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ROCKALL CONTINENTAL MARGIN PROJECT

FINAL GEOLOGICAL REPORT
(5 volumes)

TECHNICAL REPORT WB/95/11C

M S Stoker and K Hitchen

Geographical index:
Rockall Continental Margin - Hebrides Shelf, Rockall Trough, Rockall and George Bligh banks, Rosemary Bank and Anton Dohrn seamounts, Hatton-Rockall Basin, Hatton Bank.

Subject index:
Geological Framework and Prospectivity (Vol. 1), Borehole Drilling Programme (Vol. 2), Shallow Sampling Programme (Vol. 3), Organic Geochemistry (Vol. 4), Petrography and Rock Geochemistry, Interpreted Seismic Lines, Gravity and Magnetic Maps (Vol. 5).

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EXECUTIVE SUMMARY

The Rockall Continental Margin Project was a 3-year research programme, undertaken between April 1992 and March 1995, designed to investigate the geology and resource potential of part of the frontier area west of Scotland. The programme was funded by a consortium comprising the British Geological Survey (BGS) and 8 exploration companies - BP, British Gas, Conoco, EE Caledonia, Elf, Enterprise, Esso and Mobil. The study has focused on the central and northern Rockall Trough, although several long transect lines were run across the Rockall Plateau and into the Iceland Basin to provide a margin-wide assessment of the geological framework. Over the duration of the project, multichannel seismic, gravity, magnetic and bathymetry data, together with boreholes and shallow-sample information were acquired by the consortium. These data form the basis of this 5-volume report. A description of the geology and prospectivity of the surveyed area comprises volume 1, whilst the data on which the geological interpretation is based, including biostratigraphy, petrology and geochemistry of the boreholes and shallow samples, are presented in volumes 2 to 5.

The widespread distribution of Upper Cretaceous to lower Palaeogene volcanic rocks continues to hinder our understanding of the geological framework of the Rockall Continental Margin. Whilst it has been proved that Lower Proterozoic gneisses form continental basement on Rockall Bank, and are therefore part of the Islay structural terrane, the pre-Cretaceous supracrustal infill of the Rockall Trough and Hatton-Rockall Basin remains conjectural. Reworked palynomorphs of Carboniferous, Jurassic and Early Cretaceous age have been identified in lower Palaeogene sediments recovered on the western margin of the Rockall Trough, but their provenance is uncertain.

The present morphological expression of the Rockall Continental Margin largely reflects late Mesozoic-Cenozoic extensional tectonism associated with North Atlantic sea-floor spreading. In mid-Cretaceous time, the Rockall Trough was the focus of extreme crustal attenuation associated with abortive continental breakup along the axis of the basin. The growth of the axial Rosemary Bank and Anton Dohrn seamounts may have been initiated during this phase of crustal thinning. When the axis of spreading shifted westwards, the margin was affected by extensive volcanism concomitant with the split between Rockall Plateau and Greenland, that formed the North-East Atlantic Ocean. In the study area, this volcanism is manifested by the areally extensive, Paleocene to lower Eocene lavas and sills.

The continental margin subsequently underwent regional differential subsidence punctuated by intermittent tectonism. This is reflected in the post-volcanic, sedimentary succession for which, for the first time, a unified seismic stratigraphy linking the Rockall Trough and Hatton-Rockall Basin has been established. Three main post-volcanic seismic-stratigraphical sequences have been defined; upper Paleocene to lower upper Eocene, upper Eocene to middle Miocene, and middle Miocene to Holocene. Stratigraphical control and inter-basin correlation are based on a database of BGS boreholes and shallow samples, DSDP boreholes and well 164/25-2 (courtesy of BP).

Late Paleocene to early late Eocene sedimentation occurred amidst continuing tectonic instability across the margin. This has been well demonstrated on the edge of Rockall Bank where a prograding shelf-margin sequence penetrated by borehole 94/3 preserves a record of fluctuating alluvial to shallow-marine sedimentation, interrupted by phases of uplift, erosion and sporadic volcanism. Late Eocene subsidence in the Rockall Trough and Hatton-Rockall Basin provided the downwarped, basin-margin unconformity onto which upper Eocene to middle Miocene sediments onlap. This is a major sequence boundary and essentially marks the onset of deep-water, current-controlled sedimentation in both basins. In the Rockall Trough, the main buildup of the Feni Ridge sediment drift occurred during this interval.

A phase of mid-Miocene tectonism resulted in the initiation of the Barra Fan, on the eastern margin of the Rockall Trough, and may also have instigated a change in regional palaeoceanography culminating in the development of a widespread unconformity across the Rockall Trough and Hatton-Rockall Basin. On the Hebrides Slope, middle Miocene to Holocene sediments form a thick, prograding, clastic wedge. A thinner package of deep-water sediments is preserved in the Rockall Trough and, on the western margin of the trough, an erosional regime has prevailed throughout this interval. This has resulted in a marked asymmetry to the depositional sequence architecture across the Rockall Trough. The Hatton-Rockall Basin was similarly dominated by deep-water processes but, in contrast to the Rockall Trough, a much thicker sedimentary succession has accumulated in this basin.

In terms of prospectivity, circumstantial evidence suggests that Carboniferous, Mesozoic or lower Tertiary source rocks may be present in the Rockall Trough, but no definite thermogenic source has been proved. Potential hydrocarbon indicators include gas blanking, fluid-migration structures and locally high methane concentrations in surface sediments. The identification of tilted fault blocks on the western margin of the Rockall Trough, in both UK and Irish waters, illustrates one possible hydrocarbon-trapping mechanism that may be applicable to this area. Other potential trapping styles include fault-scarp fans and lowstand slope-apron or basin-floor fans.

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Responsibilities of individual authors during the production of this report have been as follows:

M S Stoker:	Introduction, stratigraphy, summary and conclusions, and Appendices 1 and 2 (description and interpretation of boreholes and shallow cores, and reformatting of biostratigraphy reports).
K Hitchen:	Structure, volcanicity, prospectivity, (contribution to summary and conclusions), and Appendix 5.

The compilation of the report was undertaken jointly by M S Stoker and K Hitchen; editorial control and constructive comment was provided by D Evans. Specialist contributors, acknowledged where appropriate in the report include:

N M Hine:	Biostratigraphy: Calcareous nannofossils (Appendices 1 and 2)
C D Hughes:	Organic Geochemistry (Appendix 3)
A C Morton:	Petrology/rock geochemistry (Appendix 4)
R A Nicholson:	Organic geochemistry (Appendix 3)
J B Riding:	Biostratigraphy: Dinoflagellate cysts (Appendices 1 and 2)
B P Vickers:	Organic Geochemistry (Appendix 3)
I P Wilkinson:	Biostratigraphy: Calcareous microfauna (Appendices 1 and 2)
M A Woods:	Biostratigraphy: Macrofauna (Appendix 2)

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BP Exploration is gratefully thanked for permission to use unreleased data for the Cenozoic section in well 164/25-2, together with a line-drawing interpretation of seismic line BP85-956.

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VOLUME 1
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ROCKALL CONTINENTAL MARGIN PROJECT
FINAL GEOLOGICAL REPORT

TECHNICAL REPORT WB/95/11C
VOLUME 1
GEOLOGICAL FRAMEWORK AND PROSPECTIVITY

M S Stoker and K Hitchen

Geographical index:
Rockall Continental Margin - Hebrides Shelf, Rockall Trough, Rockall and George Bligh banks, Rosemary Bank and Anton Dohrn seamounts, Hatton-Rockall Basin, Hatton Bank.

Subject index:
Structure, Stratigraphy, Volcanicity, Prospectivity

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CONTENTS

Cover photograph: Two sections of core from an interbedded sequence of upper Paleocene-lower Eocene clastic sediments and fine-grained, basaltic, pillow lavas recovered in borehole 94/3. Three separate pillow lavas were penetrated by this borehole; see Volume 2, Appendix 1, Fig. 10 for stratigraphical details.

The left-hand section (207.87-207.99m) illustrates the contact between the uppermost pillow lava and overlying, shelly, marine sandstones, whilst the right-hand section (208.48-208.62m) shows the contact between the middle pillow lava and overlying, shelly, marine mudstone. In both sections, the outer part of the pillow lavas is cracked, locally fragmented, and partially altered to paler coloured smectite or chlorite. The infiltration of sediment into the cracks suggests that they may represent cooling cracks. The mottled texture of the mudstone (upper right-hand section) may be due, in part, to the decomposition of the pale coloured, altered, lava fragments enclosed within the sediment.

FIGURES AND TABLES

** Large fold-out figures in plastic wallets at back of report*

1. INTRODUCTION

This report presents the results of the Rockall Continental Margin Project, a 3-year research programme designed to investigate the geology and resource potential of the frontier area west of Scotland. The project was undertaken between April 1992 and March 1995, and was funded by a consortium of 8 exploration companies and the British Geological Survey (BGS).

The continental margin west of Scotland is an area of complex bathymetry (Fig. 1.1) flanking the oceanic Iceland Basin. Morphologically, this relatively shallow platform area comprises an inner margin, the Hebrides Shelf, and an outer margin, the Rockall Plateau, separated by the deep-water basin of the Rockall Trough. The area is termed, collectively, the Rockall Continental Margin. The continent-ocean boundary is located on the western flank of the Rockall Plateau.

The main area of study is the central and northern Rockall Trough, with limits predominantly between 56°40'N in the south and 59°00'N in the north, and from 9°30'W in the east to 14°00'W in the west (Fig. 1.1). The eastern limit corresponds approximately to the limit of previous surveys by the BGS in their offshore mapping programme (Fannin, 1989); the southern limit is close to the United Kingdom (UK)-Republic of Ireland Median Line. Farther west, the geology of the Hatton-Rockall Basin is also described from the results of several long transect lines, which run both across and along the axis of the basin. Although some of these lines extended into the Iceland Basin as far as 19°45'W and 60°30'N, the geology of the continent-ocean boundary is beyond the scope of this report, but has been summarised in earlier reports by Stoker *et al.* (1990) and Stoker and Gillespie (1994). However, information from outside the report area is included where appropriate, as is reference to previous research within the study area.

1.1. History of the Rockall Continental Margin Project

The project has its origins in 1990 following a BGS desk study which reviewed the existing data on the Rockall Continental Margin and made recommendations for a regional survey programme (Stoker *et al.*, 1990). From November 1990 to March 1991, a series of presentations was given by the BGS to interested oil companies with a view to setting-up a consortium to finance a reconnaissance mapping programme for the entire western UK continental margin. Although such a programme was originally conceived by the BGS as a 10-year project, oil companies favoured a shorter duration of 3 years, tailored to meet a variety of geophysical and geological objectives in specified areas of interest. With this in mind, all interested parties met at the BGS in Edinburgh in March 1991 to discuss proposals deemed to be achievable within a 3-year period. Through discussion, the basic aims and objectives of the project (see below) were established, focusing on the area outlined above. These were ultimately accepted by the BGS together with BP, British Gas, Conoco, EE Caledonia, Elf, Enterprise, Esso and Mobil who eventually formed the consortium group. The inaugral Steering Committee meeting was held in December 1991 at which the programme of work for the period 1992-1994 inclusive and a £3.052 million budget were both agreed. Minor amendments were made to the programme at subsequent Steering Committee meetings.

