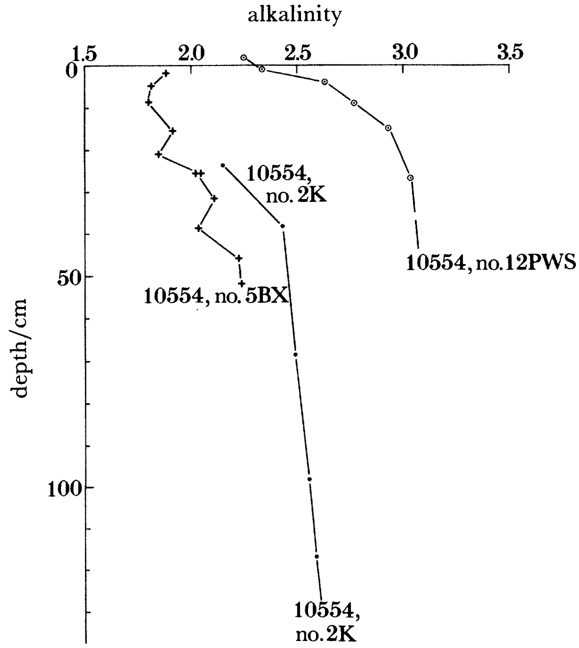

FIGURE 12. Effect of pressure on pore water composition. Alkalinity measurements on waters squeezed from sediment cores on board the ship (5BX and 2K) underestimate the values determined for *in-situ* samples (12 PWS) owing to the precipitation of calcium carbonate during the recovery of the cores. All samples were obtained from the same site in the Great Meteor East area.

Direct measurements of dissolved oxygen in the pore waters of GME sediment indicate that the oxygenated layer is only 20–40 cm thick (figure 13), indicating a much more intense metabolic rate in the sediments than the local pelagic supply of organic carbon is capable of supporting. This reflects the fact that pelagic material only makes up about 10% of the sedimentary column, which is predominantly composed of turbidites. The particulate organic carbon concentrations of individual turbidites range from 0.5 to 3.0%, probably owing to the different source areas from which they were derived (Weaver *et al.* 1985). This particulate organic carbon is unusually labile in comparison with pelagically derived organic carbon. Whereas the latter is exposed to microbial attack while sinking through the water column and at the sediment interface, the material in the turbidites was probably only briefly exposed to such attack before being buried in anoxic nearshore sediments.

After deposition of a turbidite, the pore waters trapped within it become anoxic within a very short time because of the high oxygen demand of this organic-rich material. Subsequently, dissolved oxygen diffuses in from the oxygenated layers above and below. The oxygen flux from below does not persist for very long as the quantity of oxygen available there is limited. The ocean bottom water, however, is continually renewed so that the downward oxygen flux persists. Because oxidative degradation of organic material is very efficient, the particulate organic carbon of the uppermost layers of the turbidite is quickly oxidized. Oxygen is then able to penetrate more deeply into the turbidite material. A redox reaction front is formed that penetrates down into the turbidite with time (Colley *et al.* 1984). The above is a qualitative description of the geochemical processes affecting GME sediments; mathematical models describing the behaviour of the system in more quantitative terms have been presented by Wilson *et al.* (1985).

