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THE GEOLOGY OF THE MADEIRA ABYSSAL PLAIN FURTHER STUDIES RELEVANT TO ITS SUITABILITY FOR RADIOACTIVE WASTE DISPOSAL

BY
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ABSTRACT

This report summarises work done in the UK and internationally since 1979 on site assessment aspects of the oceanic radioactive waste disposal feasibility study. Site selection guidelines were drawn up and are summarised; they stress the importance of geological stability and good barrier properties. The history of the selection and invesitgation of various study sites in the North Atlantic is briefly summarised leading to the selection of the Great Meteor East area in the Madeira Abyssal Plain for concentrated further study. The detailed geological characteristics of GME are then described with particular reference to the "10 km box" where recent work has been focussed. The results of this geological characterisation are then discussed in the light of the site assessment guidelines. It is concluded that within the confines of present knowledge the 10 km box fulfils most of the geological requirements for a radioactive waste repository, except that it contains several sandy layers at depth. It is thought that similar areas without such sands probably exist to the north of the 10 km box. Finally, unresolved issues are discussed and the requirements for further work are given.

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INTRODUCTION

This volume summarises work done in the UK and internationally, since 1979, on the site assessment aspects of a feasibility study of oceanic high level radioactive waste disposal. Apart from some minor changes of an editorial nature, chapters 1, 3, 4 and 5 are essentially the same as chapters 2 and 4.1 of the Final Report of the NEA Seabed Working Group (SWG) Site Assessment Task Group (SATG, 1987). We gratefully acknowledge the input of our colleagues on that task group, but of course they are not responsible for any parts of this report that may differ from theirs. We also wish to thank all our colleagues at IOS and elsewhere who have contributed over the years to the study.

Chapter 1 of this volume outlines the site selection guidelines that have been developed. Chapter 2 describes the selection of an area for detailed study which appeared to best fit these guidelines. The area chosen is the GME area in the Madeira Abyssal Plain. In Chapter 3 we give the detailed geological characterization of this study area. Chapter 4 summarises these characteristics in the light of the site assessment guidelines, and presents a simplified model of the geology. Finally, in Chapter 5 we discuss the major unresolved issues and the need for further work.

In order to keep the report to a reasonable length we rely extensively on references to published material, giving only brief summaries of such work. Recent (unreported) work, and work reported only in the "grey" literature, is more fully described.

DEFINITION OF SITE SELECTION REQUIREMENTS

Introduction

In order to guide the site selection and assessment process, site assessment guidelines were drawn up (Laine et al., 1982, 1983; Searle, 1979, 1984). There are two primary geoscience criteria, which reflect the need to ensure (1) geological stability (and therefore predictability) and (2) an effective sediment barrier. In applying these criteria, a large number of specific factors need to be taken into account.

Stability criterion

This criterion requires that the geological formation in a potential repository should be stable and predictable. It should assure both the mechanical predictability of the site and the resistance of the sediment barrier to mechanical disruption (e.g. by erosion). When applying this criterion we consider those factors which may affect the integrity of the repository during its lifetime (perhaps several hundred thousand years). Examples of factors considered include the history of deposition and erosion, occurrence of seismic, tectonic and volcanic activity, and varying climatic and oceanographic effects.

Barrier criterion

This criterion requires that the geological disposal medium should have characteristics that make it an effective barrier to the release of radionuclides. Examples of factors considered when evaluating the barrier criterion include permeability, sorption coefficient, redox potential, and the existence of relatively continuous, predictable sediment properties.

The relevant factors for both criteria, listed below, were used in a general sense to guide the site evaluation process. As our understanding of the seabed and deep sea processes continued to increase and the needs of other workers in the project, particularly the SWG task groups, became better defined, the factors continued to be re-evaluated. A more detailed discussion of site selection factors can be found in Searle (1979, 1984; Laine et al., 1983; and Auffret et al., 1984a).

Application of the guidelines

The factors were used in two somewhat different ways. First, they were used to guide the initial search for areas that would be studied in greater depth, and secondly they were used as a guide in the assessment of those study areas.

It is emphasised that the final efficacy of a disposal site can only be decided following a rigorous radiological assessment. That assessment should take into account the site asessment guidelines, but may not be confined to them. Furthermore it is unlikely, and perhaps unnecessary, that all site assessment factors could be simultaneously and independently optimised: it is the overall performance of the site that is important.

We have therefore used the guidelines as representing idealised conditions to be sought at any site, but not as rigid criteria by which sites should be disqualified. For the same reason, we have felt that it is more useful to have qualitative guidelines than to have strict quantitative criteria.

Site Selection Guidelines

1. Stability and Predictability Factors

Site area

Based on an estimate of 10^5 as the number of waste canisters to be disposed of at a site, and assuming a horizontal spacing of at least 30 m, a minimum site area of 10^2 km^2 is required.

Site bathymetry

Seafloor slopes should be sufficiently low to ensure sediment stability. Sites should be sufficiently far from steep slopes to avoid being affected by mass movements of coarse or erosive sediment associated with them.

Sediment thickness and structure

The minimum thickness of sediment required depends on the emplacement option. For deep (drilled) emplacement a minimum thickness of several hundred metres is assumed to be needed to emplace and confine several canisters per hole.

For shallow (penetrator) emplacement it was initially assumed that the depth of penetration would be about 30 m (Auffret et al., 1984a), though this has subsequently been revised to 50 ± 20 m (RATG, 1987). In order to assure predictable sediment barrier properties to an adequate distance on all sides of the waste canister (including the area below it) it is considered that the total sediment thickness should be at lease twice the depth of burial.

Sedimentary layers should have simple geometries to enhance stability and predictability. Structures such as faults and diapirs should therefore be avoided.

Stratigraphy

A high degree of horizontal uniformity and continuity in stratigraphy should be recognizable in acoustic profiles and core samples across a potential site. A desirable characteristic of disposal sites is that continuous accumulation of sediments should persist for a period of time that is at least equal to that during which the release of radionuclides could be a hazard to man. To help to assure this it should be demonstrable that there has been more-or-less continuous deposition in the immediate past for at least the same period of time. Absolute continuity of deposition over several hundred thousand years is probably an unrealistic condition; however, evidence of appreciable erosion in the past should be considered to be an indication of probable geological instability in the future.

Volcanism, seismicity and tectonics

All of these are potentially disruptive, and disposal sites should avoid areas of disruptive seismic activity and volcanic or tectonic disturbances.

2. Barrier Property Factors

The seabed disposal concept relies on the natural physical and chemical properties of deep sea sediments to prevent the release of radionuclides into the ocean environment where they may become an eventual hazard to humans. The following guidelines to assist site assessment studies were developed as part of the studies of the characteristics of deep sea sediments.

Pore water advection

Provided the geological barrier remains intact, any leached waste material will be able to cross the barrier only by diffusion or by advection in the pore water. Advective movement may be driven by natural thermal processes and by sediment compaction. A conservative guideline is that the rate of pore water advection should be less than the rate of diffusion. To assure low advection, sediments should have low permeabilities.

Sorption capacity

Advection flux of radionuclides will be reduced if the nuclides are sorbed onto solid phase minerals in the sediments. Sites should therefore have sediments that include sufficient minerals with high sorption capacities for the relevant nuclides: these will probably need to be predominantly clay minerals.

Redox conditions

The potential for sorption of radionuclides onto sediments, and therefore for retarding their migration, depends on the chemical form of the nuclide. An important factor in determining this is the redox potential of the sediments. However, no single set of oxidation conditions decrease the solubility of all relevant ions; indeed where some ions may be chemically reduced, others may be unaffected. It may therefore be desirable to accept sites that have sediment columns in which a range of oxidation and reduction conditions exists. Vertical variation of oxidation/reduction should range from oxidised conditions in which manganese oxides (incorporating Mn^{4+}) are stable, to reduced conditions which allow ferrous iron (Fe^{++}) to be mobilised in the pore water.

Erratic boulders

Erratic boulders within the uppermost 50 m or so of sediment could prevent successful emplacement, and areas with enough erratics to make this likely should be avoided.

Sand layers

Appreciable layers of sand could also hinder emplacement, both by penetrator and by drilling. Moreover, sand layers with their coarse grain size tend to be more permeable and have poorer sorption characteristics than finer grained sediments. Sand layers are therefore undesirable.

Bioturbation

Benthic animals in marine sediments cause some post-depositional disturbance and reworking of the sediments. Significant bioturbation or burrowing where it leaves open burrows may increase the bulk permeability and decrease the overall predictability of barrier properties. The presence of open burrows is considered an undesirable characteristic.

Other physical properties

For both shallow and deep disposal the sediments can act as an effective barrier only if they retain adequate geotechnical properties after emplacement of waste canisters. The explicit description of any physical property changes associated with emplacement is beyond the scope of this report; however, one of our guidelines is that sediments should have suitable viscoelastic properties to assure adequate sealing of the emplacement hole.

3. Other use avoidance

In the assessment of sites, consideration must also be given to other potential uses of the seafloor and subseabed. Such potential uses might be, for example, mineral and energy exploitation, commercial fisheries, and communications structures. Therefore sites should be in areas where there are no existing or likely future commercial uses.

SELECTION OF STUDY SITE SATISFYING REQUIREMENTS

All the IOS site assessment work has been carried out in close coordination with other members of the NEA Seabed Working Group through that body's Site Assessment Task Group (SATG). Early work by the SATG in the Atlantic concentrated on areas of relatively thick sediment accumulations on oceanic rises: initially the Bermuda Rise, and later the Cape Verde Rise and King's Trough Flank. At an interim meeting of the Site Assessment (then Site Selection) Task Group in 1979 the possibility of adding distal abyssal plains to the set of generic study areas was raised, and this was formally agreed at the 5th SWG annual meeting in Bristol, 1980 (Anderson, 1980, pp. 112-113).

IOS geology and geophysics work was carried out almost exclusively in two of the areas indentified by the SWG: King's Trough Flank around 42°N, 23°W (Kidd et al., 1983), and GME in the Madeira Abyssal Plain (Searle et al., 1985). However, a watching brief was also kept on work being carried out in the other study areas by other SWG members.

Gradually the SATG reduced the number of areas it was studying, either because new data indicated that an area had undesirable characteristics (e.g. the Northern Bermuda Rise, which deep-towed geophysical instruments showed to be strongly affected by erosion - Laine et al., 1980) or simply because the existing data set was too small to warrant continued investigation alongside some of the much more extensively studied areas. By 1983 the SATG had "downgraded" (i.e. given a low priority to further work in) all areas except GME, Southern Nares Abyssal Plain, and the Pacific E2 location (Auffret et al., 1984a; NEA, 1984).

In particular, the decision to downgrade King's Trough Flank was largely based on the discovery that no large (c. 100 km wide) areas of relatively smooth topography could be found there. In several areas core data suggesting a history of relatively quiet and continuous deposition appeared to be in conflict with geophysical data showing evidence of sediment surface movement or erosion. There were several smaller areas, about 10 km across, that might have proved acceptable, but considerably more work would have been needed to determine whether they were really devoid of appreciable erosion. Other reasons for the downgrading were uncertainties over the degree of ice-rafted debris that is present, and the relatively poor climate which makes field work there more difficult than at GME. By 1983 there was considerably more data available on GME, and subsequent IOS work was all carried out there.

Choice of GME

Following the 1979 SWG discussions the Netherlands Rijks Geologische Dienst (RGD - Geological Survey of the Netherlands) chose the "Great Meteor East" (GME) area of the Madeira Abyssal Plain (Figures 1, 2) as one of the areas to be studied during their first SWG cruise (see Duin, 1982), and subsequently this became one of the main SATG study areas.

GME, like the other SATG study areas, was initially chosen by applying the site selection guidelines (Laine et al., 1983; Searle, 1984) to existing archived geoscience data. These areas were chosen as places that appeared to have extensive (c. 100 km) unbroken expanses of sediment several hundred metres thick, little or no evidence of recent erosion, and, somewhat arbitrarily, latitudes of less than 40°.

The archived data for GME consisted mainly of a number of parallel seismic tracks obtained by the Vening Meinesz Laboratory of the Utrecht State University; few cores were available within the region. The archive data (compiled by McGiveron, 1980) showed the GME region to have extensive sediments in excess of 1.0 s (about 1 km) thick, with only sparse outcrops of basement.

After initial work at GME it appeared that the area best fulfilling the selection guidelines might be a basin centered near 31.5°N, 24.5°W, where an area of abyssal plain about 80 km across is entirely free from abyssal hills. However, it was subsequently discovered that this area is characterized by many geological faults, so attention moved to the more western parts of the abyssal plain.

The 10 km box

In early 1985 the Department of the Environment requested IOS to choose a 100 km^2 box in which to concentrate further site assessment activities. The area chosen is in the western part of the plain and is centered at 31°17'N, 25°24'W (Figure 2). This is the area that at that time appeared to best fulfil the site assessment guidelines.

DETAILED CHARACTERIZATION OF STUDY SITE

Introduction

This chapter presents the detailed geological characterization of the GME study site. The characteristics of the 10 km box are given, but in order that the horizontal variability of the various parameters may be estimated we also describe briefly their regional variation throughout the greater GME area.

Geographical extent

The geographical boundaries of GME were purposely never precisely defined. However, almost all of the SWG work was carried out between 30-33°N and 23-26°W (Figures 3, 4). The "10 km box" is centered at 31°17'N, 25°24'W, with its sides trending NE-SW to parallel the prevailing topographic trends (Figure 2). Since 1985 most IOS and SWG activities at GME have been concentrated in or near this 10 km box.

Field work

Table 1 summarises the field work carried out in GME. The geophysical studies comprised long-range sidescan sonar (GLORIA), single-channel seismic profiling with air-and water-guns, high resolution profiling with 3.5 kHz systems, bathymetry, and magnetometry, along a dense network of tracks spaced about 10 km apart (Figure 3). A small amount of near-bottom high-resolution profiling has also been done, together with some deep-towed sidescan sonar.

Figure 4 shows station locations. Approximately 80-90 conventional piston cores up to 22.5 m in length have been taken in the area at average spacings of about 40 km, and five "long" cores between 25 and 35 m in length were taken with the French "STACOR" device. Sampling has also been conducted by gravity coring, box coring and a small amount of dredging. Other station work included extensive bottom photography, heatflow and geothermal gradient measurements, and *in situ* measurements of pore pressure gradients.

The results of these studies are summarised in the remainder of this chapter; fully detailed accounts of both the methods and results can be found in the references given, and in particular in Kuijpers et al. (1984a), Searle et al. (1985), Weaver & Thomson (1987), and Schuttenhelm (1987).

Regional Setting

Topography

Great Meteor East is situated on the Madeira Abyssal Plain in the centre of the Canary Basin (Figure 1). The basin is bounded by the lower flank of the Mid-Atlantic ridge in the west, the Azores-Gibraltar Rise (part of the European/African plate boundary) in the north, the Northwest African continental rise in the east, and the Cape Verde Rise in the south. At its western margin the abyssal plain extends westwards between the abyssal hills of the Mid-Atlantic Ridge flank via fracture zone valleys which run at right angles to the flank's general SSW-NNE trend. Elsewhere the abyssal plain merges fairly gradually with the continental rise. Some 150 to 250 km west of GME is a line of major seamounts which reach to within less than 300 m of the sea surface.

Nature of the basement

Seismic refraction and results from the Deep Sea Drilling Project suggest that GME and its environs are mostly underlain by normal igneous crust (Ewing & Ewing, 1959; Le Pichon et al., 1965; Udintsev et al., 1976, 1977; Hayes, Pimm, et al., 1972). Possible exceptions are the seamounts, islands, and the Madeira-Tore Rise which probably have anomalously thick aseismic ridge or oceanic island crust. Seismic reflection profiles across the Canary Basin show the typical NNE-SSW ridge-and-trough fabric of ocean crust cut every 100 km or so by WNW-ESE striking fracture zone valleys (Collette et al., 1984).

Crustal age

Most of the Madeira Abyssal Plain lies within the Cretaceous Magnetic Quiet Zone, so the crust cannot be precisely dated by magnetic anomalies. However, interpolation between recognised anomalies to either side gives an age range of about 75 to 105 Ma from NW to SE across GME. The 10 km box has a basement age of about 88 Ma (Santonian/Coniacian; Searle, 1987).

Regional sedimentation pattern

The flanks of the Mid-Atlantic Ridge west of GME are mainly covered by draped pelagic sediment. Most of this is thought to be calcium-carbonate rich ooze deposited above the carbonate compensation depth (CCD), although some of the deeper, older sediments may have been deposited below the CCD and are therefore expected to be mainly pelagic clays (Weaver et al., 1986; Searle, 1987). Where there are high relief and steep slopes (e.g. the seamounts west of GME), these pelagic sediments may be unstable and give rise to more-or-less localised debris flows and turbidity current deposits (Kuijpers, 1982; Searle, 1987; Schuttenhelm, 1987). For example, Kuijpers (1982) has described a debris flow that travelled at least 70 km SW of Hyeres Seamount (31°N, 30°W).

The northwest African slope and upper rise consists mainly of Neogene sequences of pelagic carbonate overlying older sediments (Von Rad & Wissman, 1982). The lower rise began to receive terrigenous sediments in the early Miocene (Berger & Von Rad, 1972; Von Rad & Wissman, 1982). A major late Quaternary submarine sediment slide originated on the upper continental slope near the Canary Islands (Embley, 1976). The associated tongues of debris flows reach downslope to the margin of the abyssal plain, stopping, in the GME area, at 24°W (Simm & Kidd, 1984). Several similar sediment slides and major turbidity current pathways have now been mapped on the rise both to the north and south of GME (Embley, 1976; Jacobi & Hayes, 1982; Auffret et al., 1984b; Kidd & Searle, 1984; Kidd & Hunter, 1986).

Seismic activity

The nearest active plate boundary is along the Azores-Gibraltar Rise, about 500 km away from GME. Only low-level seismic activity, at a level typical of the whole North Atlantic (excluding plate boundaries), occurs within the Canary Basin (Lilwall, 1982). The estimated return periods for peak accelerations of 0.1 and 0.5 g are 10^4 and 10^5 years, respectively, assuming uniformly distributed seismicity. An acceleration of about 0.1 g may be sufficient to cause slope failure (Kastens, 1984; Searle, 1987).

Volcanic activity

There is some intraplate volcanism in the region, as evidenced by the recently active volcanic islands of Madeira, the Canaries, and the Cape Verdes and the Great Meteor-Cruiser seamount chain. These represent about 3% of the area of the Canary Basin. Most of this volcanic activity has probably occurred within the last 20 Ma (Pratt, 1963; Bosshard & McFarlane, 1970; Von Rad, 1974; Watts et al., 1975; Wendt et al., 1976; Schmincke, 1979, 1982; Banda et al.,1981; Verhoef, 1983).

Topography

Figure 2 shows the bathymetry of GME, based on soundings from the tracks shown in Figure 3 and with contouring guided by GLORIA sidescan sonar data. The depth of the abyssal plain seafloor is 5440 ± 10 m, with a slope of less than 1:3000 (Searle, 1987). Abyssal hills, which occupy about 30% of the total study area, generally rise to a few hundred metres above the plain, with a maximum of 1000 m above it in one case. The hills are 10 to 30 km across and 20 to 40 km long, with their long axes oriented NW-SE, perpendicular to the Cretaceous seafloor spreading direction. In the centre of GME (31 - 32°N, 24-25°W) there is an area about 80 km across that is free of abyssal hills. Elsewhere the spacing between hills is 50 km or less, and in the area of the 10 km box it is 20 - 25 km (Figure 2b). The hill sides facing the 10 km box have average and maximum slopes of about 10% and 30%, respectively. East of 24°W is the lowermost continental rise, where the seafloor slope increases to more than 1:2000.