1.1.1. Aims and objectives

One of the biggest problems in the exploration of the Rockall Continental Margin is the widespread distribution of Upper Mesozoic to lower Palaeogene volcanic rocks which, on seismic profiles, largely obscure the underlying geology, thereby restricting any assessment of the resource potential of the margin. However, the available evidence suggested that the volcanic sequence may be thin or absent south of 57°30'N on the western margin of the Rockall Trough, where a block-faulted basin-margin structure had been identified (Joppen and White, 1990). This potentially significant 'window area' offered an excellent opportunity to investigate the basin-margin framework. It was also recognised that until the regional extent of the volcanics was established, the scale of the 'basalt problem' would remain unknown.

The primary aim of the project was to undertake a 3-year investigation of the main study area using an integrated geophysical and geological approach. The main objectives were:

1. To try to establish a structural and stratigraphical framework for the area.

2. To assess the regional extent of the volcanic rocks.

To achieve these objectives, the main study area was divided into two sub-areas, A and B (Fig. 1.1); a detailed basin-margin study was planned for sub-area A (utilising high-resolution and multichannel seismic data), whilst sub-area B was surveyed in less detail (high-resolution seismic data) designed to identify any further 'volcanic windows' within the Rockall Trough. Additionally, two regional transects (high-resolution and multichannel seismic data) were also proposed in order to provide a broad tectonic framework across the entire margin. Gravity, magnetic and bathymetric data were also to be acquired from these surveys. Subsequently, a profile along the axis of the Hatton-Rockall Basin was added to the programme (see below). Geological calibration of the seismic data was to be achieved by shallow coring (to a maximum sub-sea-bed depth of 6m) and boreholes (to a maximum of 300m).

1.1.2. The work programme

The details of the geophysical grid and transect lines are shown in Figures 1.2 and 1.3. Figure 1.2 also includes two profiles (multichannel seismics, gravity and magnetics) acquired from Mobil on behalf of the consortium.

A suite of high-resolution seismic reflection, gravity, magnetic and bathymetry data were collected over the entire survey area (excepting the axial transect along the Hatton-Rockall Basin) by the BGS in summer 1992. This represents a total of 6311 line-kilometres of survey data, comprising 54 lines. Airgun (2 to 4 seconds two-way time (s TWT)), gravity, magnetic and bathymetry data were acquired on all these lines and additional high-resolution seismic data, predominantly sparker (0.8s TWT), were acquired concurrently on 42 lines. Gravity, magnetic and bathymetry data were also collected on an opportunistic basis as two lines (36, 37) on transit between the two regional transects in the Iceland Basin. These totalled a further 216km. The details of the equipment operated are presented elsewhere (Brett and Dobinson, 1992).

In summer 1993, 1079 line-kilometres of deeper seismic data (10s TWT) were acquired by Digicon on behalf of the consortium from the south-western part (sub-area A) of the main survey area, together with 676 line-kilometres of very deep reflection seismics (18s TWT) run part-way along the transects, as far as the axis of the Hatton-Rockall Basin in the west, and as far east as to intersect with the Mobil lines. The southern transect was continued across the Rockall Trough, into the Irish sector, as the BIRPS WESTLINE. Details of the equipment operated and recording parameters have been summarised by Bulat (1993). Gravity data were also recorded during the survey, and operational details are summarised by Wallis (1993).

The distribution of the geological sample sites is shown in Figure 1.4. The shallow sampling programme was undertaken by the BGS between April and June 1994, and collected 176 gravity cores, 22 vibrocores and 52 rockdrill cores, with a maximum sub-sea-bed penetration of 6m. Forty-eight of the core sites were chosen specifically to gather stratigraphical information across a wide part of the main study area, whilst another 170 sites were picked for organic geochemical sampling. The stratigraphical sites are prefixed by the letter 'S', whereas the geochemical sites are designated by 'G' (Fig. 1.4). A number of the 'S' sites were occupied several times (see Appendix 2, Table 1).

In September 1994, a total of 7 boreholes were drilled by the BGS on the Rockall and George Bligh banks, and on the western margin of the Rockall Trough. The total sediment and rock cored was 432.45m, with an overall recovery of 145.28m (33.6%). The deepest (sub-sea bed) borehole was 94/3 which penetrated to 209.65m. All boreholes successfully reached their geological targets. The recovered material was subsampled for biostratigraphical, petrological and organic geochemical analysis.

1.1.3. Reporting

Information on work undertaken, and data acquired, by the BGS has been disseminated to the consortium members in three main ways:

1. Regular 6-monthly Steering Committee meetings.

2. Occasional workshops.

3. Interim geological and geophysical reports, including post-cruise reports.

A full and separate listing of all of the reports generated by the Rockall Continental Margin Project is included after the main reference list at the back of this volume. Although the specialist biostratigraphical, petrological and geochemical reports have not been routinely circulated to consortium members, these data are summarised in this, the final geological report.

1.2. Report layout

This final report consists of 5 volumes. A description of the geology and prospectivity comprise volume 1, whilst the data on which the geological interpretation is based are presented in volumes 2 to 5. The contents of each volume are summarised below:

Volume 1 - *Geological Framework and Prospectivity* - Description of the structure, stratigraphy, volcanicity and prospectivity.

Volume 2: Appendix 1 - *Borehole Drilling Programme 1994* - Compilation of all of the borehole data collected during the project, together with the seismic-stratigraphical setting of each borehole and a summary of the biostratigraphical information.

Volume 3: Appendix 2 - *Shallow Sampling Programme 1994: Stratigraphical Sites* - Compilation of all the shallow core (stratigraphical 'S' sites) collected during the project, together with their seismic-stratigraphical setting and a summary of the biostratigraphical data.

Volume 4 Appendix 3 - *Organic Geochemistry* - Compilation of the analytical results from the shallow cores (geochemical 'G' sites) collected solely for geochemical study, and from selected intervals from the boreholes.

Volume 5: Appendix 4 - *Petrography and Geochemistry of Igneous and Metamorphic rocks* - Compilation of the analysis of igneous and metamorphic rocks collected in the

1994 borehole and shallow sampling cruises.

Volume 5: Appendix 5 - *Seismic Lines and Gravity and Magnetic Maps* - Examples of interpreted multichannel seismic reflection profiles from eastern flank of Rockall Bank, together with compilations of the gravity and magnetic data for the main study area.

Appendices 1 and 2 largely supplement the stratigraphy chapter (Chapter 3, this volume); the rock descriptions summarised in the stratigraphy text are given in much greater detail in the appendices. Additionally, whilst several examples of the character of the main seismic-stratigraphical sequences are included in the stratigraphy section, numerous further examples can be found in Appendices 1 and 2. The geochemical data in Appendix 3 supplement the prospectivity chapter (Chapter 5, this volume). In Appendix 4, the emphasis is mainly on the igneous rocks and, as such, these data largely supplement the volcanicity chapter (Chapter 4, this volume). However, some isotopic age dating is also reported from the metamorphic rocks and provides extra data for the stratigraphical framework.

These 5 volumes are referred to collectively by the technical report number WB/95/11C, although the specialist organic geochemistry and petrography reports also have their own series listing from their respective units, namely the analytical geochemistry unit and biostratigraphy and sedimentology unit. However, within the context of this report, the bibliographic reference for each volume is given on the respective title pages. The overall bibliographic reference is as follows:

Stoker, M S, and Hitchen, K. 1995. The Rockall Continental Margin Project: Final Geological Report. *British Geological Survey Technical Report* WB/95/11C, (5 Volumes).

2. STRUCTURE

Comments on the structure are based on the high-resolution and multichannel seismic, gravity and magnetic data acquired for this study, and previously published information. Figure 1 comprises a synoptic map of the principal structural features of the Rockall Trough and also locates most of the illustrative seismic panels of later figures. Gravity and magnetic maps, and two orthogonal multichannel seismic lines from the 'grid' area across the eastern flank of Rockall Bank (D2 and D15), are included in Appendix 5.

2.1. Regional setting and geological summary

The Rockall Continental Margin forms part of the southern portion of the North-West European plate. It is bounded by the Iceland-Faeroe fracture zone to the north and the Charlie Gibbs fracture zone to the south and is regarded as a volcanic, rifted, passive continental margin. Although the continent-ocean boundary is situated along the western margin of Rockall Plateau, there is a wide variation in crustal thickness across the margin.

At the end of the Variscan Orogeny, Britain was situated in the centre of the Pangaean supercontinent. As the compressional forces which had built Pangaea waned, they were replaced by a tensional stress regime which caused the development of intra-cratonic basins and rifts within the supercontinent. The most prominent of these was the southward-propagating Norwegian-Greenland Sea rift. Some authors suggest that this rift may have reached as far south as the Rockall Trough (Ziegler, 1988) where it was accumulating continental-style clastic sediments as early as Late Carboniferous or Early Permian. Evidence for this is largely circumstantial, based on continental refits, crustal modelling and interpretation of interval velocity structure derived from seismic refraction experiments. At this time there was also widespread volcanism in the UK, the products of which are especially apparent in central Scotland.

A tensional stress regime associated with North Atlantic sea-floor spreading is generally assumed to have prevailed across the Rockall Continental Margin throughout most of the Mesozoic and Cenozoic. As the North Atlantic Ocean propagated northwards, the Rockall

Trough may have been the site of a 'proto North Atlantic Ocean' where the transition from continental rifting to oceanic crust was halted before completion. This probably occurred during the mid-Cretaceous. Hence the Rockall Trough and contiguous Faeroe-Shetland Basin may represent the location of an aborted ocean spreading centre. In the Rockall Trough there are no indicators of true oceanic crust, such as dipping reflectors series or magnetic stripes.

During the early Palaeogene, the margin was subjected to further stretching and rifting, culminating in the development of true oceanic crust to the west of the study area between Greenland and Rockall Plateau. Together with the impingement of the Iceland Plume on the base of the lithosphere at about 62Ma (White, 1993), this caused widespread and massive intrusive and extrusive magmatism across the whole area. A significant proportion of the available melt may have underplated the base of the crust beneath the Hebrides Shelf and Rockall Plateau causing regional uplift at this time.

During most of the Cenozoic, the Rockall Continental Margin has undergone regional subsidence, albeit punctuated by intermittent tectonism. This may have been caused by wrench movements on major and subsidiary transform fractures in response to episodic reorganisation of sea-floor spreading axes, possibly combined with compressive stresses associated with the Pyrenean and Alpine orogenies (Ziegler, 1988, 1990; Boldreel and Andersen, 1993; Knott *et al.* 1993).