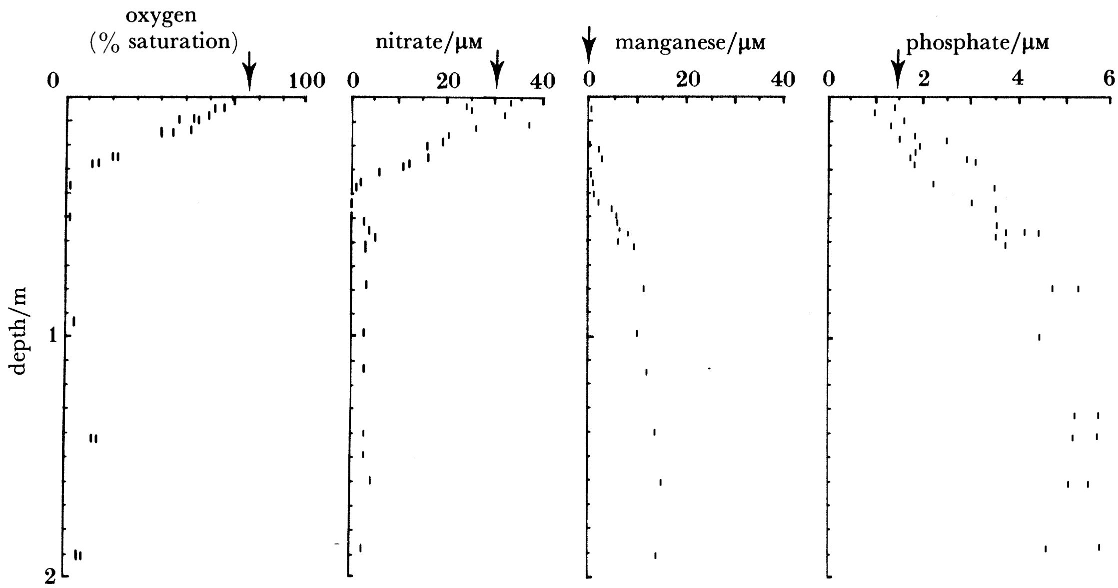

FIGURE 13. Pore water composition of sediments at station D10554 in the Great Meteor East area. Arrows indicate concentrations in seawater. (After Wilson *et al.* 1985.)

This hypothesis of the redox history of the sediment column can be used to explain the observed distribution of redox-sensitive elements. Several elements show evidence of remobilization in the region of the redox front (Colley *et al.* 1984; Wilson *et al.* 1985). Manganese, which is mobilized in reducing conditions, is undetectable in the oxidized pore waters at the top of the sediment column but its concentration on the solid phase is enhanced (figure 14). This element moves upwards in the reducing conditions deeper in the sediment until it is fixed onto the solid phase at the redox front. Uranium, which is enriched in the original turbidite material as one would expect from its well known association with organic-rich sediments, shows

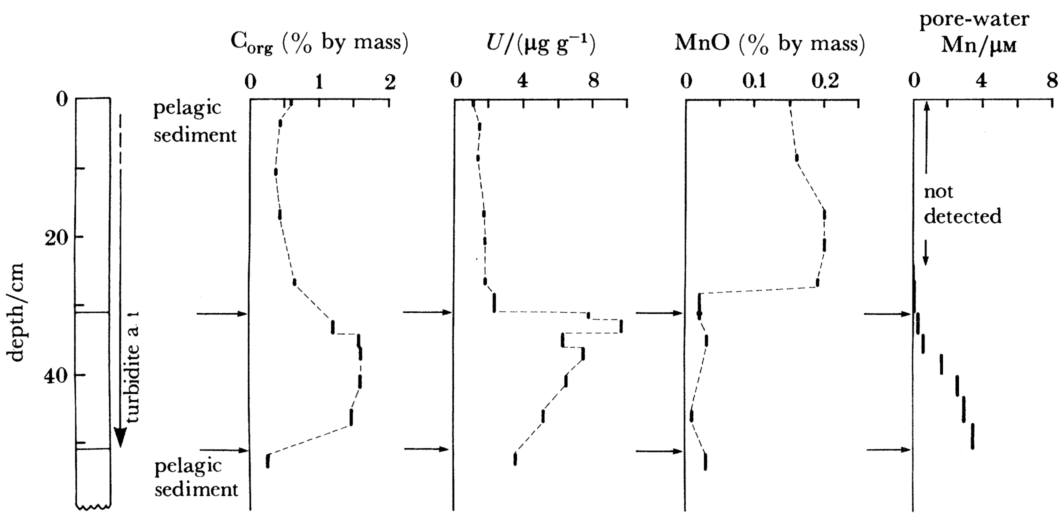

FIGURE 14. Concentration–depth profiles for the diagenesis-sensitive elements C_{org}, uranium and manganese for the box core at station D10554. The pore-water Mn^{2+} profile for the same core is shown on the right. The arrows at 31 cm indicate the position of the redox front, which is marked by a conspicuous colour change. (After Wilson *et al.* 1985.)

the opposite behaviour. Above the redox front it is depleted relative to its original concentration found in unaltered material well below the front. It is clear that the uranium is liberated from the solid phase during the diagenetic reactions localized at the front. However, most of the uranium thus liberated is not lost from the sediments but is concentrated in a peak just below the front itself. The interpretation of this observation is that soluble, oxidized uranium is liberated at the front and a steep concentration gradient develops between the oxidized pore waters and the reduced pore waters immediately below. Uranium diffusing down this gradient is rapidly reduced and removed from solution. This mechanism creates a pore-water concentration gradient that is always steeper in the downward than in the upward direction, so that most of the oxidized pore-water uranium eventually diffuses downward to produce the observed solid phase concentration peak. As the redox front migrates downward it continually overtakes and remobilizes this uranium, which again diffuses downward and is again removed onto the solid phase. Thus the region directly below the reaction front acts as a trap for the uranium stripped from the oxidized layer of the turbidite.