Sidescan sonar and 3.5 kHz data show that, on the present seafloor, debris flows, turbidity current channels and massive sand deposits extend to the foot of the continental rise near 24°W. Such features do not occur west of there, where both types of data indicate a completely uniform surface to the abyssal plain (Duin & Kok, 1984; Searle, 1987). The plain is everywhere characterised by well-laminated acoustic reflectors on 3.5 kHz records, with penetration of 3.5 kHz energy generally greater than 50 ms and reaching maxima of over 120 ms near 25°W (Figures 5, 6; Duin & Kok, 1984).

There is no evidence from existing data (including preliminary examination of deep-towed sidescan data - Figure 7) for sediment mass movement features (slumps, debris flows) associated with the abyssal hills in GME, but the possibility of some small-scale features unresolved by our surveys cannot be ruled out at present. However, the seamounts to the west of GME do give rise to slumps and small slides which generate sandy and fine grained turbidites which have been shown to be capable of penetrating into the western part of GME (including the 10 km box) via Cruiser Fracture Zone (31.4°N, 26°W).

Sedimentary and Structural Framework

Seismic Stratigraphy

Seismic reflection profiling provides an image of the structure of sub-seafloor formations (Figures 5a, 8), though it is emphasised that these cannot be unambiguously interpreted without direct sampling (e.g. by coring or drilling). The sedimentary section below the abyssal plain in GME can be divided into two general intervals (Searle, 1987): an uppermost unit (comprising units A and B of Duin & Kok, 1984, and ESOPE, 1986, here called Unit A+B), which contains many continuous, parallel and relatively flat-lying reflectors (generally sloping less than 1°); and a deeper unit (comprising units C and D of Duin & Kok, 1984) which has a rugged upper surface (slopes varying up to about 10°). This lower unit generally contains fewer and less continuous reflectors than the upper one, though there is a prominent band of strong reflectors at the top of it. The uppermost reflector in the band marks the top of the unit and was called "Reflector 4" by Duin & Kok (1984).

The upper unit is interpreted as comprising predominantly turbidites interlayered with thin pelagic beds, with the proportion of turbidites perhaps decreasing at depth where there appear to be fewer reflectors (Duin & Kok, 1984; ESOPE, 1986; Schuttenhelm, 1987; Searle, 1987). Its thickness varies between about 150 and 560 m throughout GME, being greatest near the centre of the area at 31°30'N, 25°30'W (Figure 9a). Its thickness ranges from 300 to 370m in the 10 km box (Figure 9b). Individual reflectors within this unit show a high degree of continuity across the abyssal plain, except where offset by faulting (see below).

The composition of the lower unit is less certain, but it probably contains mainly pelagic clay with minor pelagic carbonate draped over the basaltic basement, possibly together with volcanoclastics and locally derived turbidites and debris flows. Its thickness is very variable: it ranges from 300m to 750m in the 10 km box, but in some places exceeds 1000m.

The age of Reflector 4 (the probable onset of major turbidite deposition according to Weaver et al., 1986) cannot be well determined at present. It has been variously estimated, mainly on the basis of extrapolated or assumed sedimentation rates, and with wide margins of error, to be between about 2.4 and 13 Ma (Duin & Kok, 1984; Searle, 1987; Weaver et al., 1986).

Where abyssal hills stand out above the plain, they are usually covered by draped pelagic sediment up to about 100 to 200m thick, although basaltic basement occasionally outcrops along their steep sides or at their crests (Figure 6).

Basin structure

The Upper Cretaceous basement at GME ranges in depth from 5000m below sealevel under some of the abyssal hills to over 7000m in some of the deepest basement valleys (Figure 10a). The main structural elements in the basement are three fracture zone valleys that cross the area from WNW to ESE. Secondary ridges and troughs run between these valleys at high angles to the fracture zone trend. All of these structures can be well explained as the results of normal tectonic activity associated with crustal formation at the Cretaceous Mid-Atlantic Ridge (e.g. Collette et al., 1984). In the 10 km box the basement depth ranges from 600 to 1170m below seabed (6000 - 6600m below sealevel) - Figure 10b.

Because the seafloor relief in GME is low, the total sediment thickness closely reflects the basement morphology, varying between 250 and 1000m over most of the area, with maxima of more than 1750m over the fracture zone valleys. The top of the lower (mainly pelagic) sedimentary unit is a subdued version of the basement shape (Duin & Kok, 1984; Weaver et al., 1986), and the thickness of the overlying, mainly turbiditic unit varies correspondingly (Figure 9).

Lithology

Structure of the uppermost layers

Detailed knowledge of sediment properties is restricted to the uppermost 20-35m where we have been able to sample (Kuijpers et al., 1984b; Searle et al., 1985; ESOPE, 1986). In this interval cores consist of thick turbidites (1.4±1.2m in ESOPE core 10) interlayered with thin pelagic beds (0.1±0.1m) - Figure 11. Most of the turbidites are continuous across the whole of the abyssal plain, though a few of the very thin ones are restricted in their distribution, being localised around their points of entry into the plain. The pelagic intervals are generally continuous, varying slightly in thickness across the area.

Variations in thickness and grain size show that the great majority of the turbidites entered the abyssal plain via several pathways from the continental rise to the east, and then spread out across the area and ponded within it (Figure 12; Kuijpers et al., 1984b; Weaver & Rothwell, 1987). Individual turbidites west of 24°W vary in thickness by a few tens of percent, with a general increase in thickness toward the west. The turbidites tend to be thinner over basement highs and thicker over the valleys; such variability is thought to be the result of differential compaction, and probably increases with depth (compare Figures 9b and 13).

The larger turbidites have sandy or silty bases a few centimetres to a few tens of centimetres thick. These bases generally thin and become finer grained toward the west. However, thicker sands probably derived from abyssal hills or seamounts have been found at about 20m depth in the 10 km box (turbidite L, Figure 11; ESOPE, 1986), and at shallower levels below the abyssal plain in the fracture zone to the west of the box (31°10'N, 25°30' to 26°00'W; Schuttenhelm, 1987).

Turbidites

The fine grained parts of the turbidites are clay-rich calcareous oozes, generally containing 30-50% silt, 35-90% carbonate, 10-20% clay minerals and

0.1-1.0% (maximum 2.0%) organic carbon. The silty basal layers contain 30-90% carbonate intermixed with basaltic fragments. East of 24°W the bases may be much coarser and contain mainly volcanogenic minerals and forams. A massive sand lobe exists between 31°N and 32°N and east of 24°30'W. The sands in the 10 km box and the extreme western part of GME are foraminiferal.

There is little lateral variation in the composition of the fine-grained parts, but significant variation in the carbonate content occurs with depth, probably indicating the changing through time of the source areas of the turbidites. In particular, the deeper turbidites tend to have higher calcium carbonate contents (over 60% carbonate below 17m depth in the 10 km box, compared with 52% in the shallower layers - see table 2). Studies of turbidite provenance based on geochemical methods have also provided evidence for several source areas (de Lange et al., 1987).

In the 10 km box the mean and standard deviation of the grainsize, averaged over all the turbidites, is $3.5 \pm 0.6 \times 10^{-6}$ m. Here the turbidite bases are not significantly coarser than the rest of the sediments, except for the sandy turbidite L whose base has a grainsize of 7×10^{-6}m. Elsewhere in GME the mean grain size of the fine grained layers is about 3.5×10^{-6}m (Clay-sized) with 57% of the material being less than 4.0×10^{-6}m in diameter. The silty bases have a median grain size of about 40×10^{-6}m. The massive sands east of 24°W have median grainsizes of up to 450×10^{-6}m.

Pelagics

The pelagic sediments intercalated between the turbidites of the plain have accumulated near or below the carbonate compensation depth, resulting in highly variable carbonate contents ranging from pelagic clay to calcareous clays, marls and oozes. The average carbonate content in the 10 km box is 44±22%; elsewhere it is about 52%, but the range extends from less than 10% to over 80%.

The pelagic intervals have a median grain size of about 4×10^{-6}m ($(3.5 \pm 0.5) \times 10^{-6}$m in the 10 km box).

The surficial pelagic sediments on the abyssal hills are somewhat more indurated, have more hiatuses (Weaver & Kuijpers, 1983), but have similar compositions to those under the abyssal plain, except that they have greater proportions of ash and pummice as a result of winnowing. Brown clays occur at much shallower depths on the hills. Manganese nodules are found locally on top of these pelagic sediments (Huggett & Somers, 1987).

Few glacial erratics have been recovered from GME, but there are sufficient data to estimate the cumulative risk of impact on a point projectile penetrating to 15m as 0.015% (Huggett, 1985).

Stratigraphy

A reference bio-lithostratigraphy has been compiled from purely pelagic cores obtained from the abyssal hills, in order to permit the dating of the pelagic intervals intercalated between turbidites (Weaver & Kuijpers, 1983). Further correlations have been made between the turbidites on the basis of lithological properties. This work indicates that each major turbidite was depositied during a glacial/interglacial climate change (Weaver & Kuijpers, 1983). It also shows that no major erosion has occurred west of 24°W, although there was occasionally, especially around abyssal hills, a few centimetres of erosion of the tops of pelagic layers by some of the succeeding major turbidity currents.

Sedimentation rates in the pelagic units, based on U/Th dating and palaeontology, range from 2.5×10^{-3} mm a^{-1} for the pelagic clays to 6.10^{-6} mm a^{-1} for the pelagic marls and oozes (Kuijpers et al., 1984b; Searle et al., 1985). For ESOPE core 10 in the 10 km box the average pelagic accumulation rate over the past 450,000 years has been 3.7×10^{-3} mm a^{-1}. The deposition rates of the turbidites are probably very rapid, each turbidite probably being deposited in a few months. There have been thirteen turbidity current events over the past 450,000 years in ESOPE core 10, and twenty-one in 700,000 years in core 24. The bulk accumulation rate resulting from the accumulation of both turbidites and pelagics in the 10 km box over the last 450,000 years is 41×10^{-3} mm a^{-1}; elsewhere it ranges up to 105×10^{-3} mm a^{-1}.

Physical Properties

Geotechnical properties of the various sediment types found at GME have been measured by Schultheiss & Thomson (1984) and ESOPE (1986); they are summarised in Table 2 together with the physical properties discussed in the previous section. Profiles of these parameters against depth are given in Figure 11.

Disruptive Structures

Faults

Seismic and 3.5 kHz data reveal the presence of laterally discontinuous faults with small vertical offsets (Figure 14; Duin et al., 1984, Williams, 1987). The dip of the fault planes ranges from 20° to vertical and some fault planes are cylindrical (i.e. the dip direction reverses with depth). Fifty-two percent are reverse faults.

Faults observed on 3.5 kHz records within the uppermost hundred metres have vertical offsets of up to ten metres at depth, diminishing to virtually zero at the seabed. (Occasionally there may be a gentle ramp at the seabed of not more than 2m in several tens of metres.) These faults are generally parallel to the underlying basement trends, and tend to occur in bands 1-3 km across, 4-7 km apart and more than 15 km long, that lie above the crests or steep flanks of the basement ridges (Figure 15). Individual faults within these bands are up to 5 km long.

Deeper faults imaged on the low-frequency seismic records have offsets of up to 50 m. Some can be traced upwards into the 3.5 kHz records, but in general these faults are more uniformly distributed than the shallow ones and do not seem to occur in bands.

Faults tend to be more common in the central part of GME (Figure 16) where unit A+B is thickest (Figure 9). No faults have been observed in the 10 km box shallower than 200m below seabed, and few deeper ones have been identified with any degree of certainty.

The faults are considered to result from differential compaction of the sediments, but as yet there is no agreement as to the detailed mechanism of their formation (Buckley & Grant, 1985; Williams, 1987).

Diapirs

Air gun seismic records in GME sometimes show narrow vertical "transparent" zones of acoustic blanking that are often associated with bands of shallow faulting (Figures 5a, 14B). Lancelot & Embley (1977) interpreted similar features elsewhere as mud diapirs, but detailed inspection of the GME air gun records casts doubt on such an interpretation (Williams, 1987) and there seems to be no good evidence for such features on watergun records (Schuttenhelm, 1987). Camera runs over these areas show no evidence of disruption of the sediment surface. The preferred explanation is that in these areas acoustic energy is defocussed and scattered by steeply-dipping beds above the steep flanks of basement ridges (Williams, 1987), but the question is still not entirely resolved. No such features have been seen in the 10 km box.

Gas and Clathrates

There is no evidence either of free gas or clathrates in cores from GME. In theory some biogenic methane could be generated from any organic carbon in the turbidites at depths of a few hundred metres where the temperature is above 20°C and sulphates are absent (Williams, 1987). However, at the pressures pertaining in most of the turbidite sequence any gas would be combined with water into a solid "clathrate". Free gas could only exist deeper than 350m below seabed. Usually a free-gas/clathrate boundary produces a strong seismic reflector (e.g. Tucholke et al., 1977; White, 1979), and no such reflector has been recognised in GME.

Geochemistry

Both oxidising and reducing conditions can be recognised on the basis of Mn^{2+} remobilization and pore waters. The pore water dissolved oxygen content falls linearly with depth and reaches zero at a clearly defined oxidation front at a depth of a few tens of centimetres (Wilson et al., 1985, 1986). Similarly, the dissolved concentrations of nitrate and sulphate (oxidising agents for organic matter) decrease with depth, the concentration of nitrate also reaching zero near the oxidation front (Figure 17). Below this depth reduced iron and manganese are found in the pore waters. Conversely there is generally a consistent increase in dissolved concentrations of alkalinity, phosphate and ammonia (all products of organic matter decomposition) with depth in the sediments (Figure 17).

As far as can be seen in the c. 30m sections so far sampled, conditions do not appear to become strongly reducing with increased depth: sulphate is not strongly depleted, and free sulphide is absent.

Immediately after deposition a turbidite is probably free of oxygen and nitrate, any oxidising species picked up in transit having become rapidly reduced. Oxygen and nitrate then diffuse into the reduced layer from above, depleting the organic carbon and allowing the oxidants to penetrate even deeper, though since the penetration rate is limited by diffusion it will slow as the front progresses downwards. At the same time reduced metal ions (Fe^{2+} and Mn^{2+}) that are duffusing upward from deeper in the sediment are oxidised and precipitated at the oxidation front. Uranium, copper, nickel, vanadium, zinc and cobalt also show characteristic distribution patterns associated with the oxidation/mobilisation fronts (Colley & Thomson, 1985; Jarvis & Higgs, 1987).

When the next turbidite is deposited it must shut off the oxygen supply to its predecessor, leaving the turbidite in a suboxic state in which the fossil oxidation front is preserved. For example, uranium appears to be relatively mobile under oxidising conditions and can become concentrated at an oxidation front. However, once conditions there become reducing the uranium becomes strongly bound: some uranium peaks more than 500,000 years old do not appear to have migrated detectably. Diffusion coefficients for uranium calculated from these observations are given in the report of the Sediment Barrier Task Group (SBTG, 1987).

It thus appears that the majority of the sediment column at GME has remained suboxic since burial, otherwise the fossil redox record would have been erased. Even so, the extent to which the natural system is buffered against redox change is still unknown.

Dissolved silica profiles show large variations with depth, with maxima exceeding 600×10^{-6}M and intermediate minima decreasing to 150×10^{-6}M. These buried silica minimum zones suggest that diagenetic reactions occurring in certain pelagic intervals may be consuming silicon by forming new silicate minerals.

Porewater Advection

Geochemical gradients

Gradients of the dissolved concentrations of ammonia, chloride and sulphate in sediment porewaters have been studied for about 25 cores (including the four long ESOPE cores), widely distributed throughout GME. These gradients are all consistent with simple diffusional models, indicating that any porewater advection has been less than 1 mm a^{-1} (DeLange, 1984; ESOPE, 1986, 1987; Schuttenhelm, 1987).

Heatflow studies

It has been suggested that spatial variations in the heat flux through the seabed could indicate the presence of thermally driven convection within the basaltic basement, and possibly also in the sediments, while nonlinear geothermal profiles could indicate convection within the sediments (Anderson et al., 1979).

Several long transects of heat flow and thermal gradient measurements have been made in GME. Four nonlinear gradients were interpreted as indicating upward pore-water flow of 0.8-1.1 m a^{-1} within the sediments (Noel, 1985). All of the nonlinear gradients occurred in or near bands of shallow faults, and they and the high flux values were all over the crests of basement ridges.

However, there is some uncertainty about the degree of nonlinearity measured (Schultheiss & Noel, 1987) and in any case alternative interpretations of nonlinear temperature gradients are possible (Noel, 1984). It is thought that porewater movement as rapid as that proposed would physically disrupt the sediments, and no such effects have been seen on extensive photoruns in the vicinity.

In December 1985 thirty seven further heatflow measurements were made with a modified probe having closer (0.5m) thermistor spacing. These measurements failed to record any nonlinear gradients, and it was concluded that any sediment porewater advection is "absent or slow" (Noel & Hounslow, 1986). We believe that the geothermal gradient method at present probably has insufficient resolution to detect flow rates of the order of 1 mm a^{-1}.

Noel & Hounslow (1986) also modelled the observed heat fluxes at GME. Assuming no sediment porewater advection, they found that they could model heatflow profiles in the central part of GME either by assuming reasonable variations in the thermal conductivity of the basaltic basement or by assuming the existence of hydrothermal convection within (and confined to) the basement. However, neither assumption adequately predicted the observed heatflow in the 10 km box (though the second assumption was better than the first), because thick sediments there tend to damp out any heatflow variations that exist at the basement/sediment interface. Noel & Hounslow concluded that in the 10 km box there must be either significant horizontal variations in sediment thermal conductivity, or significant horizontal porewater advection. However, neither of these two effects has yet been modelled.

In situ pore pressures

Pore water flow can also be estimated from a knowledge of in situ pore pressure gradients, if the permeability is known. Most measurements in GME to date have shown no significant flow, i.e. less than instrumental resolution of about 0.4 mm a^{-1} (Schultheiss & McPhail, 1986, and unpublished data). Measurements within a few hundred metres of faults and sites of nonlinear temperature profiles have shown no significant flow except for one measurement of 1 mm a^{-1} downward. The highest value elsewhere was another downward flow of 3 mm a^{-1} at a site over a shallow buried basement high (Schultheiss & McPhail, 1986), but repeated measurements nearby have failed to confirm this. Several recent measurements just north of the 10 km box suggested pressure gradients indicative of flow as high as about 20 mm a^{-1}, but subsequent work has shown that the instrument recording those values was faulty. Other stations near the 10 km box show no significant pore pressure gradients.

It is concluded that there is no compelling evidence for any porewater advection greater than about 3 mm a^{-1}, and perhaps not more than 1 mm a^{-1}, in GME.

Other Use Avoidance

The only potential resources identified within GME to date are small patches of manganese nodules. None have been found on the abyssal plain, but they are fairly common on relatively flat, sediment-draped parts of the abyssal hills (Huggett & Somers, 1987; Schuttenhelm, 1987). However, individual patches of nodules are quite small and isolated from each other, so these would be a much less attractive resource than, say, the great fields of nodules in the equatorial Pacific.

SITE ASSESSMENT SUMMARY

In this chapter we summarize the available data and examine it in the light of the site assessment guidelines. Unless otherwise stated this summary applies only to the flat-lying abysssal plain, and not to the abyssal hills therein.

Site Summary

Site bathymetry

So long as abyssal hills are avoided, there is a large expanse of suitably flat seafloor between 24° and 26°W, including the 10 km box.

Sediment thickness and structure

The uppermost, interbedded pelagic/turbidite sequence is generally greater than 150 m thick (300 to 370 m in the 10 km box), which is adequate for shallow (penetrator) emplacement. Structures in this uppermost unit are simple and continuous, except where faults occur (see below).