2.2. Crustal structure of Rockall Trough

The nature and age of the crust beneath the Rockall Trough has been debated since the mid-1960s when attempts were made to refit the present-day, shallow-water banks (excluding Rosemary Bank, Anton Dohrn and Hebrides Terrace) back into their original, pre-drift position. The debate had concentrated on two main questions: (1) Was true oceanic crust developed in the Rockall Trough? (2) When was the main rifting episode?

In 1984 four papers were published which supported, to a greater or lesser extent, the presence of oceanic crust beneath the Rockall Trough (Bott and Smith, 1984; Hanisch, 1984; Haszeldine, 1984; Price and Rattey, 1984). Most of these authors visualised a thin strip of oceanic crust extending northwards from the southern end of the Rockall Trough to the Faeroe-Shetland Basin and offset by schematically located transfer faults. Subsequently Megson (1987) suggested that only a small part of the trough was underlain by oceanic crust and that stretched continental crust was predominant.

Roberts *et al.* (1988), using seismic refraction and wide-angle reflection data, deduced that continental crust, albeit highly stretched and asymmetrically thinned, underlay the Rockall Trough. Subsequent authors have generally agreed with this view (Joppen and White, 1990; Keser Neish, 1993; Makris *et al.* 1991; Shannon *et al.* 1994) (Figs. 2.2 and 2.3). Although there is no absolute agreement, most thickness estimates for the two-layered metamorphic basement of the crust lie in the range 8-13km. However the total range of estimates is 6-17km. Gravity modelling along Transect A (Edwards and Hitchen, 1994) suggests a minimum crustal thickness in the range 7-10km near the centre of the Rockall Trough. Interpretations differ because none of the recently published data are coincident (Fig. 2.2) and, in reality, the crustal thickness will vary both along and across the trough. Marked thickness variations are likely to occur over short distances, especially where transfer faults have offset the margins of the trough. In a direction axial to the Rockall Trough, and from data totally in Irish waters, Shannon *et al.* (1994) show that the crust also thins in a step-like manner south-westwards (Fig. 2.4).

Estimates of stretching from both crustal thinning and from subsidence indicate that the Rockall Trough has undergone extensive rifting with $\beta=6$ or more (Joppen and White, 1990). However Shannon *et al.* (1994) suggest a non-uniform stretching model for the trough which requires a mid-crustal detachment with unequal β factors above and below, the upper crust having stretched with $\beta=8\text{-}10$, and the lower crust with $\beta=2\text{-}3$. The detachment is visualized between the middle and lower crust (Fig. 2.4).

Gravity data collected for this study show an elongate, north-south, high gravity anomaly in the centre of the Rockall Trough north of Anton Dohrn (Fig. 2.1 and Appendix 5). No explanation for this can be seen on the high-resolution seismic data. It therefore seems likely that this anomaly is caused by either a dense, basic pluton intruded into the base of the crust or is associated with an area where continental rifting continued almost to the point of breakup and the establishment of oceanic crust in the centre of the Rockall Trough. A smaller, more circular gravity high anomaly just to the east may be explained in a similar way.

Lithologically the basement probably consists of medium to high-grade metamorphic rocks intruded by a significantly high proportion of syn-rift (?Cretaceous or older) or post-rift (?early Tertiary) igneous rocks.

2.3. Crustal structure of Hatton-Rockall Basin

There are less data across the Hatton-Rockall Basin than across the Rockall Trough. Crustal profiles rely upon the work of Makris *et al.* (1991) and Shannon *et al.* (1994), both of whom used the RAPIDS dataset, Edwards and Hitchen (1994) for this study, and Keser Neish (1993). All authors' models of the crust beneath the Hatton-Rockall Basin are remarkably similar. The crust here is thicker than beneath the Rockall Trough, thinning in a westerly direction from about 18 to 13km thick. Shannon *et al.* (1994) postulate a mid-basin structural high which divides the Hatton-Rockall Basin into two sub-basins. There is no evidence for this on Transect C although the two profiles are not coincident. Shannon *et al.* (1994) estimate that ß=2 for this basin.

2.4. Crustal terranes

Stretched, thinned and highly intruded continental crust probably underlies the Rockall Trough. However the original nature and age of this crust was not uniform. The rocks can be allocated to distinct crustal terranes defined by variations in geochemical and isotopic characteristics. At least two terranes have been recognised beneath the UK sector of the Rockall Trough. The northern part of the trough is floored by the Archaean Lewisian terrane; the southern part by the early Proterozoic Islay terrane.

The Lewisian comprises quartzo-feldspathic gneisses, ultrabasic to acid intrusives and metasediments. The main phase of crustal generation probably occurred during the late Archaean at 2900Ma with subsequent modifications during the Badcallian, Inverian and Laxfordian orogenic events. However Burton *et al.* (1994) have recently presented data that suggest the oldest Lewisian preserved on mainland Scotland may date back to 3300Ma.

The Lewisian terrane crops out in north-west Scotland, the Western Isles and east Greenland. It has also been directly proved on the West Shetland Shelf by commercial drilling (Ritchie and Darbyshire, 1984) and on the Hebrides Shelf by BGS shallow boreholes (Stoker *et al.* 1993). Furthermore, isotopic studies of basic lavas from BGS boreholes 88/10, 90/7 and 90/10 and commercial well 164/25-1 (on the Hebrides Shelf) and DGU (Geological Survey of Denmark) dredge samples, from George Bligh Bank, demonstrate the involvement of another component in addition to a mantle source. The most distinctive feature of these lavas is their Pb isotopic compositions which fall precisely on, or close to, the Lewisian gneiss isochron. This is strong evidence for contamination of the magma by Lewisian-type material during ascent from the mantle (Morton, 1992). Contamination of Faeroese lavas by amphibolite-facies material has also been reported by Gariepy *et al.* (1983) suggesting that the metamorphic basement beneath the Faeroe-Shetland Basin and the Faeroe Islands also comprises Lewisian terrane material. Hence most of the offshore area to the north-west of Scotland is floored by the Lewisian terrane.

The Islay terrane crops out in western Islay, Colonsay, Inishtrahull and near Erris Head (County Mayo). The rocks mainly comprise a deformed igneous association of syenite and gabbro, with minor mafic and felsic intrusions (Muir *et al.* 1994). Although previously assigned to the Lewisian, this group of rocks has now been recognised as a separate terrane, based on its lithology, geochemical and isotopic characteristics (Bentley *et al.* 1988; Marcantonio *et al.* 1988). Inherited isotopic signatures in the Caledonian granites intruding the Dalradian Supergroup of the Grampian Highlands and northern Ireland suggest the Islay terrane probably extends beneath these areas (Dickin and Bowes, 1991). The southern limit of the terrane may be the Highland Boundary Fault and the Clew Bay-Fairhead line (Fig. 2.5). Onshore the northern limit is the Great Glen Fault, but offshore the boundary between the Lewisian and Islay terranes is less certain. Dickin (1992) suggests the terrane boundary crosses the Rockall Trough and passes between George Bligh Bank and Rockall Bank (Fig. 2.5). If so, Anton Dohrn may be situated close to, or on, the boundary. Consequently, its location may have been controlled by a combination of structural configuration and crustal thinning in the centre of the Rockall Trough (Fig. 2.6).

Although Rockall Bank was allocated to the Rockall terrane (Morton and Taylor, 1991), re-interpretation of the data by Dickin (1992) suggests it is part of the Islay terrane. This has been confirmed by geochemical and isotopic analyses of basalts collected for this study from Rockall Bank. These show contamination mainly by granulite-facies crust with isotopic characteristics typical of Islay terrane material (see Appendix 3). Isotopic analysis of a banded gneiss collected from the top of Rockall Bank for this study (sample 56-15/12) has confirmed this view (see Chapter 3: Stratigraphy). This sample has been dated at 1914Ma which is consistent with isotopic data from samples previously recovered from Rockall Bank, which have yielded ages of 1911-2170Ma (recalculated from Morton and Taylor, 1991)(see Appendix 3). Hence the formation of the Islay terrane was contemporaneous with the Laxfordian orogenic event. Bentley *et al.* (1988) have suggested that the area around western Islay, Colonsay and Inishtrahull was emplaced by movement along major strike-slip faults between 620 and 540Ma. Whether this applies to the whole terrane is uncertain.

2.5. Supracrustal structure of Rockall Trough

<u>2.5.1. Sedimentary infill of Rockall Trough</u>

There is a reasonable consensus concerning the sedimentary thickness within the Rockall Trough. The common estimate is usually 5km, although Keser Neish (1993) proposed a lower figure (3.0-3.5km) and specifically suggested that Tertiary volcanic rocks extend across the full width of the trough. This view is not supported by this study although sills do appear to be widespread. Joppen and White (1990) have suggested that acoustically layered basement imaged on seismic reflection data may represent older (?Cretaceous) syn-rift volcanic rocks and interbedded sediments.

The age of the oldest sediments in the Rockall Trough is unknown. Interval velocity studies suggest they are possibly Torridonian, late Palaeozoic or early Mesozoic (Roberts *et al.* 1988) or Carboniferous to Jurassic (Shannon *et al.* 1994). Palaeogeographic studies by Ziegler (1988) led him to suggest that the Rockall Trough may have been collecting continental clastic deposits during the Permian and Triassic. Smythe (1989) quotes a figure of 2-3km for the pre-Upper Cretaceous sedimentary thickness and implies that at least some of this interval is late Palaeozoic in age. Rocks of Mid-Jurassic to Early Cretaceous age have been proved by BGS shallow drilling in the West Lewis and West Flannan Basins, beneath the Hebrides Shelf, and may be present in the adjacent Rockall Trough (Hitchen and Stoker, 1993b). Similar 'proximity' arguments may be applied to the Irish basins which are marginal to the trough (eg Donegal and Erris basins and Slyne Trough). Some of these basins contain sediments at least as old as Carboniferous in age (Tate and Dobson, 1989b).

The exact age of the main rift phase remains problematical, but the presence of pre-rift late Palaeozoic sediments cannot be excluded. Late Carboniferous to Early Permian (Smythe, 1989) and Permo-Triassic to Jurassic (Shannon *et al.* 1994) ages have been suggested for the main rifting phase in the Rockall Trough. However an Early to mid-Cretaceous event is equally, if not more, likely. Seismic reflection data across the Rockall Trough show that most of the sedimentary infill in the centre of the trough consists of near flat-lying, post-rift Late Cretaceous and Tertiary sediments. These are intruded by numerous sills. Lavas are also widespread but are not ubiquitous across the trough.

2.5.2. Basin-bounding faults

Both the eastern and western margins of the Rockall Trough are defined by major faults. The faults are covered by lavas and hence are not well imaged on seismic data.