Finally it is instructive to consider the sequence of events that occurs when a subsequent turbidite is deposited above one that is active. As already mentioned, it is expected that the oxidized layer at the top of the old turbidite will rapidly lose its oxygen and become reduced. Since oxygen and nitrate, by far the most efficient metabolic electron acceptors, are now excluded, metabolic activity effectively ceases. Examination of the oldest turbidite currently available, deposited about 0.2 Ma ago, shows that a solid-phase uranium peak may still be found, unmoved, in the same position that it occupied when this turbidite was buried and sealed off from oxygen. Thus for uranium, at least, it can be shown that a considerable difference in mobility exists between the oxidized and reduced forms of the element under natural conditions. As long as reduced conditions are maintained, movement is virtually undetectable over periods of at least the order of 10^5 years.

Engineering studies

The methods by which waste canisters might be emplaced in the sediment have already been outlined. To date only experiments into the penetrator option have been pursued at sea. Model penetrators measuring 3.25 m in length and 0.325 m in diameter have been dropped in the Great Meteor East area and acoustically tracked to sub-bottom depths of about 30 m (Freeman *et al.* 1984). These projectiles were constructed of solid steel, weighed 1.8 t in air and acquired terminal velocities through the water of about 50 m s^{-1}. The velocity of each penetrator was determined by recording the Doppler-shifted frequency of a continuous 12 kHz acoustic source embedded in its tail during its fall through the water column and deceleration in the sediments (figure 15).

Further model penetrator studies are planned in the next few years. A 3.5 kHz acoustic transponder has been developed which is designed to provide a more sophisticated communication link between buried penetrators and the surface ship. This will allow a range of measurements of the environment around the penetrator to be made, culminating in studies of what fills the disturbed zone created by the entry into the sediment.

Theoretical and experimental work on land to determine the effect of burying a heat source in saturated deep-sea sediments has been in progress for much longer and is too extensive to review in any detail here. This work has ranged from theoretical and numerical modelling studies of the effect of canister emplacement (Chavez & Dawson 1981; Karnes *et al.* 1984;

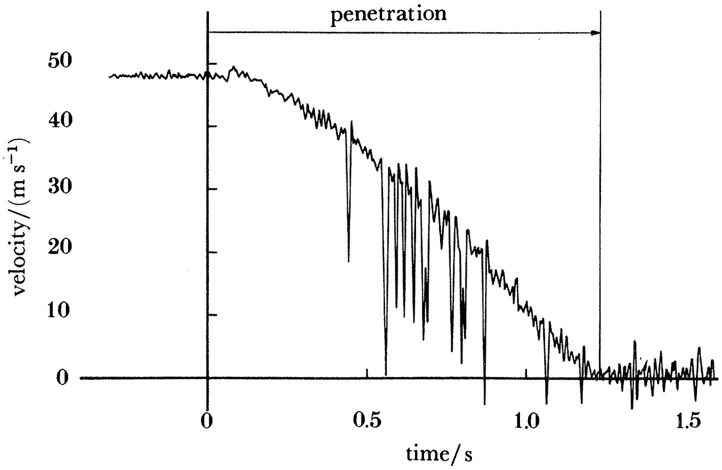

FIGURE 15. Deceleration curve of a model penetrator during burial in the sediments of the Great Meteor East area. Velocity was obtained from the Doppler-shifted frequency of a 12 kHz source attached to the penetrator, by using a sound velocity for the sediment of 1552 m s^1. The spikes on the record are the result of temporary losses of the acoustic signal during penetration.

Booker & Savvidou 1985) to measurements of sediment physical properties under the high temperatures and pressures that would prevail near a radioactive waste canister soon after burial (Hadley *et al.* 1984; Morin & Silva 1984). A particularly interesting approach has been the use of reduced-scale centrifuge modelling to explore the effects both of the penetration of the projectile and of the subsequent heating on the properties of the sediment (Maddocks & Savvidou 1984; Savvidou 1984). A 1/100 scale model subjected to 100 *g* in the centrifuge allows the same effective stresses to be developed as in the full-scale situation but on a timescale inversely proportional to the square of the linear dimensions. Thus 1 h on the centrifuge represents 416 days at full scale.

Among the more important results of the above studies are:

(1) the buried canister would not move to any significant effect, i.e. there would be no 'burp' effect (Chavez & Dawson 1981; Francis 1982);

(2) heat transfer through the sediments takes place by conduction (Hickox *et al.* 1984; Savvidou 1984);

(3) with certain types of sediment open cracks would develop around the canister. The effect of these fairly local cracks on the overall effectiveness of the sediment barrier has yet to be ascertained (Maddocks & Savvidou 1984).

Conclusions

In this paper we have reviewed research into the feasibility of high-level radioactive waste disposal in the sediments of the ocean floor. After a general introduction, the paper has concentrated on work in the Great Meteor East study area, because this is the area with which we are most familiar and because only by concentrating on one area can the range of studies that have been done be properly covered in this review. It is important to stress that the research into seabed disposal continues or is planned in a number of study areas, in the Pacific as well as the Atlantic Ocean.