Faults and diapirs

Faults are common in the central part of GME, but are less common in the far western part (west of 25°W), including the 10 km box. No shallow faults have been observed in that box. Where faults do occur they may be associated with buried dome-like areas of "acoustic blanking", whose origin is not understood; but such features are also absent from the 10 km box.

Stratigraphy

Except near faults the sedimentary layers in the turbidite sequence are continuous over tens of kilometres laterally, and display only small variations in thickness. Vertically the sediment sequence is essentially continuous to the base of the available cores, which in the 10 km box is at least 500,000 years. Some sedimentary layers suffer minor (a few centimetres) thinning near some abyssal hills, as a result of non-deposition or minor erosion. This has not been observed in the 10 km box.

Volcanism, seismicity and tectonics

The seamounts 150-200 km west of GME were volcanically active in the Miocene (between 5 and 25 million years ago), but there has been no known volcanic activity there or closer to GME for at least the last 5 million years.

GME is in an area of relatively low seismic activity. There has been no recent tectonic activity except for sediment faulting, which is ascribed to sediment compaction.

Sorption capacity

Description of the base case sorption capacities is referred to the SWG Sediment Barrier Task Group. However, we note that there is evidence of silica authigenesis throughout GME, at varying depths down to at least 22 m, implying an unknown change in mineralogy which could affect the sorption capacity.

Redox conditions

The uppermost 0.1 to 1.0 m of sediment throughout the area is oxidized with respect to manganese. Below this, mildly reducing conditions with respect to organic matter (nitrification reactions) persist to the base of all cores (up to 34 m in the 10 km box). No appreciable sulphate reduction occurs within the cored intervals, though it is still possible that it occurs at greater subbottom depths.

Erratics and other boulders and debris

The incidence of glacial erratics in GME is very low and is unlikely to affect penetrator emplacement. Small but dense fields of manganese nodules occur on some parts of some abyssal hills, but not on the plain. The only significant boulder-sized debris on the plain is man-made, primarily oceanographic equipment left as the result of this study (e.g. at least 12 penetrators and at least 8 anchor weights in or near the 10 km box).

Sand

No sand has been found in GME west of 24°30'W, except for several sand layers between 20 and 34 m in the 10 km box and shallower occurrences in the fracture zone west of the box. The distal abyssal plain north of the box appears to be free from shallow sand layers. The incidence of sand deeper than 34 m in the box and deeper than 20 m in most other parts of GME is unknown.

Bioturbation

Open burrows have been found in some GME cores but there has been no detailed study of their occurrence. It has been estimated that such burrows could increase bulk permeability by up to two orders of magnitude.

Other use avoidance

Small, isolated fields of manganese nodules occur on some abyssal hills, including one within 20 km of the 10 km box. They are thought unlikely to be commercially attractive.

Site area

A large area exists near the centre of GME (about 31°15'N to 31°45'N, 24°30'W to 25°00'W) that appears to fulfil most of the selection criteria except those requiring avoidance of faults and other unpredictable structures. To the depths sampled (34 m maximum), the 10 km box appears to fulfil all of the criteria except that requiring avoidance of sands. We think that there are probably areas of at least 100 km^2 in the westernmost part of the abyssal plain to the north of the 10 km box (31°30'N to 32°30'N) that may fulfil most of the criteria. The level of data there is less than in the box: there are fewer geophysical tracks, there has been no coring deeper than 21 m, and no <u>in situ</u> pressure measurements. However, existing data suggest that the areas are free of shallow faults and sand, and we have no reason to suppose that their other properties are very different from those in the 10 km box.

Deep disposal

At present nothing is known to rule out deep (drilled) disposal at GME, but the level of knowledge of the deeper environment there is at present too poor to make a reasoned judgement. Also, it should be realised that GME was chosen primarily on considerations of shallow disposal; it would possibly not be our preferred area for further studies into the deep disposal option.

Site Model

In order to facilitate modelling of potential radionuclide migration through the sediment barrier at GME, we give a simplified model of the site geology in Table 3. This applies to the 10 km box and is based as far as possible on observations from the box. Data in this table therefore provide a "base case". For variations within GME as a whole, see Table 2.

UNRESOLVED ISSUES

Deep geology

Despite the success of the ESOPE cruise, there are still very few deep cores in GME, and the deepest only reached 34m below seabed. This should be contrasted with the revised value of 50 ± 20 m for the envisaged emplacement depth (RATG, 1987), and the requirement in the site selection guidelines for sampling to twice the emplacement depth and preferably through the entire Pleistocene section. The fact that an unexpected sand layer was cored by ESOPE in the 10 km box shows that we cannot accurately predict deep lithology either from geophysical profiles or by extrapolating shallower sampling. The ESOPE coring also showed variations in the thickness and lithology of the deeper turbidites that we believe to reflect their origin; a full understanding of the sedimentary processes will require such variations to be fully mapped by further deep coring.

Pore water advection

A very important aspect of site assessment is the characterization of any pore water advection. Early suggestions of high advection rates (many tens of centimetres per year) based on apparent non-linear temperature gradients have not been substantiated, either by studies of geochemical gradients or by in situ pore pressure measurements, and it seems that present day heatflow measurement and interpretation techniques probably do not have sufficient resolution to reliably detect advection rates of less than about a metre per year, whereas the geochemical and in situ pore pressure techniques have resolutions of about 1 mm a^{-1}. However, it is desirable to reconcile all of these measurements by properly determining the origin of the anomalous heat flow results, and this has not yet been done.

One significant inferrence of 3mm a^{-1} downward advection has been made by in situ pressure measurements, but it has not so far been possible to repeat this result. At present it is concluded that there may be some low level advection in GME, but probably of very restricted areal extent. It would clearly be desirable to confirm this and determine the extent of the flow field, but this would require many very closely spaced and precisely navigated measurements.

In situ permeability

Permeabilities measured in the laboratory may not reflect in situ permeabilities, either because of disturbance to the sediment fabric during sampling or testing, or because of variations in permeability not reflected in the samples (e.g. due to the presence of open burrows). It would be highly desirable to develop a method for measuring in situ permeabilities.

Faulting

Although small areas (c. 10 km across) can be found that are free of it, faulting of shallow sediments is quite common at GME, and may well be in most other abyssal plains. There are three areas of uncertainty regarding faulting: their hydraulic properties, their small-scale structure, and the mechanism of fault formation.

The NEA Seabed Working Group's Radiological Assessment Task Group has suggested, on the basis of a very simple model, that the hydraulic effects of faults are negligible at distances of more than a few tens of metres from the fault plane (Anderson, 1985, pp. 21-25). However, we believe that a much better understanding of fault-related flow processes is needed, if only to address an "accident" scenario in which a repository is breached by new faulting. At present it is not known whether, or to what extent, faults might provide relatively permeable pathways for pore water flow.

The second issue concerns the small-scale structure and distribution of faults. Surface-deployed 3.5 kHz profilers can only resolve fault offsets of more than about 1 or 2 m vertically, and the deeper-penetration airgun and watergun systems can only resolve about ten times this offset. Horizontal structure may only be resolved to about 1 km, or a best a few hundred metres. We are concerned that there may be smaller scale faults as yet undetected. Furthermore, we do not know the extent to which a fine-scale fracture network may occur that appears on high-resolution profiles as a single fault plane. Such a network might have an important impact on the hydraulic properties of the fault.

Finally, it is important to understand the mechanism of faulting, in order to be able to predict how existing faults will develop and, more importantly, where new ones may occur. There are two partially conflicting hypotheses at present that need to be resolved.

Further understanding in these areas will require additional field work (deep-towed, high resolution profiling and sampling of faulted sediments), laboratory work to study such samples and carry out model experiments, and theoretical studies.

Predictability of sedimentation processes

At a certain level there is quite a good understanding of sedimentary processes at GME, so that past and future sedimentation patterns can be predicted in a general way. Thus it is clear that there has been a more or less continuous succession of interlayered pelagic sediments and turbidites; that the turbidites have several source-areas and entry points to the abyssal plain, including at least one from the west; and that sandy lobes are deposited by the more proximal turbidites in the extreme east and west of the area. However, the details of these processes are not fully quantified and predictable: we can predict which pathways and major source areas are most likely to be active in the future, but not which will be active next; nor can we predict the precise extent of future sand deposits. In order to improve these aspects of our understanding, it would be necessary to carry out more deep sampling within GME and more sampling and profiling over the sediment pathways that lead into GME.

Geochemistry

Study of the geochemistry of GME cores has revealed no evidence of strongly reducing conditions to the maximum depth cored. At greater depths it is possible that such conditions could occur, possibly with significant changes in the solubility of ions. There may also be significant authigenic and diagenetic changes at depth, which could affect ion mobility but which are at present unknown.

Acoustic blanking zones

Airgun profiles from GME sometimes show areas of "acoustic blanking", where little energy is returned. These zones usually appear to overlie basement ridges and are frequently associated with faults. It has variously been suggested that these zones might be caused by: disruption of sediments due to high pore-water advection; mud diapirism; igneous intrusions; or defocussing of acoustic energy over sharply crested basement ridges (with or without a cap of pelagic sediment). Although the last of these explanations is thought most likely, we cannot positively discount any of the others at present. In order to do so it would be necessary to carry out further geophysical work (e.g. near-bottom seismic reflection profiling and magnetometry, seismic refraction, and deep coring).

Deep disposal

We infer, mainly from geophysical profiles and regional considerations, that below the turbidite cover there may be fairly extensive areas of pelagic clays several hundreds of metres deep; these might be suitable for drilled emplacement of waste. However, this inference is tentative and must be checked by deep drilling and sampling, as must the stratigraphic history and barrier properties of these sediments. It is emphasised that our level of knowledge of the deeper sediments in GME is extremely sketchy at present.

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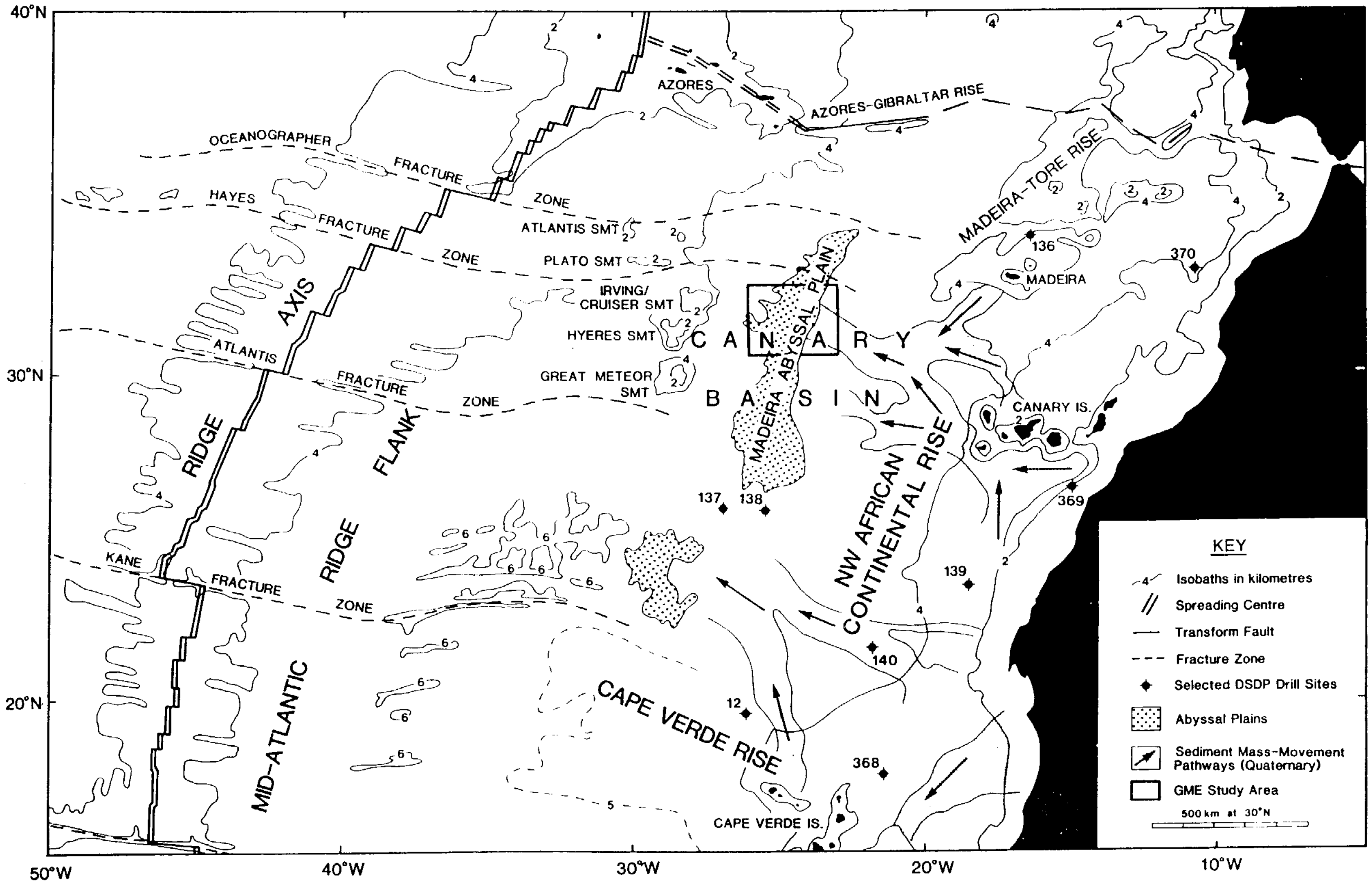
Figure 1 Regional setting of the Madeira Abyssal Plain. Box outlines GME study area. Outline bathymetry, in kilometres, simplified from Searle et al.(1982). Sediment mass-movement features compiled and simplified from Embley (1975, 1976); Jacobi & Hayes (1982); Kidd & Searle (1984); and Jacobi (unpublished chart). Fracture zones from Searle et al. (1982) and Collette et al. (1984).

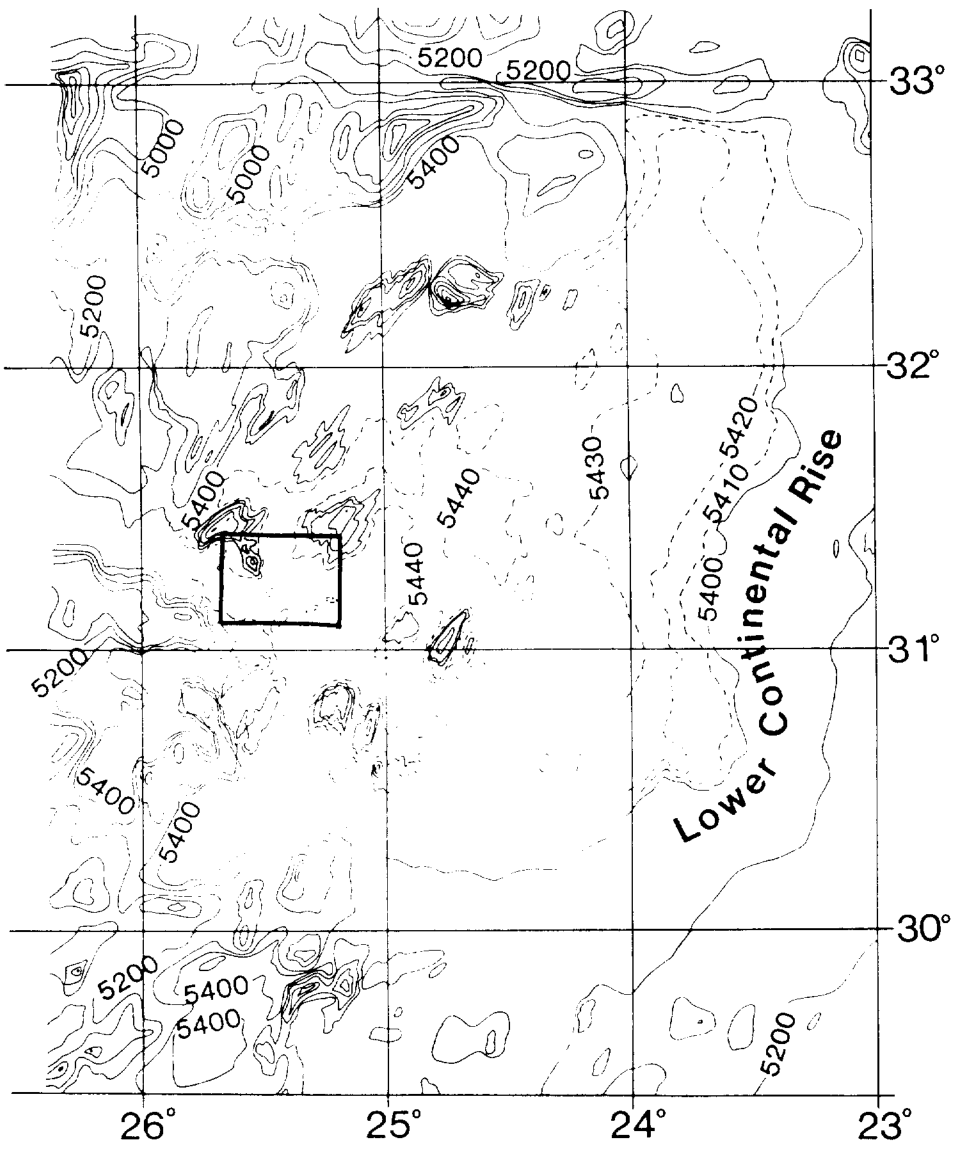


40°N
30°N
20°N
50°W
40°W
30°W
20°W
10°W
AZORES
AZORES-GIBRALTAR RISE
MADEIRA-TORE RISE
OCEANOGRAPHER FRACTURE ZONE
HAYES FRACTURE ZONE
ATLANTIS FRACTURE ZONE
KANE FRACTURE ZONE
ATLANTIS SMT
PLATO SMT
IRVING/ CRUISER SMT
HYERES SMT
GREAT METEOR SMT
MID-ATLANTIC RIDGE AXIS
RIDGE FLANK
CANARY BASIN
MADEIRA ABYSSAL PLAIN
MADEIRA
CANARY IS.
NW AFRICAN CONTINENTAL RISE
CAPE VERDE RISE
CAPE VERDE IS.
136
137
138
139
140
12
368
369
370
KEY
Isobaths in kilometres
Spreading Centre
Transform Fault
Fracture Zone
Selected DSDP Drill Sites
Abyssal Plains
Sediment Mass-Movement Pathways (Quaternary)
GME Study Area
500 km at 30°N

Figure 1

Figure 2 a) Topographic chart of GME, in metres corrected for velocity of sound in seawater. Based on soundings collected by HNLMS Tydeman, 1980; MT Farnella 3/81; MS Tyro, 1982 and 1986; RRS Discovery cruises 118, 126, 134, 144, 153 amd 163; and RRS Charles Darwin cruise 9B. Tracks shown in Figure 3. Interpolation of contours between tracks guided by GLORIA data. Box outlines area of Figure 2b, not the 10 km box.

b) Detailed bathymetry of the area outlined in (a). Contour interval 100 m, with addition of 5430 m contour. Seafloor below 5430 m is essentially flat with a depth of 5440 ± 5 m. Edges of abyssal hills controlled by deep-towed sidescan sonar data (see Figure 7). The 10 km box is outlined, and the positions of the profile in Figure 8 and of ESOPE cores 2 and 10 are shown.