In the east, the fault is inferred to occur beneath a major buried escarpment in the lavas (Fig. 2.7) This is the Hebridean Escarpment of Smythe (1989) and Evans *et al.* (1989). It can be traced for approximately 400km along the eastern margin of the Rockall Trough and, at its maximum development in the vicinity of the Geikie igneous centre, is nearly 600m high. The escarpment marks a flexure zone seaward of which the Rockall Trough subsided, relative to the Hebrides Platform, after extrusion of the lavas during the mid-late Paleocene. The escarpment is mainly Eocene in age and there has been little relative subsidence between the trough and platform since that time. However the underlying basin-bounding fault must be older, possibly being initiated in the late Palaeozoic. The Geikie Escarpment, which is a bathymetric feature, is located along the same eastern margin of the Rockall Trough. The two escarpments are not coincident and there is no direct causal relationship between them (Evans *et al.*, 1989).

The western boundary fault of the Rockall Trough separates the trough from Rockall Bank (Fig. 2.8). It can be traced along the north-eastern and eastern margin of Rockall Bank and continues southwards into Irish waters. The vertical throw of the fault varies along its length but may exceed 1000m in places at Top Basalt level. The fault is closely associated with a bathymetric scarp and moat at the sea bed, dissimilar to the eastern margin of the trough where the basin-bounding fault is buried. This may be due to the availability of a sediment supply on the eastern margin (derived from the Scottish massif) which has covered the fault, whereas in the west a similar large source area was not available.

Available data also show that George Bligh Bank is faulted on its south-eastern margin. This bank is a continental block intruded by a basic pluton (Edwards and Hitchen, 1994) and covered by lavas, and is similar to Rockall Bank. However Rosemary Bank and Anton Dohrn are volcanic seamounts of probable Cretaceous age. The thinner crust in the centre of the Rockall Trough probably accounts for their location. The steep sides are due to the original mode of formation rather than significant later faulting. The flat tops are due to marine planation probably during the ?Maastrichtian. Anton Dohrn was subsequently tilted so that the eroded lava surface now slopes south-eastwards and is overlain by a wedge of Tertiary sediments. The central part of the Rockall Trough, and the seamounts, subsided during the Tertiary. The shallowest parts of Rosemary Bank and Anton Dohrn are now 460m and 650m below sea level respectively.

2.5.3. Tilted fault blocks

The movement of Rockall Bank westwards away from the Malin and Hebrides shelves was accommodated by crustal thinning beneath the Rockall Trough and major faulting at the margins. Refraction and wide-angle reflection experiments show rapid variations in the thicknesses of interval velocity layers on the margins of the trough. These have been interpreted as representing tilted fault blocks (Fig 2.3) (Roberts *et al.* 1988; Makris *et al.* 1991). At very high stretching factors of ß=8 to 10 (Shannon *et al.* 1994) the blocks will have rotated through high angles. If syn- and post-rift deposits have blanketed this topography this may explain the apparent lack of such structures in the centre of the Rockall Trough. Furthermore the associated faults must sole out in a mid-crustal detachmant. Alternatively if the major faults are crustal-penetrating (Fig. 2.3) (Keser Neish, 1993), highly-rotated fault blocks on the margins of the trough may be less common.

Tilted faults blocks have been imaged on the eastern margin of Rockall Bank. In UK waters (this study, line D3) (Fig. 2.9) a block is imaged in approximately 1700m of water beneath a multi-reflector package, at least part of which represents lavas. Farther south, in Irish waters, multiple fault blocks are imaged on line SAP-5 (Fig. 2.9). The downthrow of the easternmost block is estimated at 1.5km, with a backward tilt of no more than 15°. A lower limit of 30° is estimated for the dip of the associated fault (Joppen and White, 1990).

It is possible that the orientation of intrusions may provide a guide to the presence of tilted fault blocks, with the intrusions being preferentially emplaced along the top of fault blocks. This is impossible to prove without corroboration from drilling. However it is likely that the faults have provided a conduit for magma to migrate upwards into the Cretaceous succession.

2.5.4. Detail of the western margin

Along the western margin of the Rockall Trough the Eocene interval (between reflectors D and C) thickens adjacent to the eastern margins of Rockall and George Bligh Banks (Fig. 3.14). The thickening is not immediately adjacent to the basin-bounding fault, as might be expected with a fault-scarp fan, but is some distance away from it. On multichannel seismic data, the thickened interval in the Rockall Trough shows few coherent reflectors (Fig. 2.10). Farther out into the basin the same interval exhibits sub-parallel, semi-continuous reflectors.

The thickened interval represents an Eocene wedge, prograding eastwards off Rockall and George Bligh banks. The thickening may may have been accentuated during formation by a gravity-sliding process which may account for the jumbled nature of the internal reflections. The onlap of Oligocene reflectors, particularly on the south-eastern side, suggests that the resultant mound may may have formed a positive sea-bed feature. The gravity-sliding process appears to have had its most profound thickening effect south-east of George Bligh Bank.

Line 92/01-50 shows a possible slide which soles out within the Eocene interval (Fig. 2.11). The overlying mobile unit now forms a rollover structure.

2.5.5. Diapiric structure

Immediately south-east of George Bligh Bank a 'diapiric' structure has been imaged on NW-SE aligned seismic profiles (lines 92/01-38; Transect A) (Fig. 2.12). The highest point of the feature crops out at sea bed where sample 58-14/54 recovered mainly sandstone. On line 92/01-19 (aligned NE-SW) the same feature appears anticlinal in form. Potential-field modelling suggests that the diapir is a body with low density but high magnetic susceptibility (Edwards and Hitchen 1994). Although a magnetic granite fits these criteria, the seismic data and sample 58-14/54 preclude this explanation. To account for the magnetic characteristics, some basaltic material must have been entrained by the upwelling sediments and transported to the near-surface. Hence the diapir may have a sedimentary core and originate from a depth close to, or below, the basalts. This corresponds to a depth of approximately 1200m below the sea bed.

On recovery to the ship, sample 58-14/54 appeared to be degassing. It seems possible therefore that the diapir owes its origin to a combination of thick, unstable sediments (in part due to a buoyancy effect) which suffered tectonic deformation. The age of the feature cannot be constrained precisely. However the age of sample 58-14/54 and the seismic relationships suggest late Eocene for the time of formation. The diapir may have been a contemporary sea-bed feature during formation.

2.5.6. Shallow faulting

On both high-resolution and multichannel seismic data, numerous minor faults are seen to affect the latest Eocene to mid-Miocene section (Fig. 2.13). Although they appear to offset reflector B they cannot readily be traced deeper into the section either because of the limits of resolution or the fact that they sole out within the late Eocene interval. Furthermore the mid-Miocene to Pliocene interval appears to be largely unaffected by the faulting. Hence the faulting can be dated as mid-Miocene in age and is probably related to the major Alpine tectonic event.

2.6. Supracrustal structure of Hatton-Rockall Basin

For this study three new seismic profiles were acquired: high-resolution line 92/01-35, and multichannel lines Transect B and Transect C. The latter was shot mainly coincident with line 92/01-35 although not extending as far to the north-west.

2.6.1. Sedimentary infill of Hatton-Rockall Basin

There is one fewer interval velocity layer in this basin than in the Rockall Trough. This may be due to thermal doming, caused by igneous underplating during the Late Cretaceous to early Tertiary, resulting in the removal of up to 1km of Cretaceous sediments (Shannon *et al.* 1994). However the interval velocity of the lowest, infill layer is the same in both basins (4.5km/s), implying similar early development. The sedimentary thickness in the Hatton-Rockall Basin would appear to be slightly less than in the Rockall Trough.

2.6.2. Basin-bounding faults

The margins of the Hatton-Rockall Basin are defined by major faults which are clearly imaged on the NW-SE seismic profiles acquired for this study (Fig. 2.13). Compared to the fault of the SE margin, the NW basin-bounding fault has a larger vertical displacement at Top Basalt level, and has affected younger sediments. It also affects the present sea floor and has been active throughout the Tertiary.

The bathymetric Hatton-Rockall Basin is 'S'-shaped, probably because the basin has been offset by NW-SE aligned transfer faults. As a consequence of this, Transect B is not located above the deepest parts of the basin along its total length but cuts across a NW-projecting lobe of Rockall Bank.

2.6.3. Shallow faulting

Shallow faulting is imaged in the upper part of the section in the Hatton-Rockall Basin above the yellow reflector. The faults commonly form small grabens between areas of strong, parallel-bedded, undisturbed reflectors (Fig. 2.14). These structures appear on both Transects B and C. Sea-bed depressions are observed above many of the grabens, indicating that the faults are still active. This style of faulting contrasts with that in the Rockall Trough (compare Figs. 2.13 and 2.15) where the faults do not form small grabens but tend towards a more dendritic pattern.

2.6.4. Compressional feature

A compressional, asymmetrical 'pop-up' feature is observed on the NE end of Transect B, shot-points 850-950 (Fig. 2.16). The top of the feature does not appear to be significantly eroded and hence was probably never above sea level. Younger reflectors downlap onto the yellow reflector (?late Eocene), which must therefore correspond with the age of the feature. Other, less pronounced, compressional features occur to the north-east.

2.6.5. Deeper structure of basin

Neither Transect B nor C indicates much structure beneath the basalts in the Hatton-Rockall Basin, probably due to the thickness of the lavas. Consequently the gravity and magnetic modelling of Edwards and Hitchen (1994) assumed a negligible thickness of sediments between the basalts and metamorphic basement. However a pre-Tertiary sedimentary succession has been described by Shannon *et al.* (1994) in Irish waters, based on seismic refraction and reflection data (Fig. 2.17) that indicate a sedimentary succession at least 2s (TWT) thick beneath the basalts. The deepest interval (unit 5) shows slightly divergent layering and is tilted towards the north-west. The overlying unit 4 is parallel bedded and downlaps onto unit 5. Hence the basin has a significant pre-Tertiary history which is largely masked in UK waters.

3. STRATIGRAPHY

This chapter outlines and summarises the stratigraphical framework of the Rockall Continental Margin as established by an integrated seismic-stratigraphical analysis of all of the available geological and geophysical data. The methodology employed followed a two-stage approach:

1. The definition of the regional stratigraphical architecture of the basins and flanking highs through recognition of unconformity-bounded depositional sequences. This utilised the BGS high-resolution seismic data collected in 1992, the multichannel deep seismic data collected in 1993, and the Mobil lines (M89-WB-2, and -3A).

2. The calibration of the seismic-stratigraphy by BGS boreholes and shallow cores collected in 1994, together with any existing well-log or sample information. Biostratigraphical information from these samples enabled a chronostratigraphical framework to be developed.

Due to the limitations of seismic reflection profiling across this volcanic terrain (see Chapter 1: Introduction), the stratigraphy is largely focused on the uppermost Mesozoic and Cenozoic section, although Lower Proterozoic rocks have also been proved. The evidence for Palaeozoic and older Mesozoic rocks remains conjectural at present, and is based largely on the interpretation of interval velocities from seismic refraction data. Current ideas concerning the nature of the deeper parts of the basin-fills have been summarised in Chapter 2 (Structure).

3.1. Seismic reflectors and stratigraphical sequences

The stratigraphical framework presented in this report is based on an earlier preliminary seismic investigation of the area (Hitchen and Stoker, 1993a). However, the stratigraphical interpretation has been refined and the sequence nomenclature considerably revised using the geological information provided by the sample data.