As far as the GME area is concerned, much remains to be learnt before a full assessment of seabed disposal can be made. The immediate need is to extend the geological, geochemical and geotechnical measurements to depths greater than the 22 m from which sediments have so far been sampled. It is hoped that coring to at least 30 m will be achieved from the research vessel *Marion Dufresne* in the summer of 1985. On the engineering side the disturbed zone left behind a projectile entering the sediments needs to be studied, i.e. 'hole closure' remains to be proved.

In a few years' time our understanding of the GME area should be sufficient for a detailed technical comparison between seabed and land geological disposal to be made. But already some interesting contrasts can be drawn:

1. The processes affecting the GME area are uniform over a much larger area than is usually found for geological processes on land. Individual turbidite deposits can be correlated over hundreds of kilometres.

2. The environment in the GME area appears to be more predictable than on land. For example, the onset of a glaciation some thousands of years in the future is likely to do no more than trigger another turbidite. On land a glaciation might either erode a hundred metres of rock away or deposit a comparable thickness of glacial sediments; on the ocean floor its effect would be just to add a few more metres to the sediment column.

3. Understanding the hydrogeology of a waste disposal area is equally important for both land and sea burial. In a few years' time it will be possible to compare the precision with which we can measure their respective hydrogeological régimes and how well we can extrapolate them into the future.

We thank our colleagues at the Institute of Oceanographic Sciences for their scientific contribution or for their technical support. We are also grateful for the fruitful collaboration that we have enjoyed with the Rijks Geologische Dienst of the Netherlands. The IOS research was carried out under contract to the Department of the Environment, as part of its radioactive waste management research programme. The results will be used in the formulation of Government policy, but at this stage they do not necessarily represent Government policy.

References

Anderson, R. N., Hobart, M. A. & Langseth, M. G. 1979 Geothermal convection through oceanic crust and sediments in the Indian Ocean. *Science, Wash.* **204**, 828–832.

Auffret, G., Buckley, D., Laine, E., Schuttenhelm, R., Searle, R. & Shephard, L. 1984 *NEA Seabed Working Group status on site qualification for nuclear waste disposal within deep-sea sediment.* SAND 83-2037. New Mexico: Sandia National Laboratories.

Bishop, W. P. 1975 *Seabed Disposal Program, a first-year report, December 1974.* SAND 74-010. New Mexico: Sandia National Laboratories.

Bishop, W. P. & Hollister, C. D. 1974 Seabed disposal – where to look. *Nucl. Technol.* **24**, 425–443.

Booker, J. R. & Savvidou, C. 1985 Consolidation around a point heat source. *Int. J. num. analyt. Meth. Geomech.* **9**, 173–184.

Chavez, P. F. & Dawson, P. R. 1981 *Thermally induced motion of marine sediments resulting from disposal of radioactive wastes.* SAND 80-1476. New Mexico: Sandia National Laboratories.

Colley, S., Thomson, J., Wilson, T. R. S. & Higgs, N. C. 1984 Post-depositional migration of elements during diagenesis in brown clay and turbidite sequences in the Northeast Atlantic. *Geochim cosmochim. Acta* **48**, 1223–1235.

Duin, E. J. T. & Kuijpers, A. 1983 *Geological studies on abyssal plains in the North Atlantic.* (107 pages.) Haarlem: Rijks Geologische Dienst Progress Report for 1982.