5200
5200
33°
5000
5000
5400
5200
32°
5420
5430
5410
5440
5400
5440
5400
Lower Continental Rise
31°
5200
5400
5400
30°
5200
5400
5400
5200
26°
25°
24°
23°

Figure 2a

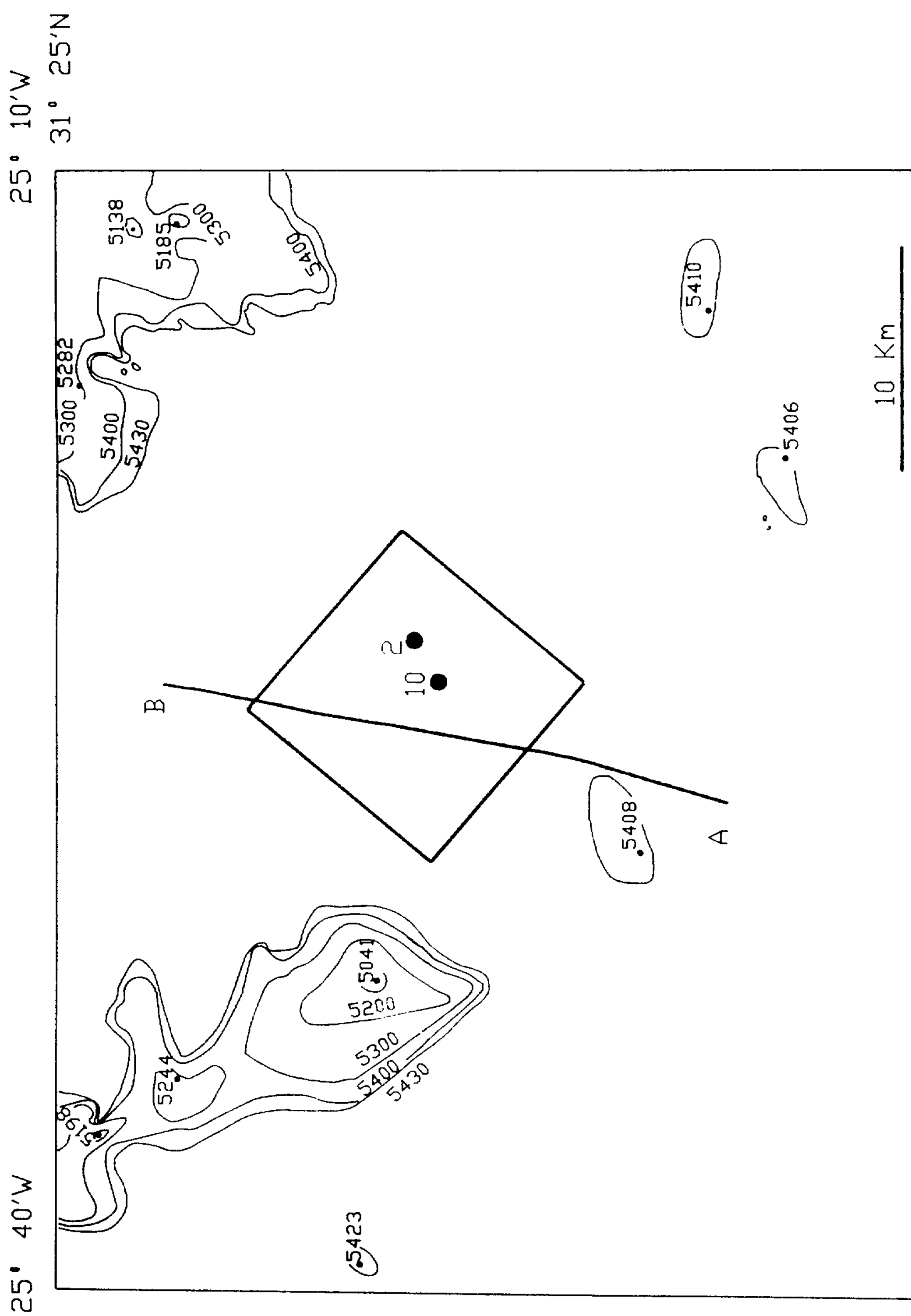

25° 10'W
31° 25'N
31° 05'N
25° 40'W
5138
5185
5300
5400
5282
5300
5400
5430
5410
5406
10 Km
2
10
B
A
5408
5041
5200
5300
5400
5430
5244
5198
5423

Figure 2b

Figure 3 a) Ship's tracks from which underway geophysical data were collected in GME (seismic reflection profiling using either air-gun or water-gun). Heavy line outlines area of GLORIA coverage. Line AJ shows position of profile given in Figure 5a. Box outlines position of Figure 5b.

b) Detail of track coverage in central and western GME, including tracks on which high frequency sediment profiling (2 kHz or 3.5 kHz) was carried out. 10 km box is outlined.

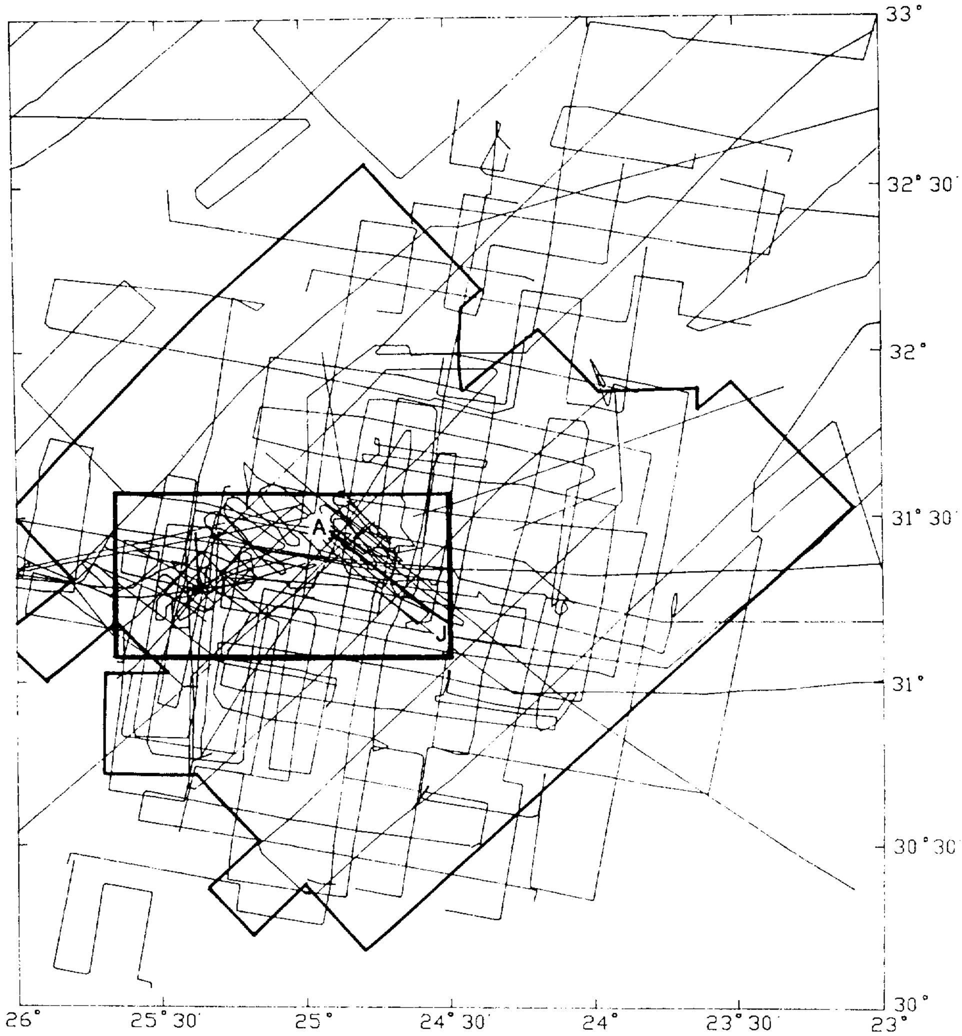


Figure 3a

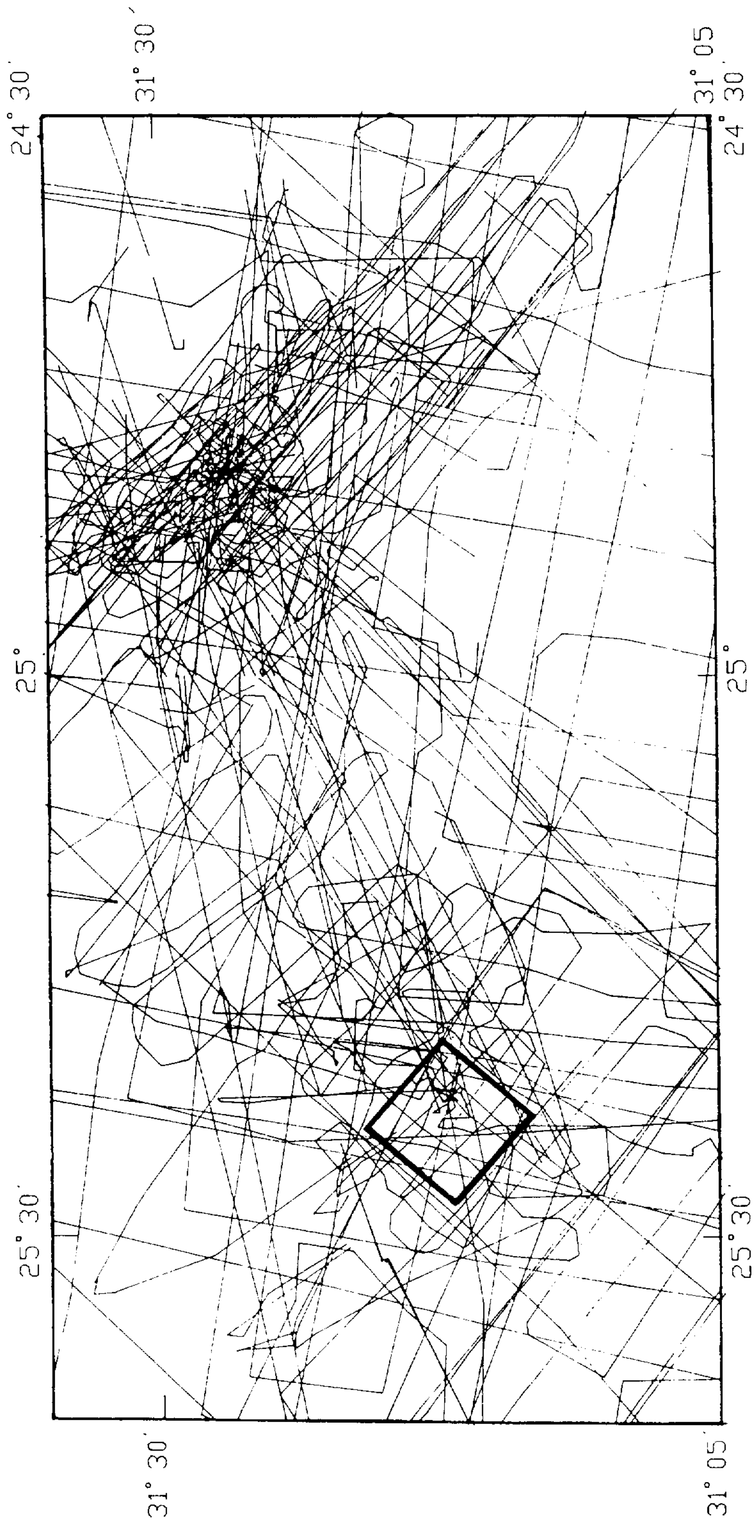


Figure 3b

Figure 4 Positions of sampling or measurement stations in GME. See key for station type.

a) Whole of GME, box shows area of Figure 4b;

b) detail of central and western GME.

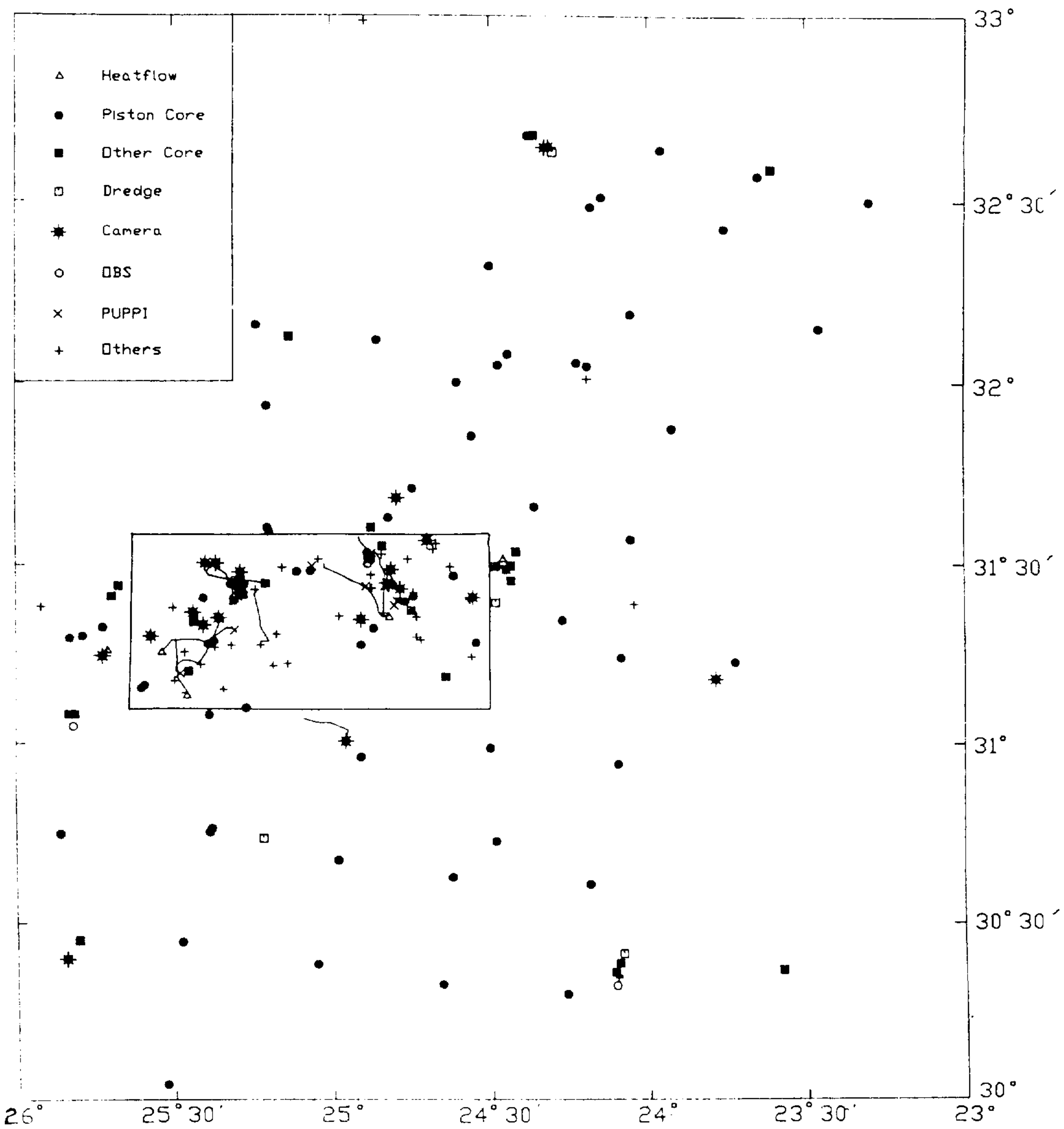
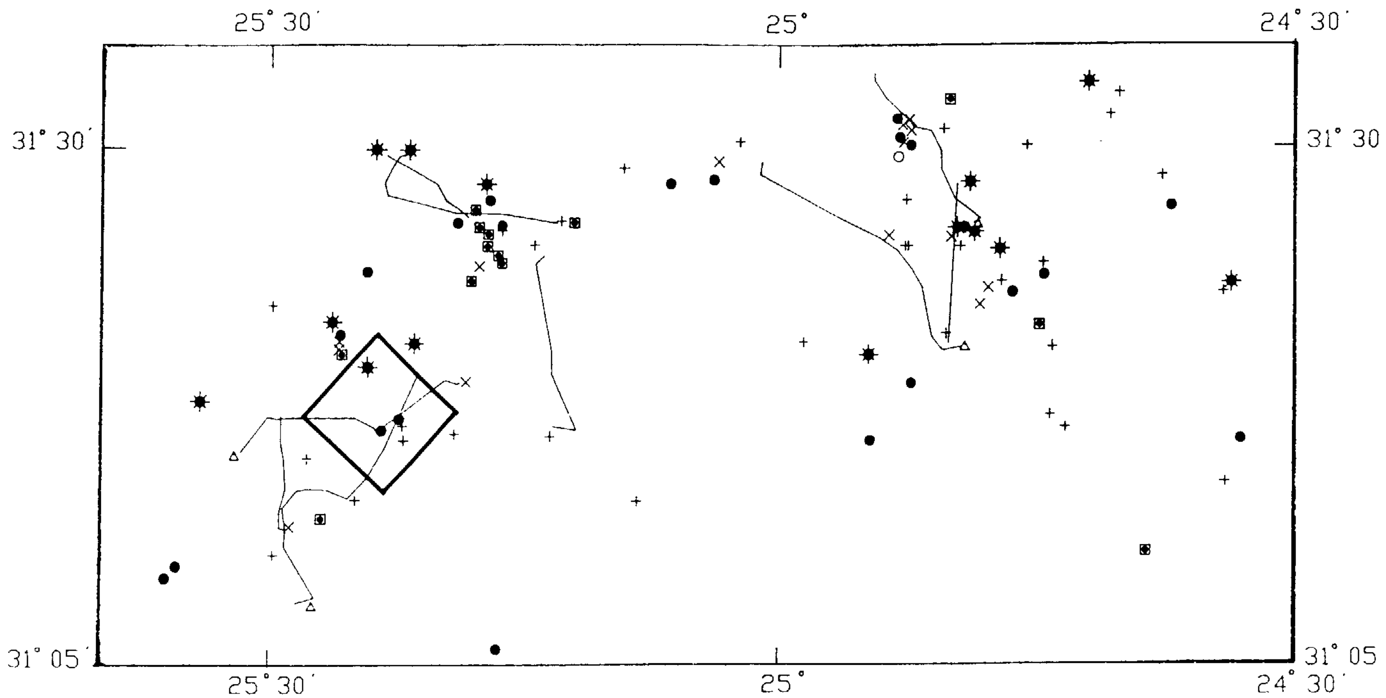

Heatflow
Piston Core
Other Core
Dredge
Camera
OBS
PUPPI
Others
33°
32° 30´
32°
31° 30´
31°
30° 30´
30°
26°
25° 30´
25°
24° 30´
24°
23° 30´
23°

Figure 4a



△ Heatflow ⊠ Other Core ○ OBS + Others

● Piston Core ✷ Camera × PUPPI

Figure 4b

Figure 5 a) Typical airgun and 3.5 kHz profile from the central part of GME, after Williams, 1987. See Figure 3 for location.

b) 3.5 kHz record between ESOPE cores 2 and 10 in the 10 km box. See Figure 2b for core locations. Positions and simplified lithologies of ESOPE cores 2 and 10 are shown on the profile. White intervals are turbidites, black pelagites. Note that the depth scale applies to the cored section, not the acoustic profile.