In the Rockall Trough, four regional seismic reflectors (A to D) have been recognised, with several locally important reflectors (B_0, C_1, C_2 and D_1) identified on the western flank of the trough and on, and around, the axial seamounts of Anton Dohrn and Rosemary Bank. The characteristics of each of these reflectors is summarised in Table 3.1, and their stratigraphical relationships are illustrated in Figures 3.1 to 3.3. Correlation between the preliminary informal stratigraphy of Hitchen and Stoker (1993a) and the stratigraphical terminology used in this report is shown in Table 3.2. The stratigraphical framework depicted in Figure 3.1 is also correlated with the lithostratigraphical scheme established for the Central and Northern North Sea, although this is intended as a reference guide only.

The regional reflectors A, C and D define four main seismic-stratigraphical sequences (Figs. 3.1 & 3.2), with reflector D representing acoustic basement. Age control on these sequences is based primarily on the occurrence of a variety of microfossil groups (Tables 3.3 & 3.4), supplemented with radiometric age data obtained from igneous and metamorphic rocks. Although some of the sequences have been sampled in greater abundance than others (Table 3.5), the available stratigraphical data both from BGS and non-BGS samples adequately constrain their age ranges. This information is summarised on the stratigraphical range charts in Figures 3.4-3.7, together with the thickness and generalised lithologies of the rocks and sediments recovered from the sequences. Figure 3.4 presents all of the sample data, distinguishing between proven and inferred stratigraphical range, whereas Figures 3.5 to 3.7 make a clearer distinction between lithological variation. The biostratigraphy and lithological descriptions are presented in much greater detail in Appendices 1 and 2, which also illustrate the seismic-stratigraphical setting for these data. It is recommended that Appendices 1 and 2 be referenced in conjunction with this chapter. The geological timescale used throughout this report is that of Harland *et al.* (1990). For Cenozoic correlation purposes, the calcareous nannofossil zonal scheme of Martini (1971) is utilised; the prefix 'NP' applies to the Palaeogene zones (NP1 to 25), and 'NN' for the Neogene and Quaternary zones (NN1 to NN25).

The sequences mapped in and adjacent to the Rockall Trough span a Late Cretaceous to Quaternary age range (Fig. 3.1). The apparent diachroneity of reflector D is a function of the inability of the seismic system to distinguish between age-variable igneous strata or metamorphic basement, all of which act as major impedance zones to acoustic energy, and appear as acoustic basement. On the flanks of the trough, this age variation ranges from

Paleocene to earliest Eocene; on Rosemary Bank and Anton Dohrn, igneous activity is probably Late Cretaceous in age and acoustic basement is here locally designated as reflector D_1. The D-C seismic interval is late Paleocene to early late Eocene in age, with reflectors C_1 and C_2 representing intra-Eocene events identified within the sediment wedge on the eastern flank of Rockall Bank. Reflector C, at the top of the sequence, is a major unconformity which is particularly well developed on the flanks of the Rockall Trough (Fig. 3.2). The overlying sequences are separated by reflector A, a basin-wide, mid-Miocene unconformity. The late Eocene to mid-Miocene sequence includes reflectors B and B_0 which are, respectively, late Eocene and late Eocene to earliest Oligocene in age. Despite the regional extent of reflector B within the trough, the C-B seismic interval is the least well-constrained by sample data, not having been directly sampled. Whilst reflector B may constitute the basis for future subdivision of the late Eocene to mid-Miocene sequence, for the purpose of the present report it is retained within the broad framework as depicted in Figure 3.1. In the following description of the stratigraphical framework, the thickness of the various sequences, as measured from seismic profiles, is given in milliseconds (ms) two-way time. Borehole and shallow-core thicknesses are in metres (m).

The regional geology of the continental margin as far west as the Hatton-Rockall Basin is summarised in Figure 3.2 which reveals broadly comparable Cenozoic basin histories for the Rockall Trough and the Hatton-Rockall Basin. In the latter basin, the most prominent reflecting surface has been termed R4 by earlier workers (Roberts *et al.,* 1970; Roberts, 1975); this has the expression of a strong angular unconformity on the margin of the basin, comparable with reflector C in the Rockall Trough. DSDP site 116 was terminated at or close to this horizon and proved a late Eocene age for the sediments at about the level of reflector R4. On this basis, the composite Cenozoic stratigraphy for the Rockall Trough, derived from the BGS sample data, shows strong similarities with that deduced from DSDP sites 116 and 117 in the Hatton-Rockall Basin. Whilst the thickness of the sequences may vary between basins, the four-fold seismic-stratigraphical subdivision of the Rockall Trough may also apply to the Hatton-Rockall Basin.

Farther north, this stratigraphical framework is supported by petroleum exploration data from the northern part of the Hebrides Slope where well 164/25-2 drilled the entire preserved

Cenozoic section (Fig. 3.8). Reflector A has been traced from the Rockall Trough into well 164/25-2 where it corresponds to a mid-Miocene unconformity (Fig. 3.9). Additionally, the basin-margin unconformity of reflector C, which is well-developed in this area, corresponds to an early late Eocene unconformity entirely consistent with the new Rockall Continental Margin data.

The only area, to date, where rocks older than Late Cretaceous have been proved is the central part of Rockall Bank where Lower Proterozoic strata crop out at the sea bed. These form the core of the inter-basinal high which separates the Rockall Trough and Hatton-Rockall Basin, and on seismic profiles represent acoustic basement on this part of the bank. Consequently, dependent upon its location within the study area, acoustic basement may consist of rocks of either Early Proterozoic, Late Cretaceous, or Paleocene to earliest Eocene age.

3.2 Stratigraphical framework

The sequences outlined above, including the Proterozoic strata, are described below in ascending stratigraphical order, with emphasis on their distribution, acoustic character, lithology and origin. The main focus is on the Rockall Trough and adjacent banks, although relevant information from the Hebridean region, Hatton-Rockall Basin and areas to the west is included where available.

3.2.1. Lower Proterozoic (metamorphic acoustic basement)

Lower Proterozoic strata have been proved to crop out on the west-central part of Rockall Bank (Fig. 3.10). On seismic profiles, the most distinctive characteristic of the metamorphic basement is the ruggedness of the sea-bed topography in the area of outcrop in comparison to the relatively smooth and flat-lying sea bed more typically associated with the Palaeogene volcanics to the east (Fig. 3.11). A similarly rugged sea bed has also been described from Lewisian (Archaean) inliers in the Hebridean region (Stoker *et al.,* 1993). The overall distribution of Lower Proterozoic rocks at or near to sea bed remains unknown due to the sparsity of seismic profiles traversing the bank. However, they have been sampled at several sites on the bank (Fig. 3.11).

Shallow cores 56-15/11 and 12 recovered banded granulitic gneisses from the area of rugged topography illustrated in Fig. 3.11. These supplement previously drilled sites (samples A and B on Fig. 3.11) to the north-east and south-west (Roberts *et al.,* 1973), together with dive sites (samples C to E on Fig. 3.11) on basement outcrops (Institute of Oceanographic Sciences, 1974). Samples A to D are mafic to intermediate, banded granulititc gneisses (Morton and Taylor, 1991). Their high-grade mineral assemblages are dominated by one or two pyroxene-orthoclase-plagioclase assemblages, together with biotite and occasional amphibole. Minor phases include quartz, apatite and opaques (ilmenite and magnetite). Alteration products include hornblende, biotite, chlorite, carbonate and fibrous epidote. In contrast, sample E has a silicic composition and is classified as a granite (Morton and Taylor, 1991).

Sample A has been dated at 1670±24 Ma (K-Ar, whole rock) and 1566±33 Ma (K-Ar, secondary hornblende), indicating an apparent Laxfordian age (Roberts *et al.*, 1973). Similarly, sample B has yielded an Ar^{40}/Ar^{39} Grenvillian date of 987±5 Ma (Miller *et al.*, 1973). These data had been taken to indicate that Rockall Bank was underlain by Lewisian basement. A reappraisal of these data together with new Pb, Rb-Sr and Sm-Nd data on samples A to E has suggested that these rocks were formed at about 1625 Ma (Morton and Taylor, 1991). Whilst this age is broadly contemporaneous with late Laxfordian events in north-west Scotland, the isotopic composition of the rocks indicates that they cannot have been derived from the reworking of older Lewisian rocks. Thus, Morton and Taylor (1991) inferred an origin related to a separate early Proterozoic crust-forming event.

More recently, Dickin (1992) has revised the Sm-Nd data of Morton and Taylor (1991) and postulated a slightly older age of crustal formation for the Rockall area, between 1900 and 2000 Ma. This is consistent with an Sm-Nd age of 1914 Ma derived from shallow core 56-15/12. Similar ages have been acquired from rocks on Islay and Inishtrahull; all of these data have significant implications for an early Proterozoic basement province across the whole region. Its relation to the older Archaean basement to the north is discussed in Chapter 2 (Structure). The previously published younger ages from Rockall probably represent later, milder, overprinting by mid- to Late Proterozoic tectono-thermal events. Additionally, the granitic rock may be a later crustal melt of the gneissic terrane (Dickin, 1992).

3.2.2. Upper Cretaceous to Paleocene/lowest Eocene (volcanogenic acoustic basement)

These rocks form acoustic basement over most of the study area, and are imaged as a highly reflective surface which is commonly irregular and locally faulted. The rocks are predominantly of igneous origin and their age range shows a geographic variation (Figs. 3.4, 3.5 & 3.10). In the study area, regionally extensive Upper Cretaceous strata have been proved only on the axial seamounts of Rosemary Bank and Anton Dohrn, whereas Paleocene to lowest Eocene rocks mainly form acoustic basement on Rockall and George Bligh banks, although the Helen's Reef ultramafic complex forms an Upper Cretaceous intrusive inlier on Rockall Bank (Roberts *et al.,* 1974; Harrison *et al.,* 1975). In Figures 3.1 to 3.3(m & n), this variation in age of the acoustic basement is indicated by the D and D_1 reflector notations, where D_1 represents Upper Cretaceous rocks. Where uncertainty remains on the age of the acoustic basement, a D/D_1 reflector notation is used. The combined distribution of these rocks is shown in Figure 3.10, which also reveals several 'window' areas in the Rockall Trough where these strata may be absent. In these 'windows', acoustic basement is represented by intrusives, mostly sills (Fig. 3.2), emplaced into Cretaceous (and older?) sediments (Stoker *et al.,* 1993), although the nature of the pre-Tertiary basin-fill and underlying structural basement in the trough remains unproven.