Duin, E. J. T., Mesdag, C. S. & Kok, P. T. J. 1984 Faulting in Madeira Abyssal Plain sediments. *Mar. Geol.* **56**, 299–308.
Embley, R. W. 1975 Studies of deep-sea sedimentation processes using high frequency seismic data. (334 pages.) Ph.D. thesis, Columbia University, New York.
Embley, R. W. 1976 New evidence for the occurrence of debris flow deposits in the deep-sea. *Geology* **4**, 371–374.
Francis, T. J. G. 1982 Thermal expansion effects in deep-sea sediments. *Nature, Lond.* **299**, 334–336.
Francis, T. J. G. 1984 A review of IOS research into the feasibility of high-level radioactive waste disposal in the oceans. *Sci. tot. Environ.* **35**, 301–323.
Freeman, T. J., Murray, C. N., Francis, T. J. G., McPhail, S. D. & Schultheiss, P. J. 1984 Modelling radioactive waste disposal by penetrator experiments in the abyssal Atlantic Ocean. *Nature, Lond.* **310**, 130–133.
Hadley, G. R., McVey, D. F. & Morin, R. 1984 Thermophysical properties of deep ocean sediments. *Mar. Geotechnol.* **5**, 257–295.
Heath, G. R. 1979 Ion transport in deep-sea sediments. In *Geological disposal of nuclear waste*, pp. 25–29. Albuquerque, New Mexico: American Society of Mechanical Engineers.
Hickox, C. E., Gartling, D. K., McVey, D. F., Russo, A. J. & Nuttall, H. E. 1984 Analysis of heat and mass transfer in subseabed disposal of nuclear waste. *Mar. Geotechnol.* **5**, 335–360.
Higgo, J. J. W., Rees, L. V. C. & Cronan, D. S. 1983 Sorption of americium and neptunium by deep-sea sediments. *Radioact. Waste Mgmt nucl. Fuel Cycle* **4**, 73–102.
Higgo, J. J. W., Rees, L. V. C. & Cronan, D. S. 1985 Sorption of plutonium by deep-sea sediments. *Radioact. Waste Mgmt nucl. Fuel Cycle* **6**, 1–9.
Holliday, F. G. T. 1984 *Report of the Independent Review of Disposal of Radioactive Waste in the Northeast Atlantic.* (60 pages.) London: H.M.S.O.
Huggett, Q. 1985 *The distribution of glacial erratics in the Northeast Atlantic: final report.* Institute of Oceanographic Sciences Report. (In the press.)
Karnes, C. H., Dawson, P. R., Silva, A. J. & Brown, W. T. 1984 Sediment mechanical response due to emplacement of a waste canister. *Mar. Geotechnol.* **5**, 379–401.
Kershaw, P. J., Rutgers Van Der Loeff, M. M. & Whitehead, N. E. 1985 Sediment sorption properties. In *Interim Oceanographic description of the Northeast Atlantic site for the disposal of low-level radioactive waste* (ed. R. R. Dickson, P. A. Gurbutt & P. J. Kershaw), vol. 2, pp. 88–94. Paris: Nuclear Energy Agency, OECD.
Kuijpers, A. 1982 *The sedimentology of two northeast Atlantic study areas: the Western Madeira Abyssal Plain and the area West of Great Meteor Seamount.* (61 pages.) Haarlem: Rijks Geologische Dienst Progress Report for 1981.
Laine, E. P., Anderson, D. R. & Hollister, C. D. 1983 Site qualification for the Subseabed Disposal Program. In *Wastes in the ocean* (ed. P. K. Park, D. R. Kester, I. W. Duedall & B. Ketchum), vol. 3 (*Radioactive wastes in the oceans*), pp. 345–358. New York: John Wiley & Sons.
Lilwall, R. C. 1976 *Seismicity and seismic hazard in Britain.* Institute of Geological Sciences Seismological Bulletin no. 4 (9 pages.)
Lilwall, R. C. 1982 *Intraplate seismicity and seismic risk in the Atlantic Ocean based on teleseismically observed earthquakes.* Institute of Oceanographic Sciences Report no. 136. (43 pages.)
Maddocks, D. V. & Savvidou, C. 1984 *The effects of heat transfer from a hot penetrator installed in the ocean bed.* Cambridge University Engineering Department, CUED/D-SOILS/TR.144.
Morin, R. & Silva, A. J. 1984 The effects of high pressure and high temperature on some physical properties of ocean sediments. *J. geophys. Res.* **89** (B1), 511–526.
Noel, M. J. 1984*a* Origins and significance of non-linear temperature profiles in deep-sea sediments. *Geophys. Jl R. astr. Soc.* **76**, 673–690.
Noel, M. J. 1984*b* *Measurements of sediment temperatures, conductivity and heat flow in the North Atlantic and their relevance to radioactive waste disposal.* Institute of Ocenographic Sciences Report no. 172. (92 pages.)
Noel, M. J. 1985 Heat flow, sediment faulting and porewater advection in the Madeira abyssal plain. *Earth planet. Sci. Lett.* (In the press.)
OECD 1984 *Seabed disposal of high-level radioactive waste. A status report of the NEA co-ordinated research programme.* (248 pages.) Paris: Organisation for Economic Co-operation and Development.
Savvidou, C. 1984 Effects of a heat source in saturated clay. Ph.D. thesis, University of Cambridge.
Sayles, F. L., Mangelsdorf, P. C., Wilson, T. R. S. & Hume, D. N. 1976 A sampler for the in situ collection of marine sedimentary pore waters. *Deep-Sea Res.* **23**, 259–264.
Sayles, F. L., Wilson, T. R. S., Hume, D. N. & Mangelsdorf, P. C. 1973 In situ sampler for marine sedimentary pore waters: evidence for potassium depletion and calcium enrichment. *Science, Wash.* **181**, 154–156.
Schneider, K. J. & Platt, A. M. (eds) 1974 High-level Radioactive Waste Management Alternatives. Section 6: Seabed Disposal. BNWL-1900, Battelle Pacific Northwest Laboratories.
Schultheiss, P. J. 1982 *Geotechnical properties of deep-sea sediments: a critical review of measurement techniques.* Institute of Oceanographic Sciences Report no. 134. (73 pages.)
Schultheiss, P. J. & Gunn, D. E. 1985 *The permeability and consolidation of deep-sea sediments.* Institute of Oceanographic Sciences Report no. 201. (In the press.)
Schultheiss, P. J. & McPhail, S. D. 1985 Direct indication of pore water advection in the Madeira abyssal plain sediments from pore pressure measurements. *Nature, Lond.* (Submitted.)