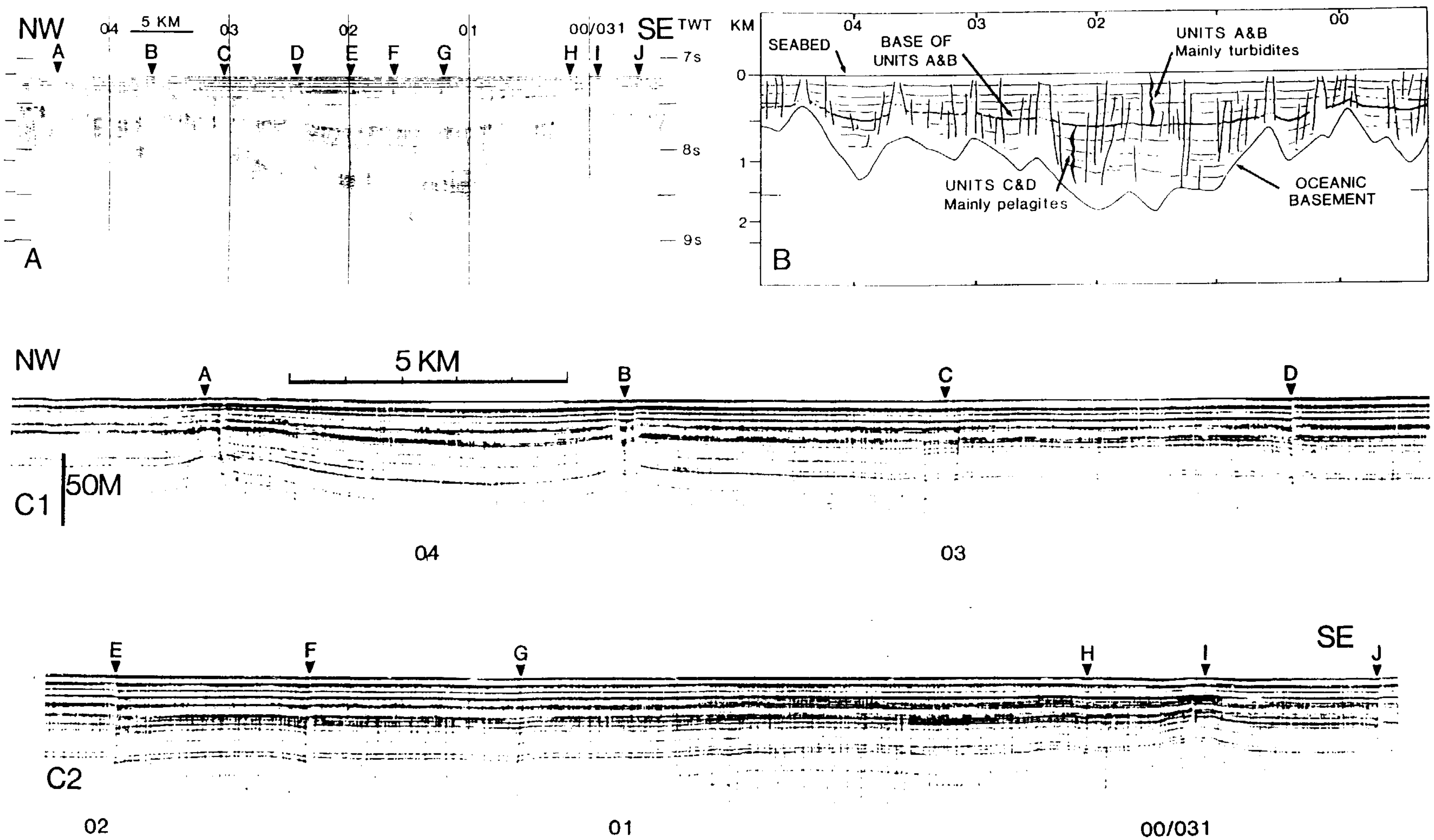

NW
SE
TWT
5 KM
04
03
02
01
00/031
A
B
C
D
E
F
G
H
I
J
7s
8s
9s
KM
0
1
2
SEABED
BASE OF
UNITS A&B
UNITS A&B
Mainly turbidites
UNITS C&D
Mainly pelagites
OCEANIC
BASEMENT
00
50M
C1
C2

Figure 5a

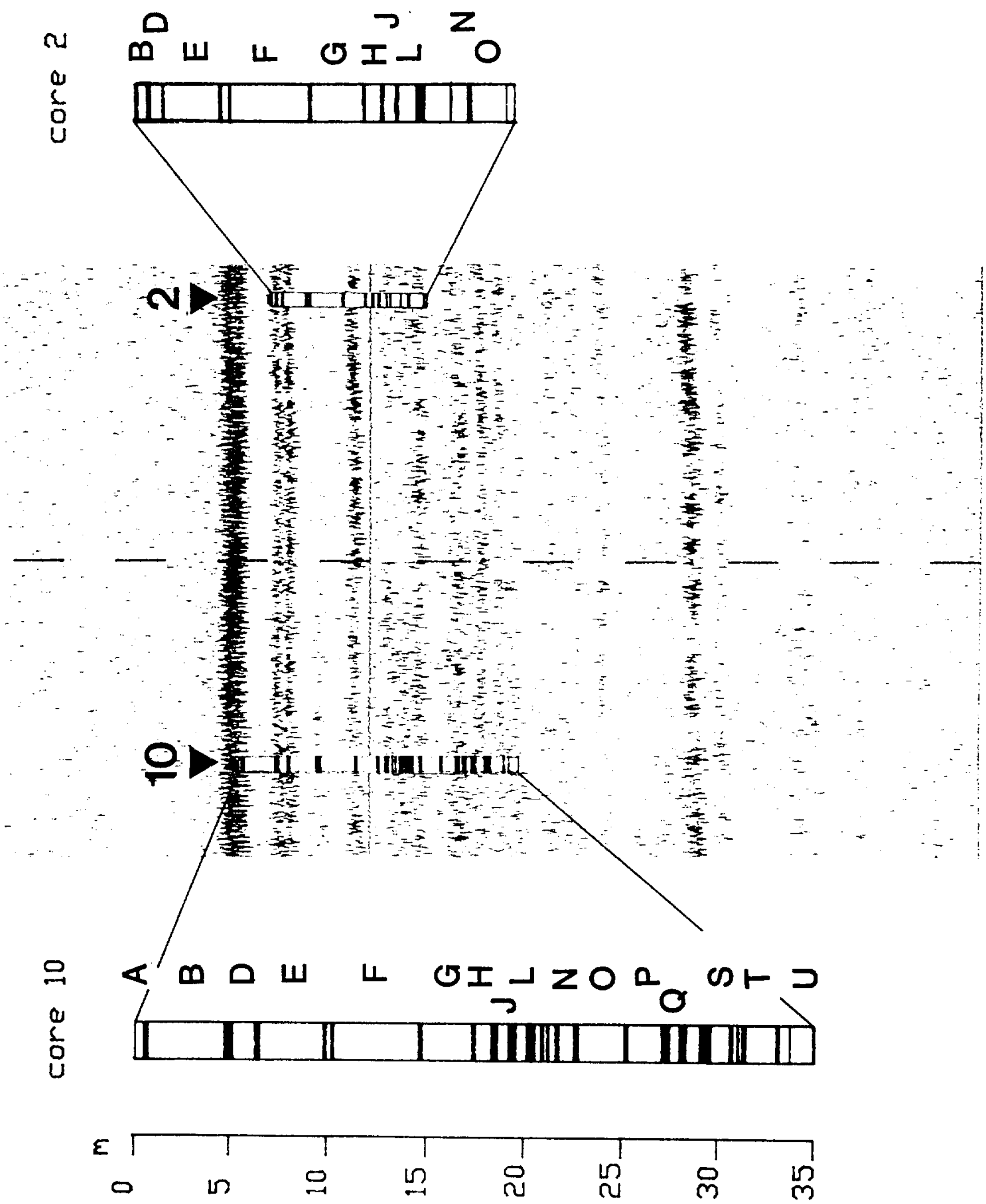

core 2
B D E F G H J L N O
2
10
core 10
A B D E F G H J L N O P Q S T U
m
0
5
10
15
20
25
30
35

Figure 5b

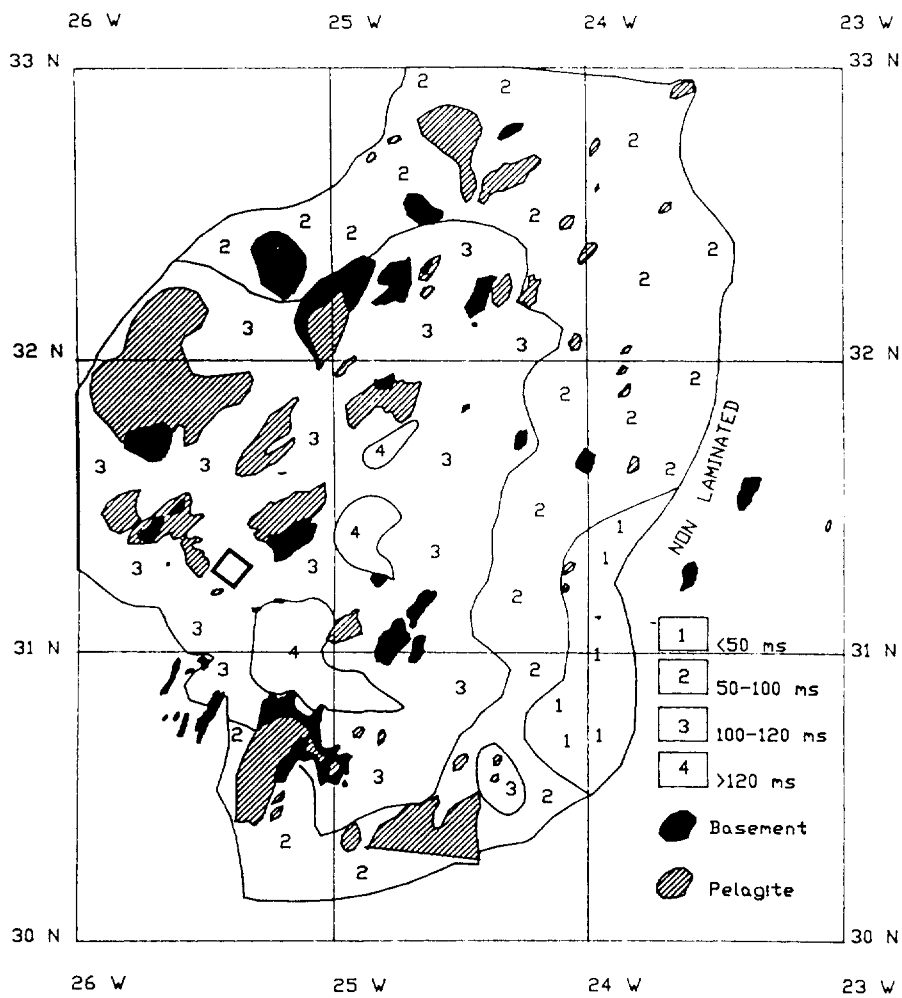


Figure 6

Figure 6 Surficial sediment facies within GME. White numbered zones indicate acoustically well-laminated turbidites, with penetration of 3.5 kHz energy as given in the key. Blank area to the east of 23°30'W contains predominantly poorly laminated turbidites and debris flow deposits of the continental rise. Blank areas to NW, SW and S are unmapped. 10 km box is outlined.

Figure 7 Extent and preliminary interpretation of deep-towed sidescan sonar data obtained in November 1986. Areas of strong reflectors correlate well with abyssal hills and indicate occurrences of basaltic outcrop, pelagic sediment, and/or manganese nodules. 10 km box is outlined.

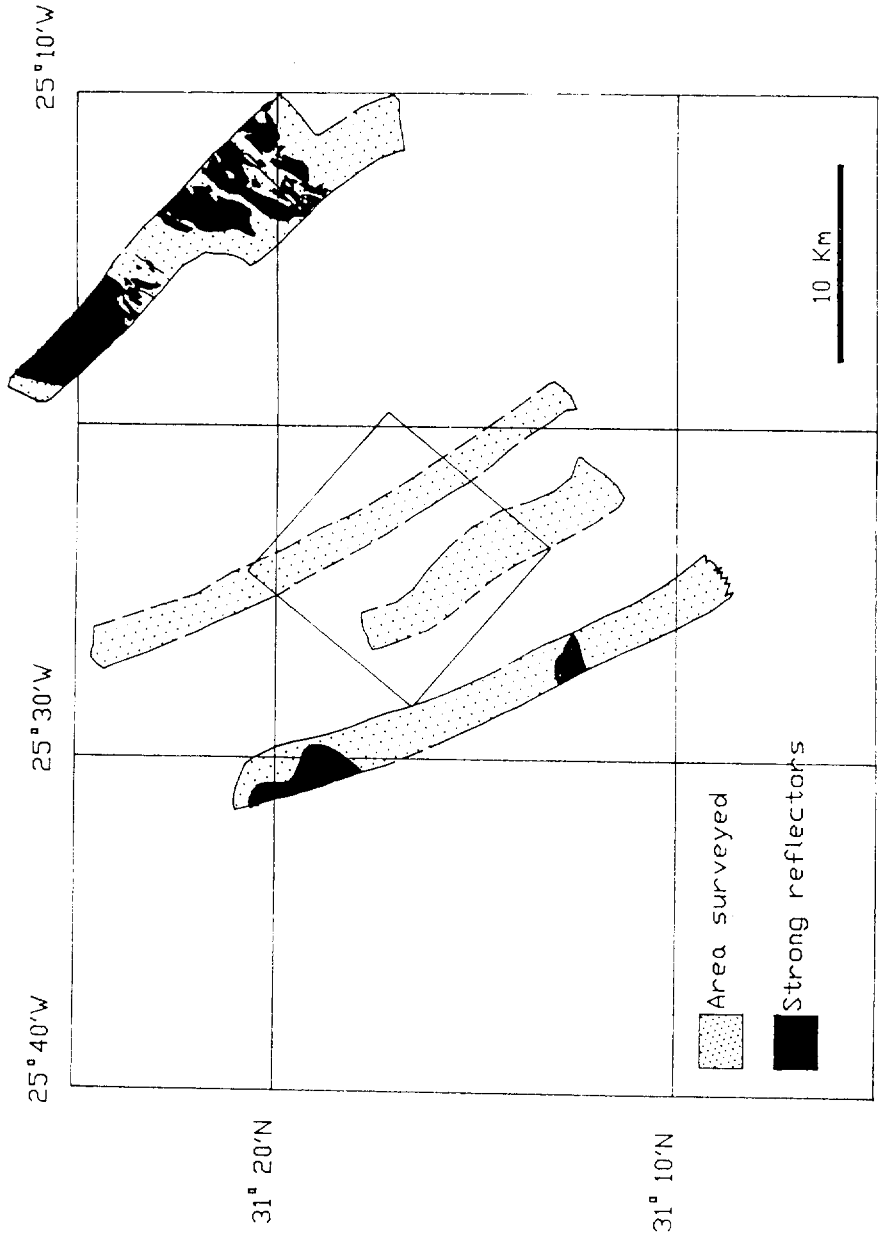

25°10'W
25°30'W
25°40'W
31° 20'N
31° 10'N
10 Km
Area surveyed
Strong reflectors

Figure 7

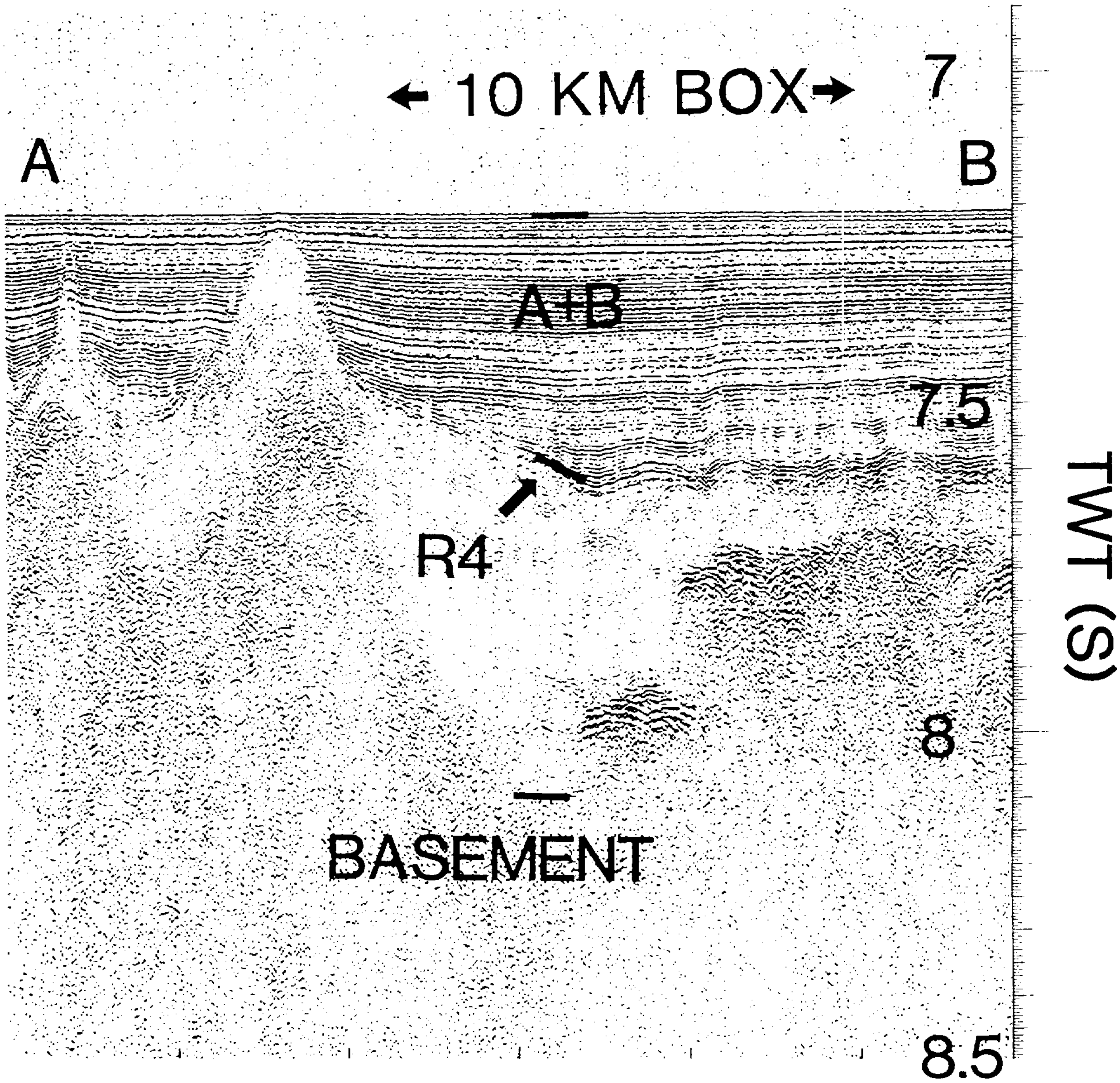


Figure 8

Figure 8 Typical watergun seismic reflection profile from the 10 km box in GME. The profile runs SSW-NNE across the box and is 26 km long (see Figure 2b for profile location).

Figure 9 Thickness in metres of the uppermost sediment unit A+B, interpreted as the mainly turbiditic section of GME. a) Throughout GME, after Duin & Kok, 1984; b) in the region of the 10 km box (which is outlined). The 10 km box is outlined, and the positions of the profile in Figure 8 and of ESOPE cores 2 and 10 are shown.