Upper Cretaceous

On Rosemary Bank, acoustic basement appears to be mostly buried beneath a partially-faulted cover of younger sediments, although it locally crops out as knoll-like features on the top of the bank, and on its steeper flanks (Figs. 3.2 & 3.3m). BGS borehole 90/18 recovered 1.53m of shallow-marine conglomerate, consisting of basaltic clasts set in a recrystallised bioclastic limestone matrix, overlying interbedded subaerial basalts and volcaniclastic deposits (Stoker *et al.,* 1993; Morton *et al.,* In press). Calcareous nannofossils indicate that the conglomerate is of Late Cretaceous (late Maastrichtian) age, and Morton *et al.* (In press) have used magnetostratigraphical data to suggest either a Campanian or Maastrichtian age for the volcanism. This association of shallow-marine carbonate-rich sediments with volcanics is further proved by shallow core 59-11/12 (S1) which recovered 4.05m of interbedded ultrapotassic lavas (see Chapter 4: Volcanicity) and thin bioclastic limestones (Fig. 3.5). On the seismic profile across the bank, hints of internal reflections are locally observed within the basement (Fig. 3.3m); these may in part represent sediments interbedded with the volcanics. Farther north, dacites of possible Late Cretaceous age (but see Chapter 4: Volcanicity) form part of the Darwin igneous complex, as proved by well 163/6-1A (Morton *et al.,* 1988). These appear to be restricted to the vicinity of the now-buried volcano (Abraham and Ritchie, 1991: their Fig. 3).

On Anton Dohrn, acoustic basement appears to be at or near to sea bed on the western half of the bank, as well as its upper slope; the eastern half is buried beneath a sediment wedge which locally exceeds 100m in thickness (Fig. 3.3n). Although acoustic basement has not been conclusively sampled, Jones *et al.* (1974) recovered a conglomerate which is of Late Cretaceous (late Maastrichtian) age (Figs. 3.4 & 3.5) and is lithologically similar to that from Rosemary Bank. This provides a minimum age for the volcanism on the bank, as represented by the basalt clasts within the conglomerate. On seismic profiles, intra-basement reflectors are locally observed (Fig. 3.3n). Seismic refraction data suggest that sedimentary and volcaniclastic units may be important constituents of the volcanic pile forming the seamount (Jones *et al.,* 1994).

One occurrence of Upper Cretaceous rocks has been proved on Rockall Bank: the ultramafic complex of Helen's Reef, near Rockall Island (Fig. 3.10), yielded a Late Cretaceous (Campanian) K-Ar whole-rock age of 83±3 Ma (Pankhurst, 1982). Whilst this location represents a restricted occurrence of Upper Cretaceous rocks relative to the more extensive axial seamounts, it does provide further indication for Late Cretaceous volcanism in and around the area of the Rockall Trough (see Chapter 4: Volcanicity).

Paleocene to lowest Eocene

BGS reconnaissance mapping (Hitchen and Ritchie, 1993; Stoker *et al.,* 1993) has demonstrated that basaltic lavas of this age form a major component of acoustic basement along the eastern margin of the Rockall Trough. Sediments and volcaniclastics also form an important part of the sequence as proved in BP well 164/25-2 on the Hebrides Slope, which cored an interbedded volcanic and sedimentary succession of late Paleocene to earliest Eocene age (Fig. 3.8). Sub-basalt Paleocene sediments have also been proved in BGS boreholes on the Hebrides Shelf (Stoker *et al.,* 1993). The present study has extended the mappable limit of this volcanogenic acoustic basement onto the western side of the Rockall Trough, and these rocks probably constitute acoustic basement over most of the study area, especially on the margin of the Rockall Trough and adjacent highs. (Figs. 3.4 & 3.10).

On seismic profiles, reflector D (acoustic basement) can be traced from outcrop on the Rockall and George Bligh banks to greater depth within the Rockall Trough (Figs. 3.2 & 3.3). On the edge of the banks, the basement is buried beneath a prograding sediment wedge on the edge of the banks; however, a major basin-bounding fault contributes to up to several seconds of downthrow of the basement into the trough, where it is overlain by a much thicker sediment cover (Figs. 3.2 & 3.3a-l). This appears to be an analogous situation to that encountered on the eastern flank of the trough (Fig. 3.2) where acoustic basement is downthrown along the line of the Hebridean Escarpment (Evans *et al.,* 1989).

On Rockall Bank, short, discontinuous, sub-parallel, easterly dipping, intra-basement reflectors are commonly observed at shallow depth (Figs. 3.3a-g & 3.12). Boreholes 94/2, 94/5 and 94/6 tested this basement and recovered extrusive basalt flows, whilst shallow core 57-14/53 (S18) proved trachyte. The latter yielded a late Paleocene to earliest Eocene K-Ar age of 57.8±1.6 Ma. The off-bank dips of the intra-basement reflectors indicate that the borehole sites are located stratigraphically higher than the shallow core (eg. Fig. 3.3a), hence a slightly younger age is likely for the basalts. However, this is unlikely to be substantial as borehole 94/3, similarly located on the edge of the bank but beneath the thick sediment wedge, proved interbedded pillow lavas and shelly mudstones of late Paleocene to earliest Eocene (NP4-10/11) age (Fig. 3.13).

Interbedded packages of volcanics and sediments may be partly responsible for the intra-basement reflections. This concept is supported by the recovery of sediments and volcaniclastics from acoustic basement elsewhere on the edge of the bank; shallow cores 57-

14/31 and 32 (S12) sampled a conglomerate of basalt clasts in a carbonate matrix, whilst core 57-13/54 (S17) proved agglomerate (Fig. 3.5). These data imply that the edge of the bank was at or close to sea level, and that it was accumulating mixed siliciclastic/carbonate sediments, together with volcaniclastic material, and subaerial and submarine lavas. The localised erosional truncation of the intra-basement reflections by reflector D below the sediment wedge (Figs. 3.3b,d,e & 3.12b,c) implies a hiatus before the deposition of the overlying strata. Again, this may not have been a prolonged interval of time, as the basal part of the sediment wedge also records a late Paleocene to earliest Eocene age (see below). Whilst no obvious unconformity surface associated with reflector D was recorded in borehole 94/3 (Fig. 3.12a), a sharp change in lithofacies indicative of shallowing is evident; the uppermost pillow lava is overlain by shelly, nearshore sands, in contrast to the black mudstones interbedded with the lavas (Fig. 3.13). Rapidly changing palaeo-environments on the Rockall Plateau were common at this time, as evidenced by the Edoras Basin farther to the south-west (Fig. 1.1), where fluctuating coastal and shallow-marine sedimentation occurred in response to tectonic instability of the margin prior to continental break-up and sea-floor spreading in the North-East Atlantic (cf. Stoker and Gillespie, 1994).

On George Bligh Bank, acoustic basement is marked by a prominent high-amplitude reflector. In common with Rockall Bank, reflector D locally truncates flat- to steeply-dipping intra-basement reflections. The nature of the basement was tested by shallow cores 58-14/8 and 42 (S7) and 58-14/57 and 58 (S41), and borehole 94/7. All of the shallow cores recovered shallow-marine conglomerate, composed mainly of basalt clasts in a carbonate matrix, which in core 58-14/42 was underlain by an extrusive basalt flow (Fig. 3.5). Borehole 94/7 also proved basalts; two flows were cored separated by a very thin, shelly sandstone layer. Calcareous nannofossil data from the conglomerates, and foraminiferal analysis of the thin sandstone, revealed a Paleocene age, probably pre-NP6 biozone on the basis of regional stratigraphical evidence from younger strata (Fig. 3.4). Although the acoustic character and palaeo-environmental setting of these strata is comparable with Rockall Bank, the biostratigraphical data suggest that they are slightly older.

In the Rockall Trough, acoustic basement has a more variable distribution (Figs. 3.2 & 3.10). Around the margin of the trough, reflector D is of high-amplitude and relatively continuous albeit commonly irregular due to faulting and/or the original morphology of the surface which reflects its volcanogenic origin. Away from the basin-bounding faults, the attitude of the reflector becomes more flat-lying, in character with the overall shape of the basin. The variable depth to reflector D within the basin is illustrated in Figure 4.1. The character of reflector D is similar to that on the banks and appears to mark the top of a package of short, sub-parallel reflections. As noted above, well 164/25-2 proved an interbedded volcanic and sedimentary sequence on the north-eastern flank of the trough; the volcanogenic nature of the basinal section is equally well demonstrated by well 163/6-1A, north of Rosemary Bank (Fig. 1.1), which drilled about 670m of basalt overlying about 360m of ?Late Cretaceous dacites (Morton *et al.,* 1988; Abraham and Ritchie, 1991). Between Rosemary Bank and Anton Dohrn, acoustic basement becomes more discontinuous, and to the south of Anton Dohrn the area is largely devoid of volcanics (Fig. 3.10). In these areas, highly reflective, discontinuous seismic horizons are present at stratigraphical levels well below that of reflector D (Fig. 3.2). These features probably represent sills intruded into a presumed thick sedimentary succession which pre-dates reflector D in the trough. The nature of this succession remains uncertain at present.

In the Hatton-Rockall Basin, acoustic basement was tested at DSDP site 117 (Fig. 3.2) on the eastern flank of the basin, which proved upper Paleocene to lower Eocene basalt (Laughton *et al.,* 1972). This age is compatible with that of acoustic basement in the Rockall Trough and hence the reflector D notation is confidently extended into the Hatton-Rockall Basin. Seismic profiles within this basin image the volcanics as a relatively continuous reflector, although some discontinuity and/or irregularity on its south-eastern margin is possibly related to intra-basinal faulting. Such activity may also be responsible for the progressive downstepping of the basement to the south-west, from near-outcrop in the north-east (Fig. 3.2). Highly reflective sills are locally imaged below reflector D.

West of the Hatton-Rockall Basin, acoustic basement locally rises to sea bed on Hatton Bank (see Fig. 3.17). On the bank, DSDP data suggest that basement consists, at least in part, of late Paleocene volcanogenic rocks (cf. Stoker and Gillespie, 1994). Farther west, the basement includes the vast accumulation of basalts that form the volcanic dipping reflector sequence at the continent-ocean boundary. The Iceland Basin is underlain by true oceanic igneous crust dating from latest Paleocene/earliest Eocene time to the present day (Roberts *et al.,* 1984).

3.2.3. Upper Paleocene to lower upper Eocene (seismic interval D-C)

The upper Paleocene to lower upper Eocene sequence is widely distributed in the study area; it is preserved mainly in the Rockall Trough and Hatton-Rockall Basin, with more restricted accumulations on the adjacent banks and seamounts (Figs. 3.2, 3.3 & 3.14). In the basins, the top of the sequence is marked by reflector C, which forms a prominent unconformity and onlap surface on the basin margins; its base is reflector D where observed. In the Rockall Trough, BGS boreholes and shallow cores, and data from well 164/25-2, indicate conclusively that reflector C is of early late Eocene age (NP18/19) (Figs. 3.4, 3.5 & 3.8). In the Hatton-Rockall Basin, DSDP site 116 terminated in upper Eocene (NP19) sediments at about the level of reflector R4 (Roberts, 1975). This is broadly compatible with the information from the Rockall Trough, and the reflector C notation is confidently extended to the Hatton-Rockall Basin. It is also interesting to note that a significant mid- to late Eocene hiatus is recorded in several DSDP boreholes on the south-west Rockall Plateau (cf. Stoker and Gillespie, 1994).