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Schultheiss, P. J., McPhail, S. D., Packwood, A. R. & Hart, B. 1985 *An instrument to measure differential pore pressures in deep ocean sediments: Pop-Up-Pore-Presure Instrument (PUPPI)*. Institute of Oceanographic Sciences Report no. 202. (57 pages.)
Searle, R. C. 1979 *Guidelines for the selection of sites for disposal of radioactive waste on or beneath the ocean floor*. Institute of Oceanographic Sciences Report no. 91. (46 pages.)
Searle, R. C. 1984 Guidelines for the selection of sites that might prove suitable for disposal of high-level radioactive waste on or beneath the ocean floor. *Nucl. Technol.* **64**, 166–174.
Searle, R. C., Schultheiss, P. J., Weaver, P. P. E., Noel, M., Kidd, R. B., Jacobs, C. L. & Huggett, Q. J. 1985 *Great Meteor East (Distal Madeira Abyssal Plain): geological studies of its suitability for disposal of heat-emitting radioactive wastes*. Institute of Oceanographic Sciences Report no. 193. (In the press.)
Simm, R. W. & Kidd, R. B. 1984 Submarine debris flow deposits detected by long-range sidescan sonar 1000 kilometres from source. *Geo-Marine Lett.* **3**, 13–16.
Toole, J., Thomson, J., Wilson, T. R. S. & Baxter, M. S. 1984 A sampling artefact affecting the uranium content of deep-sea pore waters obtained from cores. *Nature, Lond.* **308**, 263–266.
Weaver, P. P. E. & Kuijpers, A. 1983 Climatic control of turbidite deposition on the Madeira abyssal plain. *Nature, Lond.* **306**, 360–363.
Weaver, P. P. E., Searle, R. C. & Kuijpers, A. 1985 Turbidite deposition and the origin of the Madeira abyssal plain. In *Geol. Soc. Lond. Spec. Publ. on North Atlantic Palaeoceanography* (ed. N. J. Shackleton & C. P. Summerhayes). (In the press.)
Wilson, T. R. S., Thomson, J., Colley, S., Hydes, D. J. & Higgs, N. C. 1985 Early organic diagenesis: the significance of progressive subsurface oxidation fronts in pelagic sediments. *Geochim. cosmochim. Acta* **49**, 811–822.

Discussion

S. H. U. Bowie, F.R.S. (*Tanyard Farm, Clapton, Crewkerne, Somerset, U.K.*). Pore-water movement was small and in a downwards direction. Is there any evidence that in the Great Meteor East region there is a closed basin situation such as occurs in parts of the Basin and Range region of the U.S.A.? This could be extremely important in relation to the possible return of radionuclides to the ocean.

T. J. G. Francis. The five PUPPI measurements made in the GME area to date were all on the abyssal plain sediments. Not enough measurements have yet been made for the scale or the nature of the hydrogeological régime in the area to be defined.

If the observed flows were part of a convectively driven circulation, pore water flowing down through the sediments might join horizontally moving water in the upper few hundred metres of the more permeable basement rocks and eventually find its way back into the ocean through one of the neighbouring hills in the area where the basement is exposed or only thinly covered by sediment. This kind of model has been proposed for the hydrogeology of isolated sediment ponds close to the axis of the Mid-Atlantic Ridge (Langseth *et al.* 1984).

Underpressured basement rocks have been found in a number of Deep Sea Drilling Project drill holes with the result that once a hole has been drilled ocean bottom water flows down it into the basement (Becker *et al.* 1983; Langseth *et al.* 1984). An alternative explanation for this to the hydrothermal one cited above is that the underpressuring is the result of diagenetic processes in the basement. If this is correct then water flowing into the basement would remain there and not return to the sea. Whatever the cause, many more measurements are needed to establish the correct interpretation for the downflows observed in the GME area.

References

Becker, K., Langseth, M. G., Von Herzen, R. P. & Anderson, R. N. 1983 Deep crustal geothermal measurements, Hole 504B, Costa Rica Rift. *J. geophys. Res.* **88**, 3447–3457.
Langseth, M. G., Hyndman, R. D., Becker, K., Hickman, S. H. & Salisbury, M. H. 1984 The hydrogeological régime of isolated sediment ponds in mid-oceanic ridges. *Init. Rep. DSDP* **78**, 825–837. Washington, D.C.: U.S. Government Printing Office.