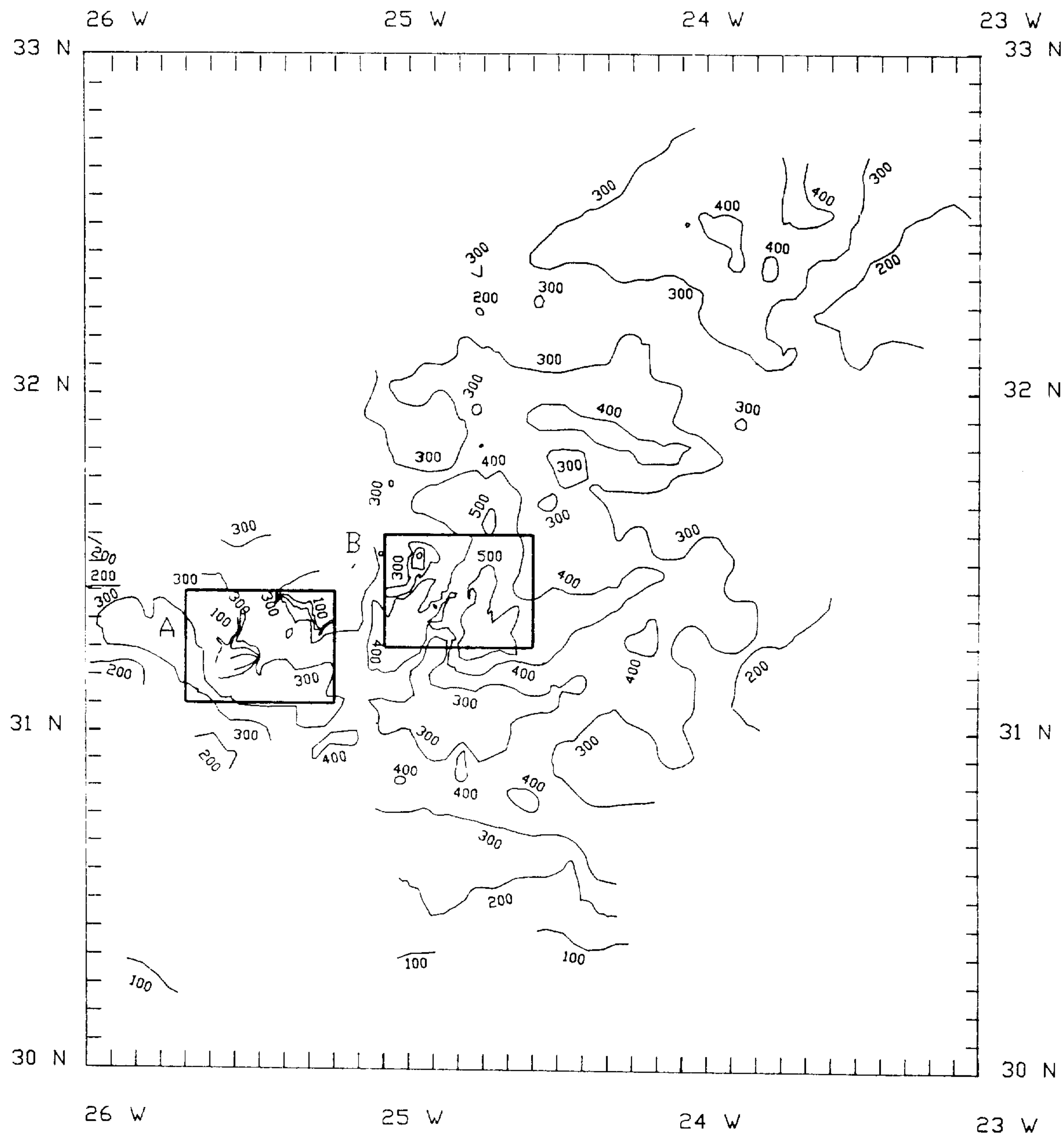


Figure 9a

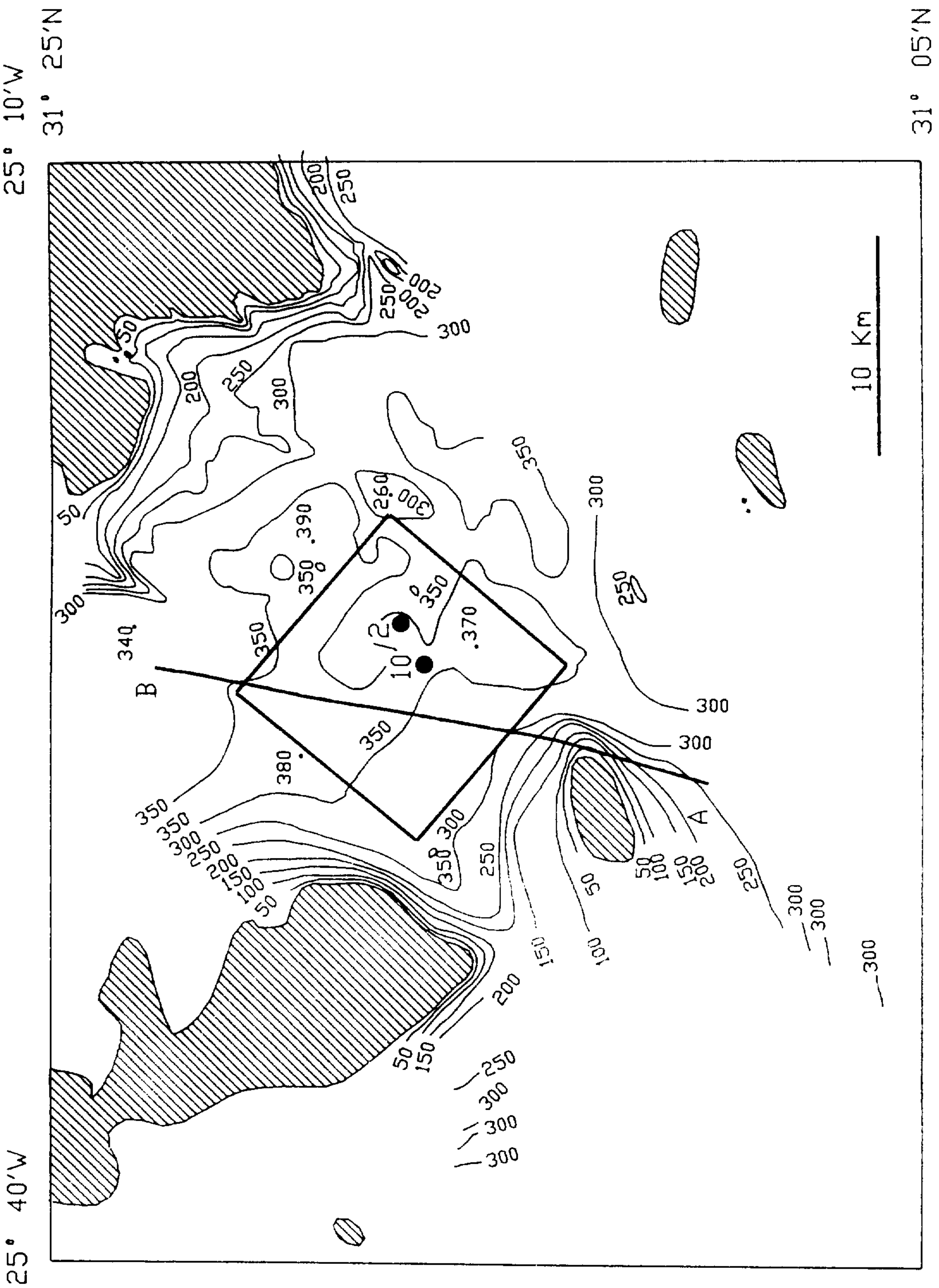


Figure 9b

Figure 10 a) Total depth to basement in GME, in metres below sealevel, inferred from seismic reflection profiles, after Searle (1987): contour interval 250 m.

b) Depth to basement in the region of the 10 km box (outlined), in metres below seabed. Contour interval 100 m. Abyssal hills, where the reference plane (seabed) is above the 5440 m level of the abyssal plain, are shaded. The 10 km box is outlined, and the positions of the profile in Figure 8 and of ESOPE cores 2 and 10 are shown.

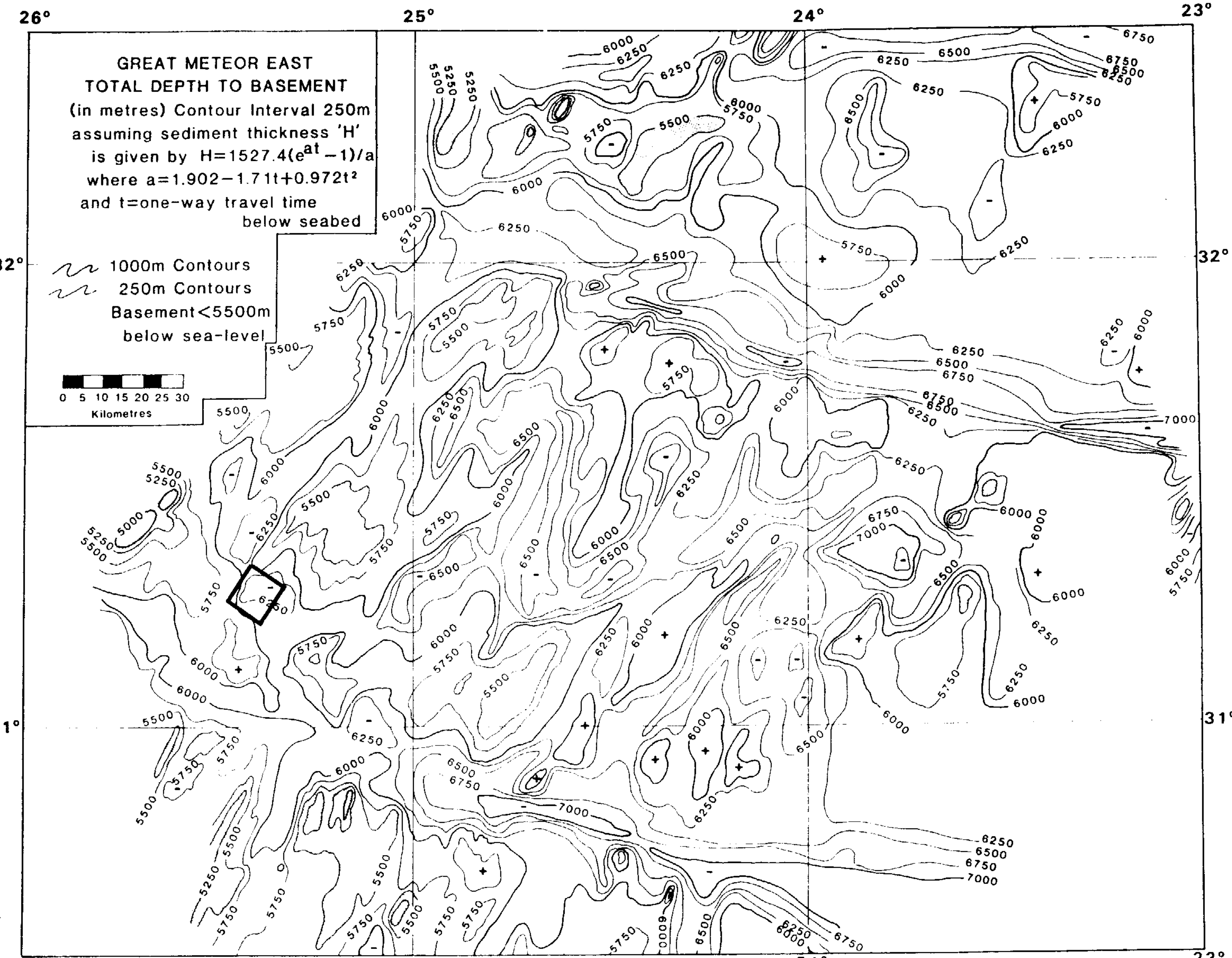

GREAT METEOR EAST
TOTAL DEPTH TO BASEMENT
(in metres) Contour Interval 250m
assuming sediment thickness 'H'
is given by H=1527.4(e^at −1)/a
where a=1.902−1.71t+0.972t²
and t=one-way travel time
below seabed
1000m Contours
250m Contours
Basement<5500m
below sea-level
0 5 10 15 20 25 30
Kilometres
26°
25°
24°
23°
32°
31°

Figure 10a

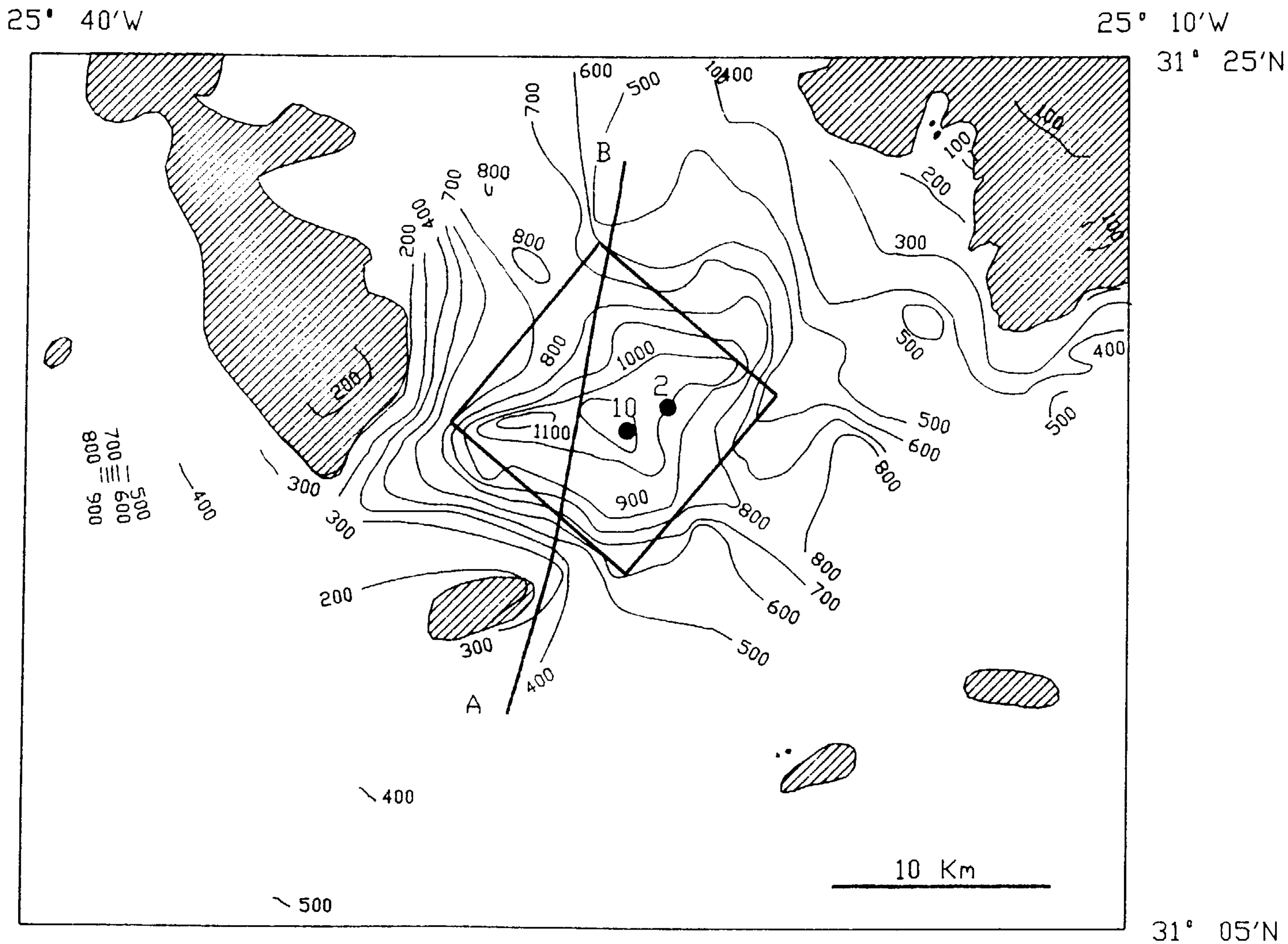
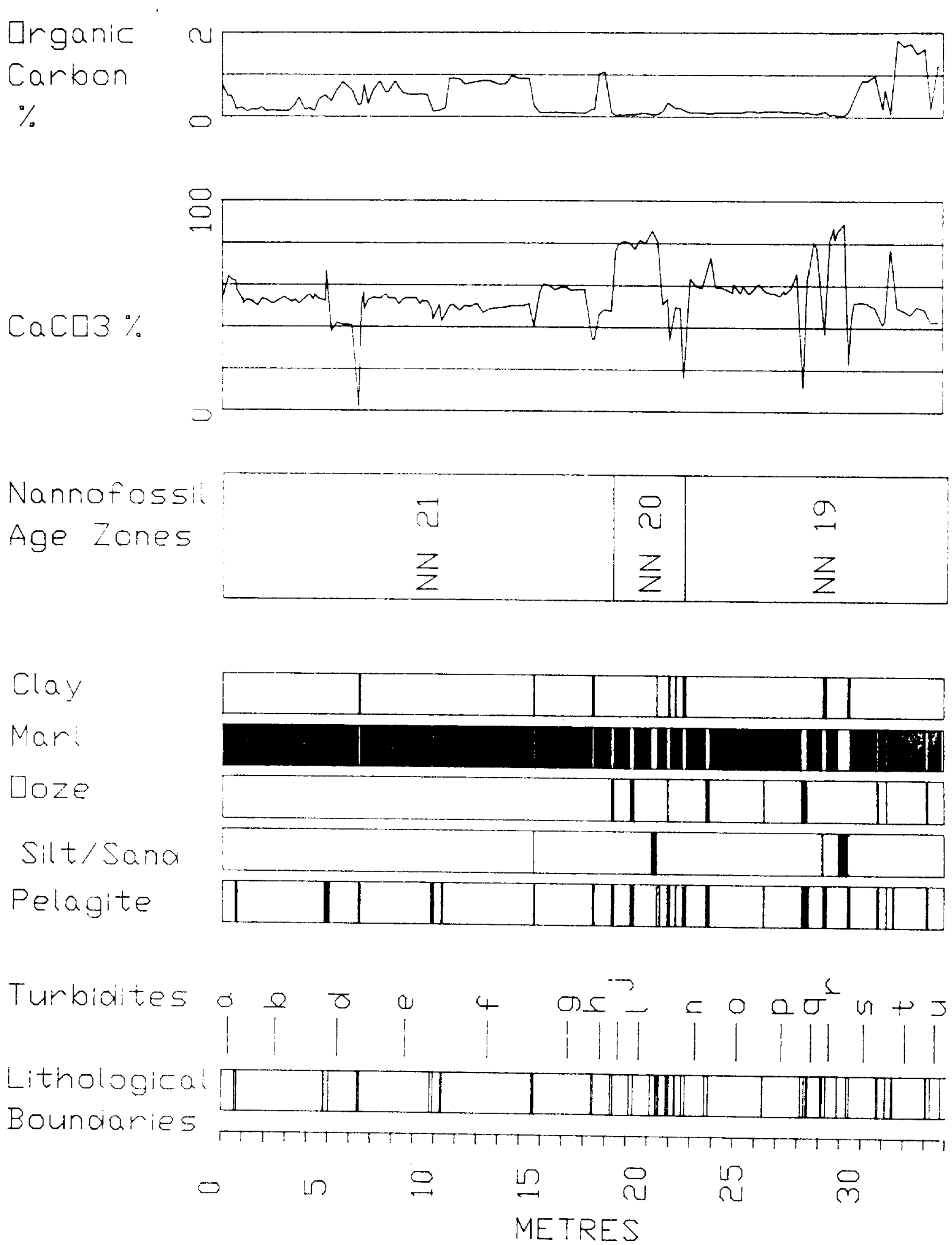


Figure 10b

Figure 11 Plots against depth of lithology, stratigraphy, carbonate content, organic carbon, water content, porosity, median grain size, permeability, and shear strength in ESOPE core 6 or 10 in the 10 km box of GME. Permeabilities at depths shallower than 12m have not yet been measured in these cores; the data plotted are extrapolated from measurements elsewhere in GME (mainly Discovery core 10695 at 31°24'N, 24°46'W). Lithology is indicated by a black zone in the corresponding sediment class.