On regional seismic profiles across the Rockall Trough (Fig. 3.2), the overall geometry of the sequence displays a basinward thickening. In the Rockall Trough, maximum axial thickness may exceed 800ms compared with maximum thicknesses of 100ms and 200-300ms, respectively, on the Anton Dohrn seamount and Rockall/George Bligh banks (Fig. 3.14). The greatest observed thickness occurs on the western flank of the trough, adjacent to George Bligh Bank, where more than 1000ms of sediment is preserved. In this area, the sequence displays a prism-like geometry (Fig. 3.2) which broadly resembles the type of depositional architecture associated with a rapidly prograding shelf-margin. The presence of possible large-scale rotational slides and/or diapiric structures within this section (Figs. 2.9-2.11 & 3.3j,k) implies penecontemporaneous instability consistent with such a setting. A similar, albeit less-dramatic thickening of the sequence occurs adjacent to Rockall Bank (eg. Fig. 3.3d,f-h). Whilst this marginal geometry is not observed on the eastern side of the Rockall Trough within the study area, it is a feature of the sequence farther to the north-east in the area of well 164/25-2 (Fig. 3.8). Comparison between the geometry of the prism-like accumulation preserved in the north Hebridean region with that on the western flank of the trough suggests that the latter has been modified to some extent by subsequent faulting and associated instability.

The extent to which syn-depositional fault activity has influenced the geometry of the sequence is unclear. The effects of contemporaneous tectonism are preserved in the sediments on Rockall Bank, where unconformities and lithofacies changes are well-imaged on seismic profiles and proved in borehole 94/3 (Fig. 3.3c). Such activity may account for the variable onlap/offlap stratal geometry observed on Rockall Bank (see below), as well as the thickening of the sequence across the basin-bounding fault between Rockall and George Bligh banks and the Rockall Trough (Fig. 3.3). However, there is no doubt that some of the marginal faulting post-dates deposition of the sequence. On the eastern margin of the trough, the sediments are locally faulted-out against the Hebridean Escarpment (Fig. 3.2).

On the western side of the Rockall Trough, upper Paleocene to lower upper Eocene sediments occur at or near to sea bed, and it has been possible to sample the 'modified' shelf-margin prism with boreholes and shallow cores. Both Rockall and George Bligh banks are fringed by prograding sediment wedges which pass laterally downslope into the thicker shelf-margin deposits currently preserved on the downthrow-side of the basin-bounding fault on the flank of the trough (Figs. 3.2 & 3.3). Locally, the lateral continuity has been broken by the faulting, and acoustic basement crops out on the fault scarp. The deeper, basinal part of the sequence remains untested.

On Rockall Bank, the sediment wedge consists of several discrete depocentres ranging in thickness from 50ms to >300ms (Fig. 3.14). Locally, the wedge has been divided into three unconformity-bounded sub-units separated by reflectors C_1 and C_2 (Figs. 3.3a-e & 3.12), which can be mapped on several adjacent seismic lines (Fig. 3.15). The lowest unit (seismic interval D-C_2) displays sub-parallel, easterly-dipping reflections which locally downlap onto reflector D (acoustic basement). In the overlying units (seismic intervals C_2-C_1, and C_1-near sea bed), stratal geometry varies from onlapping to offlapping, and internal reflection configurations display both oblique- and sigmoid-progradation, with reflectors locally wavy and undulatory, which typically downlap onto the erosional unconformity surface at their base. The lower part of the wedge is locally cut by high-angle normal faults; the top surface has been modified and reworked during Quaternary lowstands of sea level, and exhibits several wave-cut terraces or platforms (Fig. 3.3a-d,f). Although seismic-stratigraphical subdivision of the wedge is not possible everywhere, especially where the wedge is relatively thin, its prograding character remains evident.

Borehole 94/3 penetrated the entire wedge on the eastern side of Rockall Bank (Fig. 3.13), where the sub-units are well defined, and proved about 196m of upper Paleocene to upper middle Eocene strata overlying pillow lavas of the acoustic basement. Biostratigraphical analysis confirmed the threefold subdivision of the wedge above acoustic basement, the units of which are assigned ages of late Paleocene to earliest Eocene, latest early Eocene to mid-Eocene, and late mid-Eocene (Figs. 3.5 & 3.13). The upper Paleocene to lowest Eocene section (seismic interval D-C_2) consist of 72.04m of interbedded sandstones and conglomerates, with occasional shell fragments and organic material in the lower and upper parts of the section (Fig. 3.13). These are unconformably overlain by 101.90m of upper lower Eocene to middle Eocene, interbedded mudstones, sandstones and conglomerates (seismic interval C_2-C_1), which are highly tuffaceous in the lower part of the section, and include a thin, discrete basalt lava flow near the top of the unit. The upper unit (seismic interval C_1-near sea bed) consists of about 22m of upper middle Eocene gravels and shelly muddy sands, subsequently partly reworked during the Quaternary. Sedimentation occurred in a variety of depositional environments that fluctuated between shallow-marine, siliciclastic shoreline, deltaic/paralic and alluvial settings (Fig. 3.13). This rapid variation in sedimentary environment implies an inherent tectonic instability, as does the volcanism on the Rockall Bank from the late Paleocene to the mid-Eocene.

The seismic interval C_2-C_1 has been further sampled by shallow cores 57-13/65 (S19) and 57-14/43 (S22) which recovered 0.2 and 0.3m, respectively, of marginal-marine mudstones and sandstones (Fig. 3.5). The sediment wedge has also been tested by boreholes 94/2 and 94/6 which penetrated thinner parts of the sequence (Fig. 3.14). Borehole 94/2 recovered 1.61m of lower middle Eocene limestone, volcaniclastic sandstones and tuffs, unconformably overlain by 14.52m of upper middle Eocene conglomerate and shelly, marine sandstones (Fig. 3.5). Although seismic-stratigraphical subdivision of the wedge is not possible at this site, the lithostratigraphical and biostratigraphical data correlate well with borehole 94/3, sited approximately 40km to the north-east. On the northern edge of Rockall Bank, borehole 94/6 recovered 8.92m of lower middle Eocene shallow-marine sandstones (Fig. 3.5).

On George Bligh Bank, the depositional architecture of the sediment wedge is comparable to Rockall Bank, although the sequence displays a more aggradational geometry (Fig. 3.3k-l). The succession locally exceeds 200ms in thickness, and may be divisible into several sub-units, although the relative sparsity of seismic lines across the bank precludes any detailed attempt at sub-division at this stage. Where best imaged, the wedge deposit consists of a lower unit with sub-parallel internal reflections and an eroded upper surface. This is overlain by a prograding and aggrading succession which both onlaps and downlaps onto the bank. Internal reflection configurations are oblique- to sigmoid-progradational in style. The downslope edge of the wedge locally terminates in a steep, submarine cliff up to 50m high, below which acoustic basement may be exposed.

The sequence on George Bligh Bank has been tested at four sites (Fig. 3.14), which together sampled the youngest and oldest portions of the wedge (Figs. 3.4 & 3.5). Borehole 94/7 cored the uppermost, feather-edge of the sequence on top of the bank, and proved 10.37m of middle to lowest upper Eocene shallow-marine sandstones and limestone. Farther east, shallow cores 58-14/10 and 43 (S9), 58-14/11 (S10) and 58-14/55 (S40) sampled stratigraphically lower parts of the wedge that are exposed on the slope of the bank. They recovered calcareous mudstones and bioclastic sandstones with a late Paleocene to early Eocene age range (Fig. 3.5). All of these samples suggest a mixed siliciclastic/carbonate environment of deposition.

The shelf-margin succession, downslope from the bank-edge sediment wedges, displays a variable seismic character ranging from acoustically well-layered to jumbled and chaotic, discontinuous reflections. A continuum is commonly observed where a layered texture is disrupted by faulting, slumping and sliding on the flank of the trough (Figs. 2.9 & 3.3f,j-l). Farther into the trough, the upper Paleocene to lower upper Eocene sequence appears largely acoustically structureless.

On the slope of Rockall Bank, borehole 94/1 cored the sequence immediately below reflector C. It recovered 31.55m of upper middle Eocene strata (Figs. 3.4, 3.5 & 3.14) consisting of

25.03m of black, organic-rich mudstones overlying 6.52m of pebbly sandstones, which were deposited in a nearshore-marine setting. These sediments correlate with the upper sub-unit (seismic interval C_1-near sea bed) in the adjacent sediment wedge on Rockall Bank. Shallow-marine sandstones of slightly older age were proved in shallow core 57-13/77 (S56) farther north-east along the slope. On the northern slope of Rockall Bank, shallow cores 58-14/29 and 30 (S13) sampled a deeper level within the sequence and recovered a 4.66m-thick, upward-coarsening section of lower to middle Eocene, deltaic siltstones and very fine-grained sandstones (Fig. 3.5).

On the western flank of the Rockall Trough, between Rockall and George Bligh banks, numerous shallow cores have sampled the sequence at several stratigraphical levels, and proved a lower to upper Eocene succession (Figs. 3.4, 3.5 & 3.14). Adjacent to George Bligh Bank, shallow core 7710 (Ferragne *et al.*, 1984) recovered shallow-marine mudstones. Farther to the north-east, shallow cores 59-14/8 (S3), 59-14/7 (S4), 59-14/5 and 6 (S5) and 59-14/9 and 10 (S6) recovered lower to middle Eocene mudstones and claystones with occasional thin, interbedded siltstones and bryozoan-rich sandstones. These were deposited in a mixed siliciclastic/carbonate, shallow-marine shelf setting. Farther into the basin, shallow cores 58-14/53 (S11), 58-14/34 (S14) and 58-14/44 and 45 (S49) similarly collected middle Eocene shallow-marine sandstones, whereas 58-14/54 (S42) sampled middle to upper Eocene sandstones from an area of probable diapiric activity.

The only other part of the sequence sampled within the study area is from the more-isolated top of the Anton Dohrn seamount, where an eastward-thickening wedge of sediment, locally >100ms thick, is preserved (Figs. 3.2, 3.3n & 3.14). On seismic profiles, the sequence is locally well layered with occasional downlap onto the igneous basement. Borehole 90/15,15A cored 12.4m into the thin part of the wedge on the top of the bank and recovered Paleocene to lower Eocene, shallow-marine limestone overlying gravel (Stoker *et al.*, 1993). In contrast, shallow core 57-12/18 (S30), on the northern side of the seamount, proved middle to upper Eocene conglomerate composed largely of igneous clasts set in a carbonate matrix (Fig. 3.5). A clastic-influenced, shallow-marine carbonate bank (isolated seamount) environment is envisaged. Probable remnants of Eocene strata have also been inferred on the flank of Rosemary Bank, where abundant early to mid-Eocene dinoflagellate cysts have been reworked into the Pleistocene veneer sampled in shallow core 59-11/16 (S43); however, this remains to be tested, and an ice-rafted origin cannot be discounted.