A. S. Laughton, F.R.S. (*Institute of Oceanographic Sciences, Wormley, U.K.*). The paper has given a considerable amount of indirect evidence about the nature of the sediments at potential burial depths of 30 m below the ocean floor but we still do not have samples at this depth nor in the immediate depths beneath. It will be necessary to confirm the interpretations by direct sampling either with the extended coring facilities that are being developed both in the United States and in France or by deep ocean drilling with hydraulic piston coring technique. The free fall penetrators, however, can make observations at the depths to which they penetrate and acoustically telemeter this information back to the surface. This is the chief objective of the instrumented penetrator deployment.

J. Rae (*Theoretical Physics Department, AERE, Harwell, U.K.*). I should like to draw one or two points together. Dr Girardi asked me earlier if I knew of a good analogy for migration in fractured rock. Dr Laughton suggests thermal measurements on the seabed as an analogy to be modelled. We have in fact tried to do this for land surface measurements in regions of anomalously high geothermal flux in crystalline rock. In principle, heat should be a good analogy for radionuclide migration as they both experience similar advection, diffusion and dispersion in groundwater. In practice the idea does not work because the water flows are too slow to perturb the temperature field, which is entirely governed by conduction in the rock. I should therefore be very interested if high flow rates were found through seabed sediments.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF

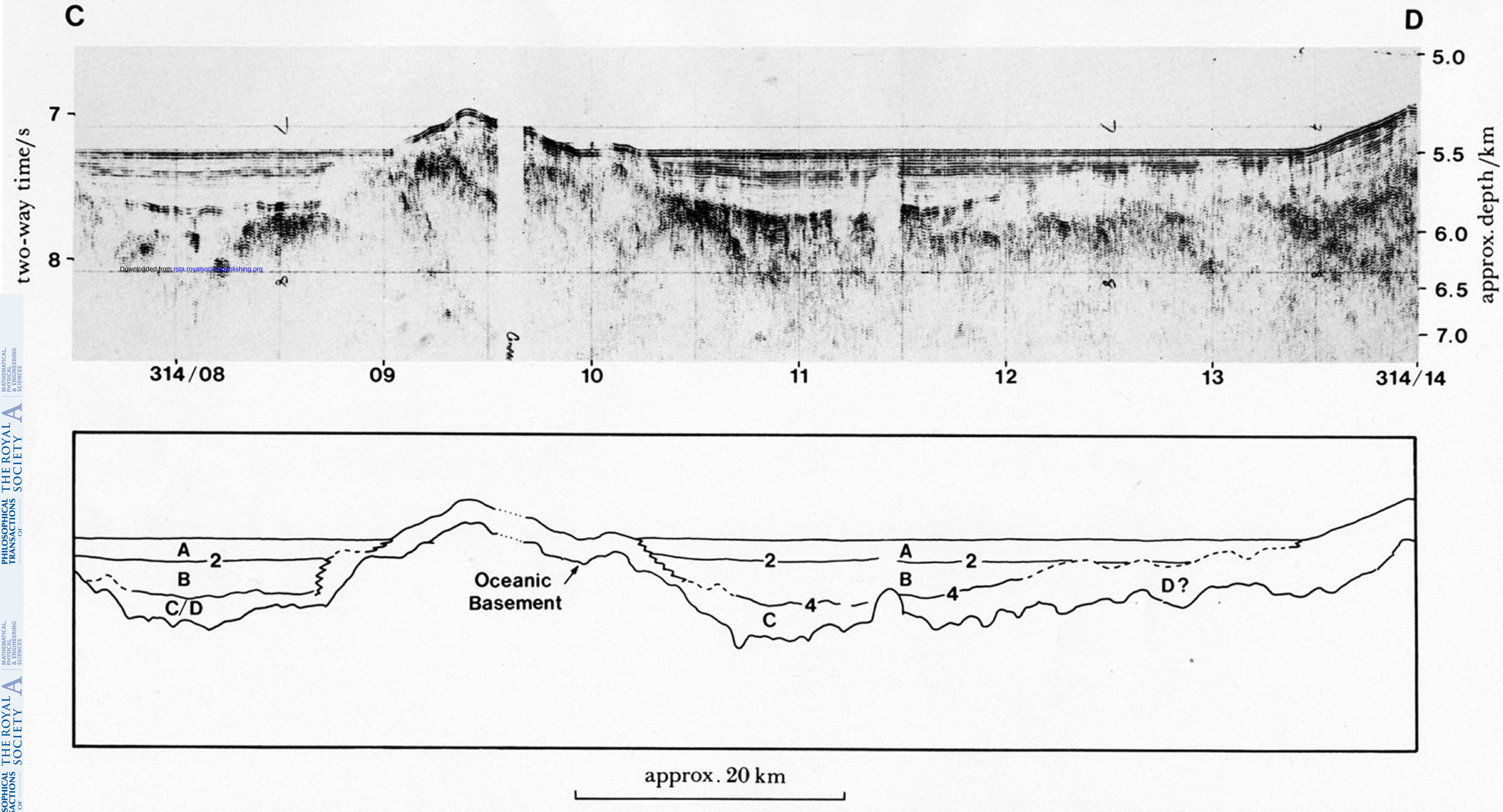

FIGURE 6. Seismic reflection profile obtained along line CD in figure 5, with interpretation. See text for details of interpretation.

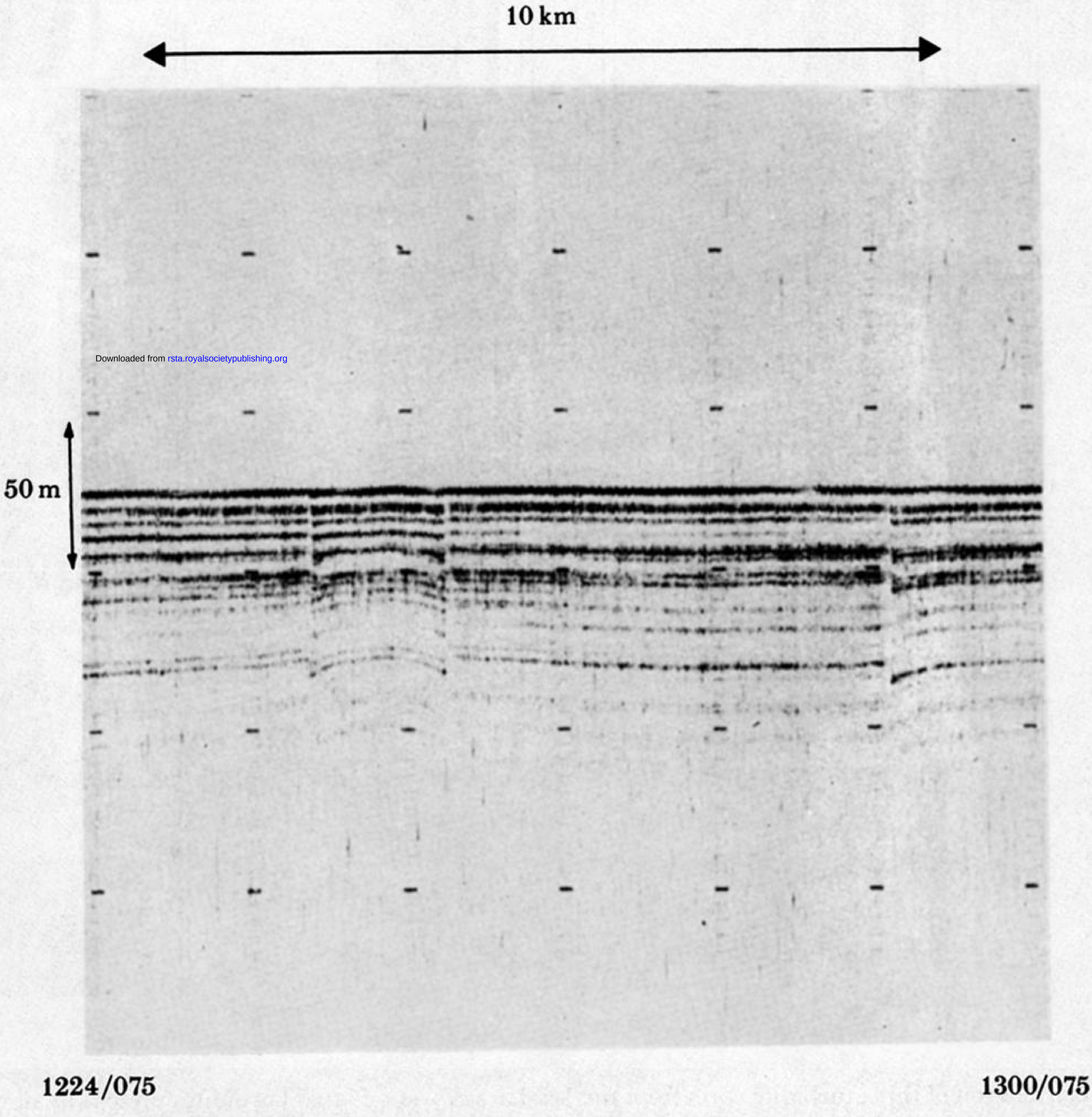

FIGURE 8. Examples of fault-like features observed on a 3.5 kHz profile in the Great Meteor East area.