Figure 11 (Part 1)



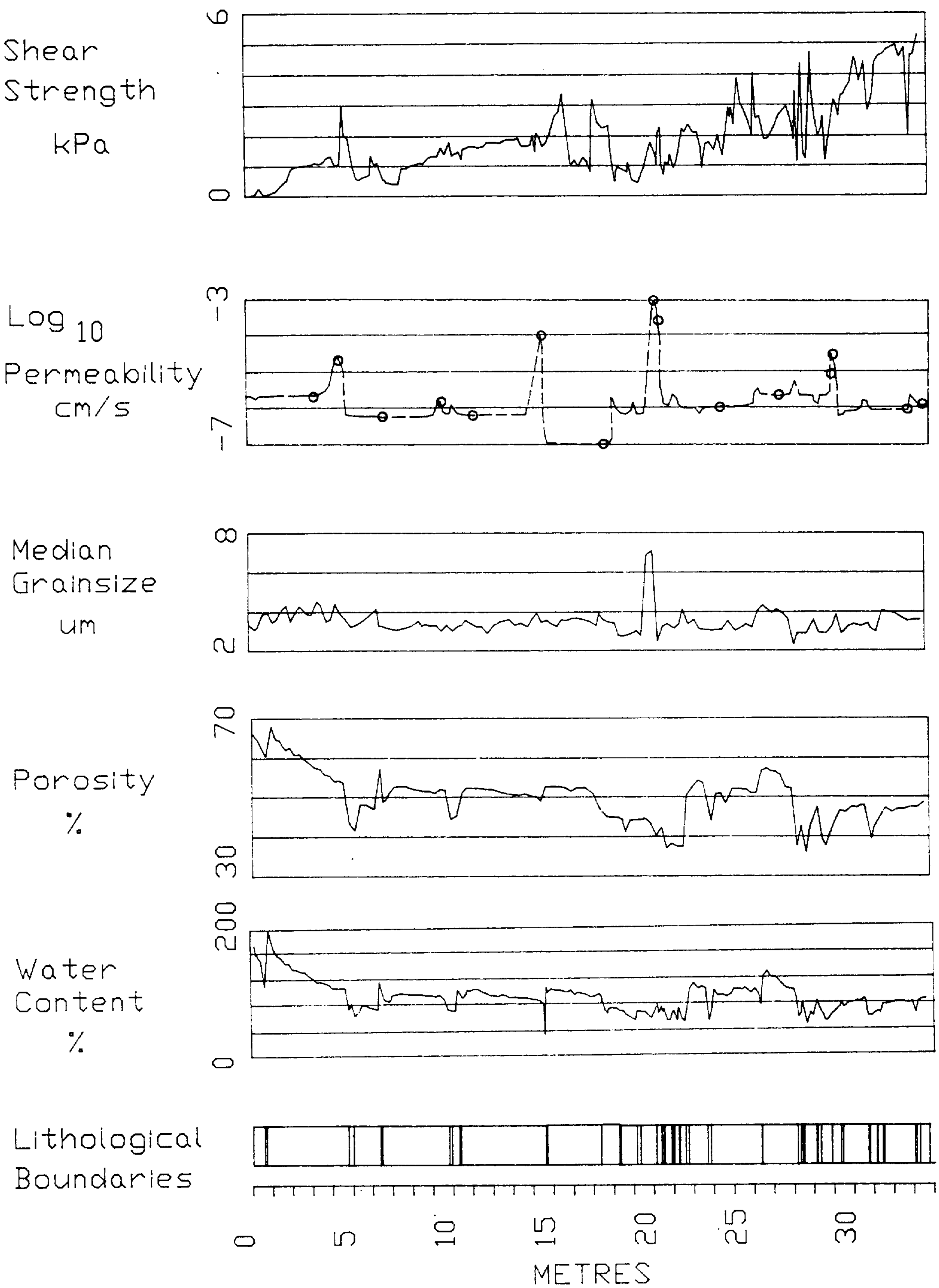


Figure 11 (Part 2)

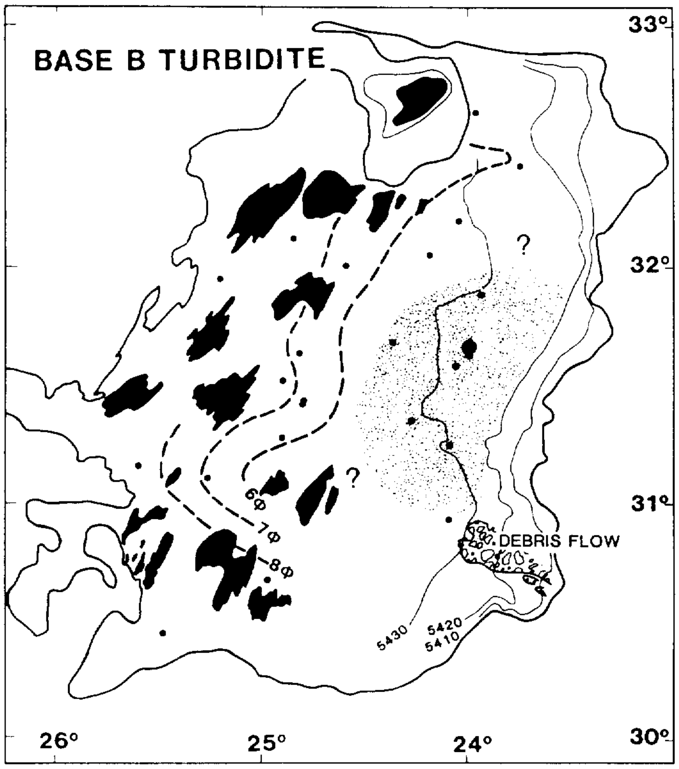


Figure 12

Figure 12 Distribution of the B turbidite (depth range 1-3 m in central GME, 1-5 m in 10 km box), after Weaver & Rothwell, 1987. Continuous lines are isobaths to seafloor, in metres; broken lines give graphic mean grainsize of basal centimetre of turbidite in phi units: phi=-log$_2$(mu), where mu is the grainsize in mm. Stippled area indicates sand at base of B that has not been penetrated by coring.

Figure 13 Depth to a prominent shallow reflector seen on 3.5 kHz records, in the region of the 10 km box. Contours in metres. Note that the reflector, which almost certainly is associated with a particular turbidite, is deeper over the deeper basement in the centre of the basin. The 10 km box is outlined, and the positions of the profile in Figure 8 and of ESOPE cores 2 and 10 are shown.

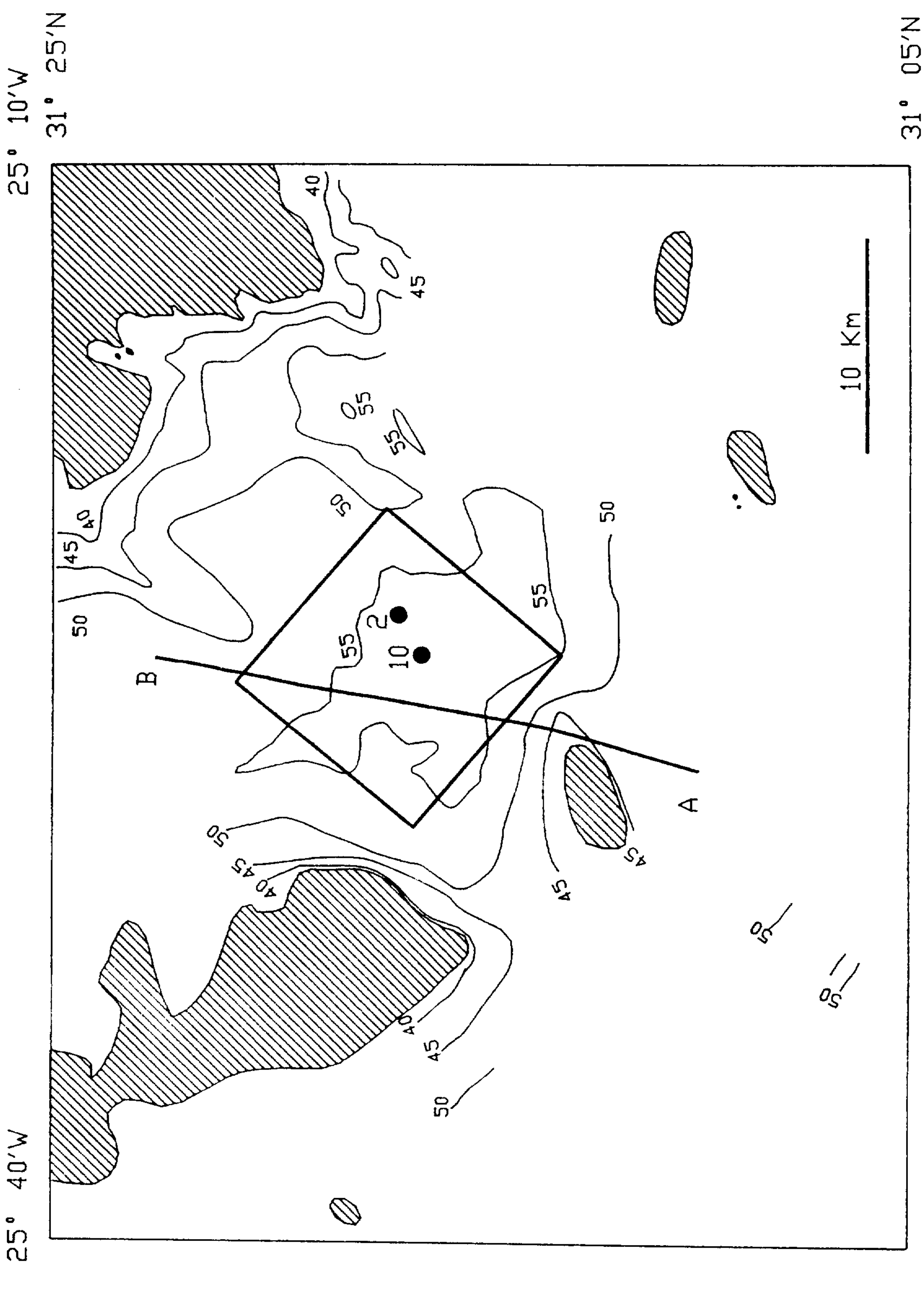


Figure 13

Figure 14 Examples of seismic profiles across a reverse fault (double arrows) in the central part of GME. A) 3.5 kHz record, vertical exaggeration 16:1; B) airgun record, vertical exaggeration 7:1. Single arrow in (B) points to zone of acoustic blanking. After Williams (1987).

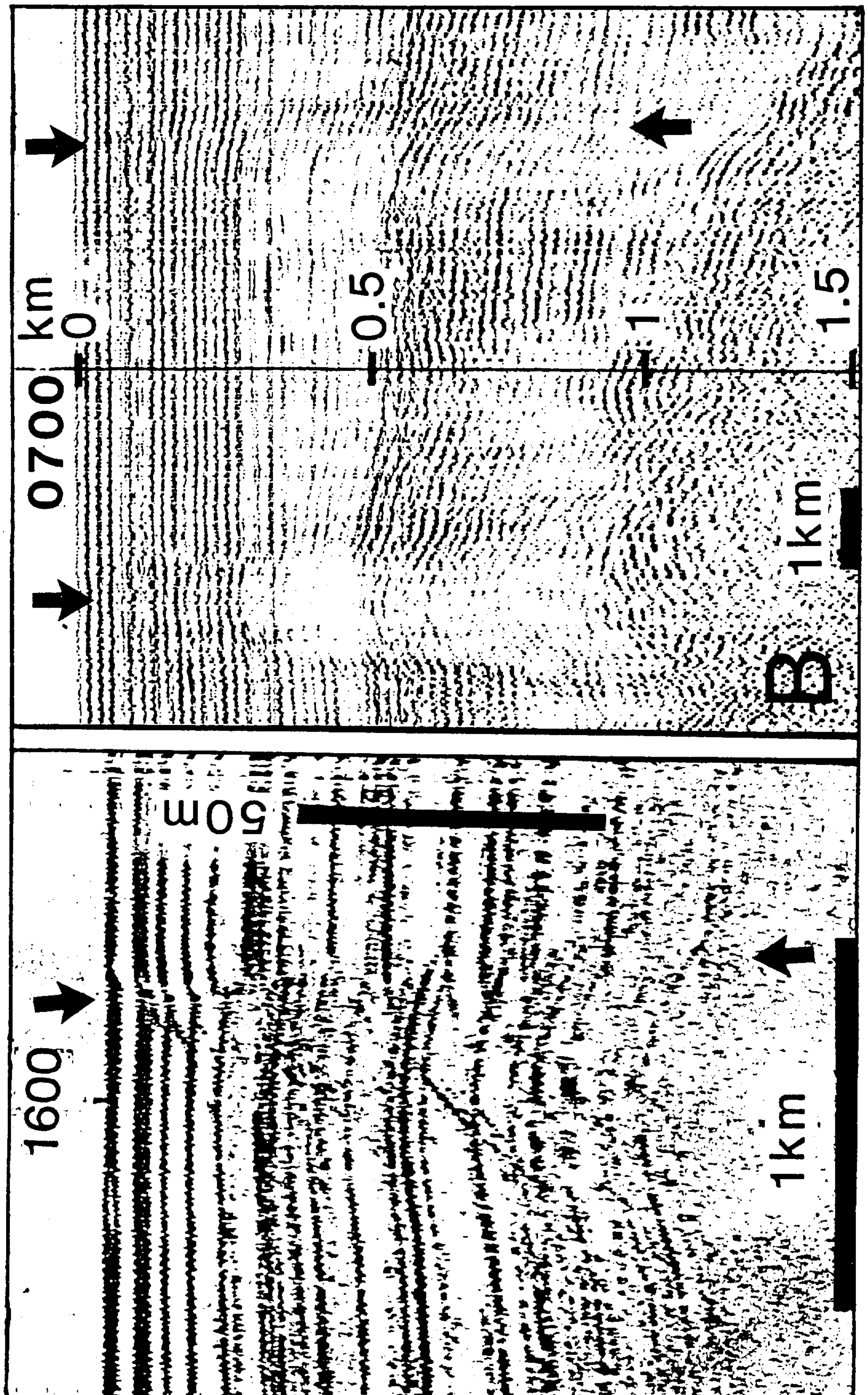


Figure 14

Figure 15 Distribution of shallow faults in the central part of GME, based on 3.5 kHz data. Different fault types are indicated as follows: (a) dip direction uncertain, tick on downthrow side; (b) cylindrical; (c) reverse; (d) normal; (e) sense of throw uncertain; (f) dip direction and sense of throw uncertain. Contours are depth to basement. Modified from Williams (1987).

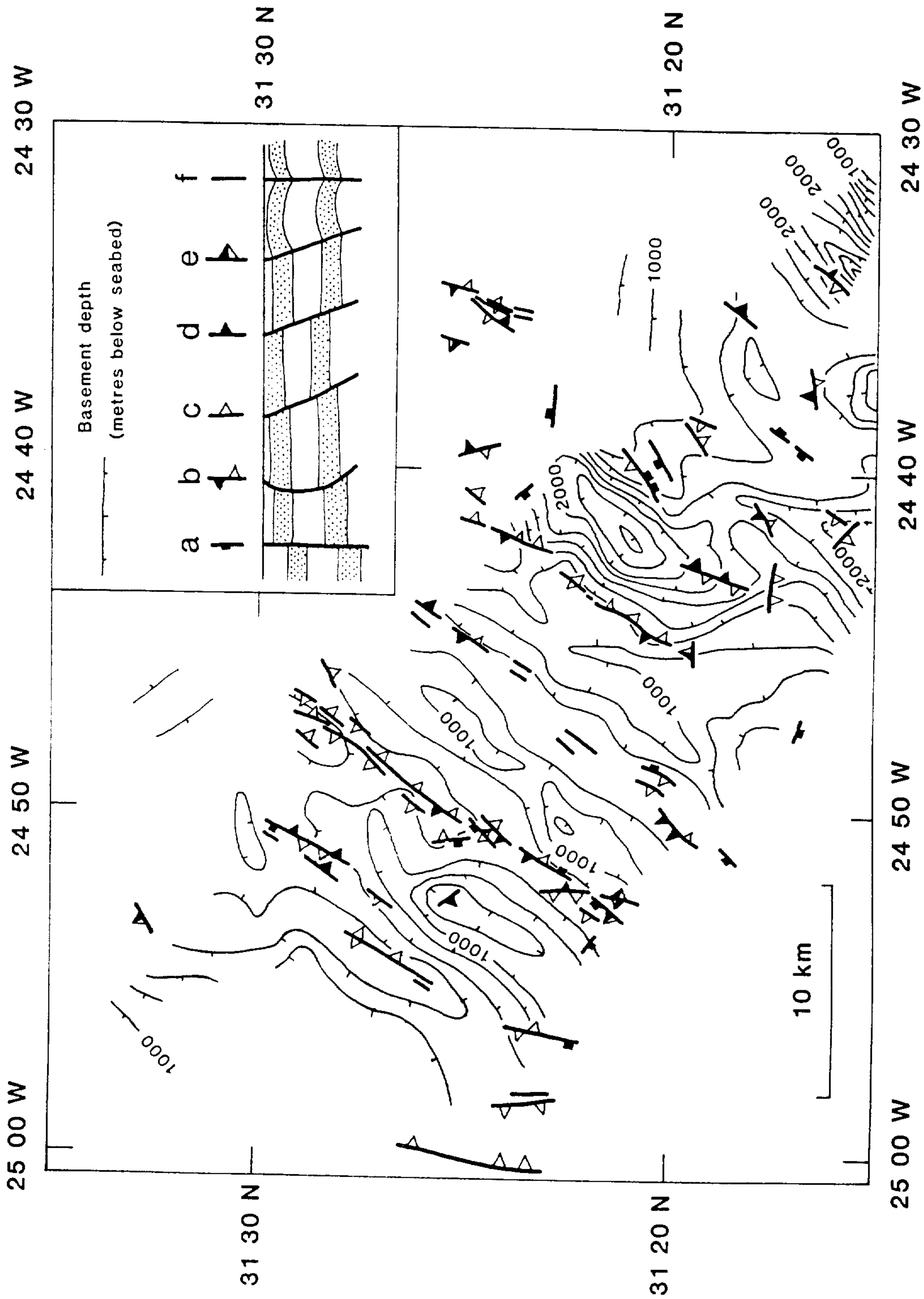

Basement depth
(metres below seabed)
a
b
c
d
e
f
24 30 W
24 40 W
24 50 W
25 00 W
31 30 N
31 20 N
1000
2000
10 km

Figure 15

Figure 16 a) Density of deep faults in GME, based on air and water gun data.
b) Density of shallow faults in GME, based on 3.5 kHz data. Shading indicates average number of faults per line kilometre in each square. Blank areas and squares contain no data; note that the lowest level of non-blank shading indicates no faults. The procedure normalises the fault density as well as possible, but it should be noted that more or fewer faults per line kilometre can be distinguished depending on sound source, recording and processing, and weather conditions.

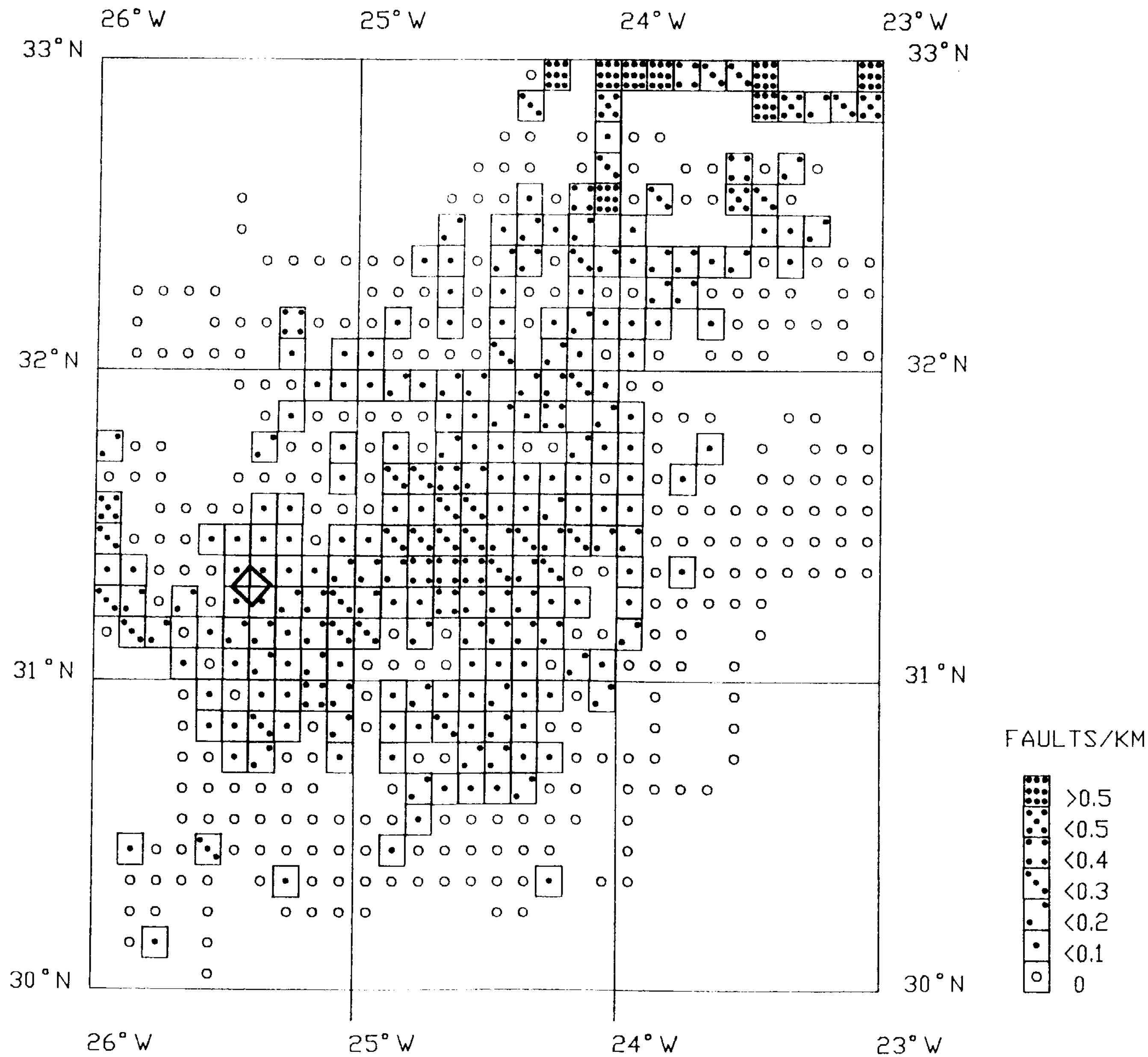


Figure 16a

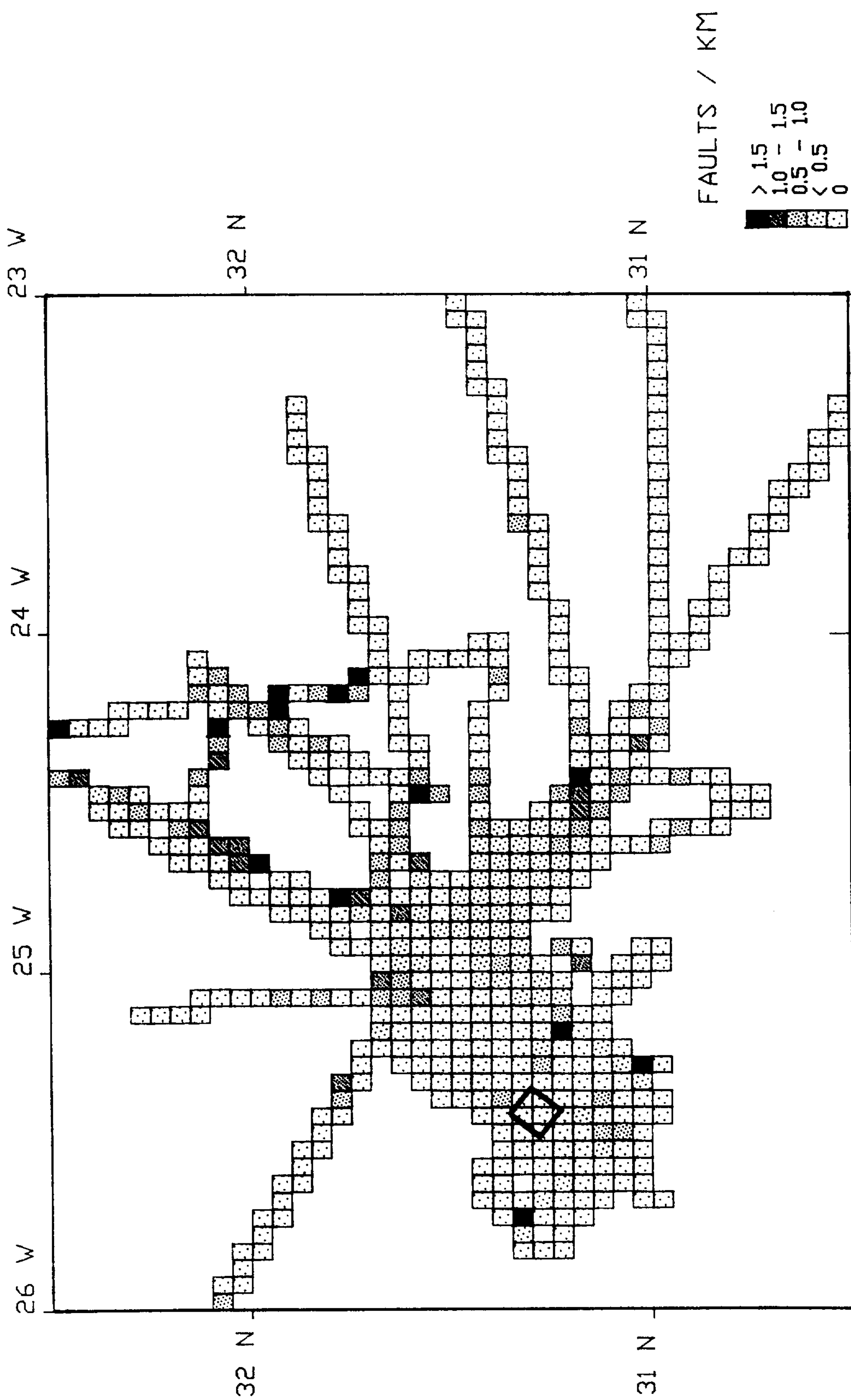


Figure 16b

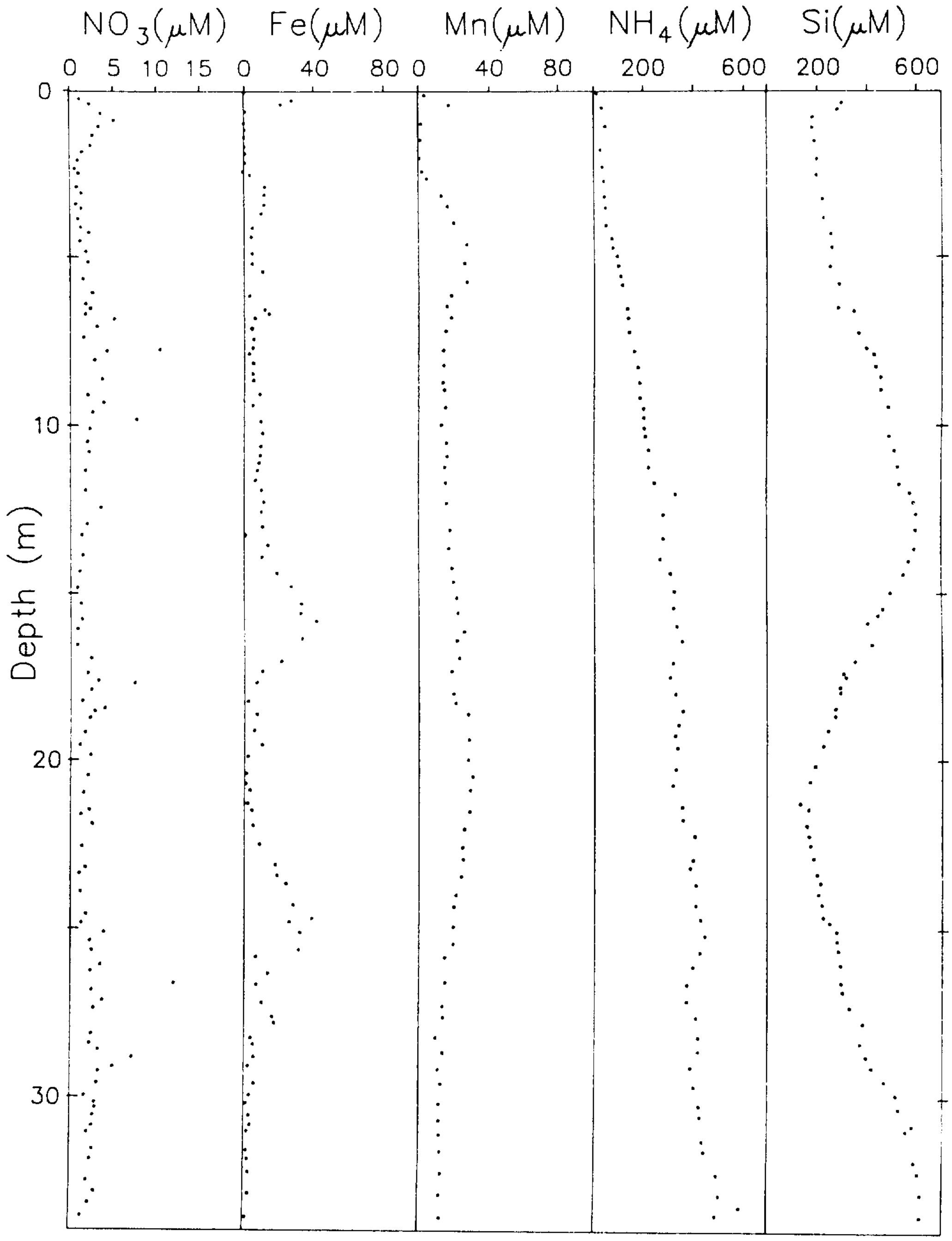


Figure 17

Figure 17 Profiles of concentrations (in micromoles) of dissolved nitrate, iron, manganese, ammonia, and silica from the porewaters of ESOPE core 10 in the 10 km box.

TABLE 1

Summary of main data types collected at GME

Year	Cruise	Country	GLORIA sidescan km^2	Deep-tow sidescan km^2	Deep-tow seismic km	2-12kHz sounding km	Lowfreq. seismic km	Magnetics km	Cores[a]	Photo runs	Heatflow lines	Insitu pore press.
80	Tydeman	Neth.	-	-	-	4,050	3,500	3,500	17	-	-	-
81	Discovery 118	UK	-	-	2	1,450	450	600	4	1	1	-
81	Farnella 3/81	UK	50,000	-	-	1,000	1,000	1,000	-	-	-	-
82	Discovery 126	UK	-	-	13	1,200	-	-	3	1	3	-
82	Tyro	Neth.	-	-	-	4,200	3,250	3,250	28	3	-	-
83	Discovery 134	UK	-	-	50	500	-	-	4	2	-	-
84	Discovery 144	UK	20,000	-	40	750	650	500	5	-	2	-
84	Discovery 153	UK	-	-	-	1,800	180	420	4	4	-	6
85	M. Dufresne	France	-	-	15	1,600	210	-	10[b]	-	-	-
85	C. Darwin 9B	UK	-	-	-	4,000	800	550	3	3	4	5
86	Tyro	Neth.	-	-	-	5,500	5,000	-	39	-	-	-
86	Discovery 163	UK	-	200	-	1,850	200	160	3	1	-	4

Notes:

a) Includes standard piston cores, pipe cores and box cores.

b) Includes 5 "long" piston cores.

TABLE 2

Summary of physical and geotechnical properties at GME

Unit	Depth m	Thickness m	$CaCO_3$ %	Org. Carbon %	Water % wet	Grainsize[a] 10^{-6} m	Permeability[b] cm s^{-1}	Shear strength kPa
10 km box[c]								
	range	mean sd	mean sd	mean sd	mean sd	mean sd	mean±sd or range	mean sd
Pelagics[d]								
1P	1.0-17.3	0.1 0.1	45 21	0.31 0.15	53 7	3.8 0.3	( )[e]	17.4 9.0
2P	17.3-22.7	0.1 0.1	40 22	0.17 0.11	45 4	3.4 0.5	($1x10^{-7}$[f] – $3x10^{-6}$[g])	13.1 6.8
3P	22.7-27.1	0.1 0.1	58 -	0.14 -	57 -	4.0 -	( )	12.9 5.0
4P	27.1-33.8	0.1 0.1	44 27	0.13 0.02	44 4	3.2 0.7	( )	31.4 9.9
Turbidites[d]								
1T	1.0-17.3	2.7 1.5	52 41	0.53 0.29	56 6	3.5 0.4	$1.5x10^{-5} \pm 3.1x10^{-5}$ e	11.0 5.6
2T	17.3-22.7	0.6 0.3	65 16	0.22 0.32	44 5	3.6 1.3	$3.0x10^{-4}$ – $1.0x10^{-3}$ e	16.9 7.6
3T	22.7-27.1	2.1 0.5	59 4	0.12 0.02	52 3	3.5 0.5	$1.5x10^{-6}$ – $2.5x10^{-6}$ e	24.6 6.7
4T	27.1-33.8	0.8 0.5	62 18	0.7 0.70	44 4	3.3 0.4	$1.6x10^{-6} \pm 1.6x10^{-5}$ e	35.7 12.6
Rest of GME								
		range	range	range	range	range	range	range
Pelagics		0.05-0.2	5-90	0.0-0.2	49-56	2.0-4.5	$1x10^{-7}$[f] – $3x10^{-6}$[g]	0 - 50[h]
Turbidite fines		0.0-4.3	35-90	0.1-1.0	35-70	3.0-16	c. 10^{-6}	0 - 55[h]
Turbidite bases		0.0-0.5	30-90	0.0-0.3	36-45	2.5->200	10^{-4} – 10^{-5}	0 - 55[h]

Notes

Mean and standard deviation are given where sufficient suitable data exist; elsewhere we give a range.

a) Nominal grain diameter. Grainsize is measured in terms of the median intra-sample diameter. "Mean" is the mean of many samples within each unit. "sd is the inter-sample standard deviation, not the intra-sample one.

b) Open burrows have been found in some sediments at GME, and it is estimated that where they occur the bulk permeability may be increased by up to two orders of magnitude above the values shown here.

c) Based on ESOPE cores 6 and 10 (10 km box).

d) Sediments in 10 km box are divided into four units, each containing several pelagic and turbiditic intervals.

e) Based on ESOPE core 6 (10 km box) below 12 m; extrapolated from Discovery core 10695 above 12 m.

f) Calcareous clay.

g) Foram nanno ooze.

h) Shear strength increases with depth; ranges given are for 0.35 m interval.

See Figure 11(1) for more detailed picture of variations of physical properties with depth.

TABLE 3: GME Site Model

Water Depth: 5440 ± 10m

Position: 31°17'N, 25°24'W

Vertical and horizontal structure

To a first approximation, the uppermost 350 m of the lithological section is thought to comrise a simple alternation of two types of sediment (pelagic, P and turbiditic, T), each with constant properties, except that there is a sandy turbidite, S, at a depth of 19-20 m. A more complicated but slightly more realistic model would use four different sets of turbidite properties, depending on depth (see Table 2). There is no significant variation in the properties of pelagic sediments with depth. Our simplified model therefore has the following structure:

T	Seabed	Slope: < 1:1000
P		
T		
:		
T		
P		
S	19-20 m	Slope: 0 to 1°
P		
T		
:		
T		
P	350 m	Slope: 0 to 10°

Below this the lithology is very uncertain, but our best estimate is that it consists of a continuous unit whose properties are similar to those of the pelagites (P), extending down to basaltic basement at a depth of about 1000 m below seabed. Basement slopes from 0 to at least 40°.

This lithology is laterally continuous over distances of 20-30 km. Abyssal hills covered in pelagic sediment may outcrop within 5 km of a potential disposal area, and basaltic basement may outcrop within 15 km.

Lithology

The physical properties of the units are given in the table below.

Unit	Thickness		CaCo₂ content		Org. Carbon content		Water content		Grainsize[a]		Permeability[b]	Shear strength
	m		m		%	%	% wet		10^{-6} m		cm s^{-1}	kPa
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	(mean ± sd) or range	range
Pelagics P	0.1	0.1	45	21	0.31	0.15	53	7	3.8	0.3	$1.0x10^{-7}$ to $3.0x10^{-6}$	0 to 50[c]
Turbidites T	1.4	1.2	57	11	0.43	0.42	50	6	3.5	0.6	$1.5x10^{-5}$ ± $2.4x10^{-5}$	0 to 50[c]
Turbidite S	1.1	-	80	4	0.08	0.02	43	2	4.9	2.6	$3.0x10^{-4}$ to $1.0x10^{-3}$	4 to 18

Notes:

a) Nominal grain diameter. Grainsize is measured in terms of the median intra-sample diameter. "Mean" is the mean of many samples within each unit. "sd" is the inter-sample standard deviation, not the intra-sample one.

b) Open burrows have been found in some sediments at GME, and it is estimated that where they occur the bulk permeability may be increased by up to two orders of magnitude above the values shown here.

c) Shear strength increases with depth; ranges given are for 0-35 m interval.

RADIOACTIVE WASTE MANAGEMENT

RESEARCH PROGRAMME 1979/87

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Report Title: The Geology of the Madeira Abyssal Plain: further studies relevant to its suitability for radioactive waste disposal.

Author/Affiliations etc.

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Date of Submission to DOE: 30 March 1987

Period covered by report: 1979 - 1987

Abstract (100-200 words as desired) This report summarises work done in the UK and internationally since 1979 on site assessment aspects of the oceanic radioactive waste disposal feasibility study. Site selection guidelines were drawn up and are summarised: they stress the importance of geological stability and good barrier properties. The history of the selection and investigation of various study sites in the north Atlantic is briefly summarised leading to the selection of the Great Meteor East area in the Madeira Abyssal Plain for concentrated further study. The detailed geological characteristics of GME are then described with particular reference to the "10 km box" where recent work has been focussed. The results of this geological characterisation are then discussed in the light of the site assessment guidelines. It is concluded that within the confines of present knowledge the 10 km box fulfils most of the geological requirements for a radioactive waste repository, except that it contains several sandy layers at depth. It is thought that similar areas without such sands probably exist to the north of the 10 km box. Finally, unresolved issues are discussed and the requirements for further work are given.

Keywords (suggested maximum of five to be taken from DOE standard keyword list provided):

299 - DoE sponsored research	105 - Site survey
94 - Disposal under deep ocean bed	110 - Geology
104 - Site selection	225 - Ocean sites

This work has been commissioned by 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.