Other sampled occurrences of upper Paleocene to Eocene strata have been documented by Stoker *et al.* (1993) in the area to the north-east of the study area. Although many of these samples remain poorly dated, several are well constrained; these include uppermost Paleocene to lowest Eocene tuffaceous sandstones which overlie acoustic basement on the top of the Wyville-Thomson Ridge (Stoker *et al.*, 1988), together with lower Eocene tuffs dredged from the southern flank of the ridge (Jones and Ramsay, 1982). These data are important in that they provide evidence that the Wyville-Thomson Ridge was at or close to sea level during latest Paleocene/earliest Eocene time, similar to the banks and seamounts in the study area, as well as indicating the regional extent of early Eocene volcaniclastic activity.

In the north Hebridean region downslope from the shelf-margin prism (Fig. 3.8), well 164/25-2 penetrated a thick section of siltstones with occasional limestones. A coarser-grained, sandstone-dominated sequence was sampled further upslope in well 164/25-1 (Stoker and Gillespie, 1994).

In the Hatton-Rockall Basin, DSDP site 117 proved upper Paleocene to lower Eocene conglomerates, sandstones and mudstones on the flank of the basin, deposited in a subsiding coastal to shallow-marine environment (Laughton *et al.*, 1972). Farther into the basin, DSDP site 116 terminated in upper Eocene limestones at about the level of reflector C (Roberts, 1975). However, it remains uncertain whether the sediments were recovered from immediately above or below this reflector; if the former applies, the sequence was not tested at this site. In either case, the bulk of the sequence in this basin remains to be tested.

Farther west, coastal and shallow-marine clastic sedimentation prevailed in the area of the Edoras and North Hatton basins (Fig. 1.1) during latest Paleocene to earliest Eocene time (cf. Stoker and Gillespie, 1994). However, following the early Eocene onset of sea-floor spreading in the North-East Atlantic, sedimentation in these basins was terminated and the outermost part of the margin rapidly subsided, with clastic sedimentation largely replaced by biogenic carbonate deposition, although volcaniclastic activity persisted into late mid-Eocene time.

3.2.4. Upper Eocene to middle Miocene (seismic interval C-A)

The upper Eocene to middle Miocene sequence is widely distributed throughout the Rockall Trough and Hatton-Rockall Basin (Fig. 3.2). The base of the sequence is marked by reflector C, whilst its top is marked by reflector A; both of these reflectors represent unconformity surfaces. The sequence is largely a basinal deposit which displays variable onlap and upslope accretion around the margins of the basins and the bases of the axial seamounts. Locally, the sequence is absent either through erosion or non-deposition, particularly along the margins of the Rockall Trough. It may also have been previously more extensive in the Hebridean region, landward of the Hebridean Escarpment, prior to subsequent erosion (Stoker *et al.*, 1993).

Although not extensively sampled, BGS boreholes from the western Rockall Trough, together with well 164/25-2 from the north Hebridean region and DSDP site 116 in the Hatton-Rockall Basin, provide constraints on the late Eocene to mid-Miocene age of the sequence (Figs. 3.4-3.9), and confirm its broad, inter-basinal correlation and distribution as depicted in Figure 3.2). However, the thicker accumulation of sediments preserved in the Rockall Trough has enabled a preliminary sub-division of the sequence in this basin, which distinguishes upper Eocene, upper Eocene to lowest Oligocene and Oligocene to middle Miocene units, separated by reflectors B and B_0 (Figs. 3.1-3.3). These units are described in more detail below, with information from the north Hebridean region and Hatton-Rockall Basin included where appropriate.

Upper Eocene

The upper Eocene unit is a basinal facies which, to date, has only been defined for the Rockall Trough. The base of the unit is marked by reflector C; its top is a highly reflective zone up to 100ms thick, the top of which is designated reflector B. The geometry of the unit displays a ponded, transparent to acoustically-layered, onlap fill that locally exceeds 600ms in thickness (Figs. 3.2 & 3.16). Internal reflections onlapping onto reflector C at the basin margins and around the base of the axial seamounts (Fig. 3.3a,h,i,m,n). The sediments which comprise this unit have not been tested by BGS sampling, the section being largely beyond the limit of the sampling techniques available. Moreover, whereas the unit occurs widely within the study area, it does not appear to continue into the north-eastern part of the trough; a seismic profile running between Rosemary Bank and the Hebridean Escarpment shows that the unit pinches out in this area (Fig. 3.9). Consequently, this section has not been tested in well 164/25-2 in the north Hebridean region. Despite this lack of geological information, regional stratigraphical considerations - it being sandwiched between seismic intervals D-C and B-B_0 - support a late Eocene age (Fig. 3.5).

On seismic profiles, the internal reflections commonly display a wavy or undulatory character, and a mounded form is locally preserved at the margins of the basin (Fig. 3.3a,h,i). This is interpreted to mark the onset of bottom-current activity within the Rockall Trough. According to Wold (1994), the Feni Ridge sediment drift originated around the time of the Eocene/Oligocene boundary, coincident with a major phase of sedimentation lasting only 3 or 4My. This rapid influx of sediment into the basin may be associated, in part, with subsidence of the trough and the development of the marked angular unconformity, reflector C. Extensive erosion of the underlying Eocene strata (seismic interval D-C) is a characteristic of this unconformity, and the sediments comprising the upper Eocene unit could be largely derived through the erosion of these older deposits.

In the Hatton-Rockall Basin, DSDP site 116 terminated in upper Eocene limestones (Laughton *et al.,* 1972) which may be partly correlatable with the unit in the Rockall Trough although, as previously stated, the position of the recovered sediments relative to reflector C remains uncertain. In contrast to the Rockall Trough, the upper Eocene section is relatively thin and indistinct on seismic profiles (Fig. 3.17). Upper Eocene carbonates have also been recovered from the south-west Rockall Plateau (cf. Stoker and Gillespie, 1994).

Upper Eocene to lowest Oligocene

This unit occurs as a discrete wedge of sediment on the western flank of the Rockall Trough. It is best preserved adjacent to the north-east slope of Rockall Bank where it is up to 400ms (TWT) thick (Fig. 3.18), but loses expression both to the north and south along the strike of the bank. The base of the unit is marked by either reflectors C or B; the latter represents a downlap surface (Fig. 3.3h). The top of the unit is represented by reflector B_0 which is onlapped by younger sediments, including those of seismic interval B-A which, when traced into the north Hebridean region and well 164/25-2, are predominantly of early Oligocene age (Figs. 3.8 & 3.9).

On the north-east slope of Rockall Bank, the geometry of the unit is fan-like, with the internal reflections indicating progradation from the slope into the basin (Figs. 3.3h & 3.19). Borehole 94/4 recovered 33.0m of upper Eocene to lowest Oligocene, massive, bioclastic sandstones (Figs. 3.4 & 3.5). Although the clean, porous, coarse-grained nature of the sandstones implies a high-energy, shallow-water origin, their deep-water, fan-like setting suggests redeposition as mass-flow sands onto the slope during a lowstand of sea level. The nature and style of this sedimentation contrasts markedly with the more-restricted basinal limestone deposit of similar age proved at DSDP site 116, in the Hatton-Rockall Basin (as noted above). Carbonate sedimentation prevailed on the south-west Rockall Plateau at this time (cf. Stoker and Gillespie, 1994).

Oligocene to middle Miocene

The Oligocene to middle Miocene sediments occur widely within the study area, occurring in the Rockall Trough, the region landward of the Hebridean Escarpment, and in the Hatton-Rockall Basin (Figs. 3.2 & 3.20). In the Rockall Trough, the base of the unit is marked predominantly by reflector B, although on the flanks of the basin the sediments progressively onlap onto reflectors B_0 and C. The top of the unit is marked by reflector A over most of the basin, except on the western margin of the trough where it occurs at or near to sea bed. The unit is locally absent on the flanks of the trough due, in part, to the effects of syn- and post-depositional bottom-current activity. Farther north-east, these sediments can be traced into the north Hebridean region; well 164/25-2 confirms an early Oligocene to mid-Miocene age for the unit although sedimentation was not continuous throughout this interval (Figs. 3.8 & 3.9).

Landward of the Hebridean Escarpment, the base of the unit rests for the most part directly on acoustic basement (upper Paleocene-lower Eocene volcanics). The top of the unit, although seismically well-defined, is not everywhere equivalent to reflector A of the basin, and may represent a composite surface sculpted by several erosional events (see below). The unit is absent from other platform areas such as the Rockall Bank and the axial seamounts.

Farther west, in the Hatton-Rockall Basin, DSDP site 116 indicates that Oligocene to upper lower Miocene sediments comprise the bulk of the seismic interval C-A in this basin (Fig. 3.17). Both DSDP site 116 and well 164/25-2 suggest that reflector A is of mid-Miocene age, and most probably correlates with the R2 reflector of Miller and Tucholke (1983) which has expression throughout the north-east Atlantic.

In the Rockall Trough, the unit displays a partly eroded, sheetform to locally mounded geometry up to 600ms thick (Fig. 3.20). On seismic profiles, the sediments are acoustically well-layered with a subparallel to wavy and undulatory reflection configuration (eg. Fig. 3.3h, i). The reflection character commonly becomes more complex adjacent to the margins of the trough and seamounts, where cut-and-fill structures and current-moulded bedforms are present, indicative of a vigorous syn-depositional bottom-current regime. Figure 3.21 from near the base of the Anton Dohrn seamount includes deep-water migrating sediment waves, 100 to 150m high and with a wavelength of 2 to 3km. Adjacent to Rockall Bank, Figures 3.3(a-d,f,g) and 3.22 illustrate the lateral migration of the sediments by upslope-accretion onto the western flank of the trough; this build-up is part of the development of the Feni Ridge sediment drift. This sediment drift is a large-scale, depositional body which typically forms a positive feature on seismic reflection profiles. This is reflected in the isochron data in Figure 3.20. Internal reflections in the drift vary from sigmoidal to planar, and variably display onlap and downlap onto the underlying strata (Fig. 3.3a-d,f,g). A prominent moat commonly separates the drift from the Rockall Bank. Locally, the drift appears to become detached from the main basinal succession (Fig. 3.22). Whilst at first sight this may appear to suggest post-depositional erosion, with the assumption that the erosional surface was created at the same time, the probability is that sedimentation and erosion occurred penecontemporaneously in response to changes in bottom-current activity (Christie-Blick *et al.,* 1990). The sediment drift has previously been (wrongly) interpreted as a major zone of slumping (Roberts, 1972). However, faulting has locally affected the main basinal part of the unit in the Rockall Trough (Figs. 2.12 & 3.3h,i,l).

The feather-edge of the sediment drift was cored in borehole 94/1 which proved deep-water muddy sands and gravels of probable mid-Miocene (NN6-7) age (Figs. 3.4 & 3.6). This unit has not been sampled in the Rockall Trough within the study area, but well 164/25-2 in the north Hebridean region proved Oligocene and middle Miocene clastics with thin carbonates (Fig. 3.8). The bulk of this section, which can be traced into the study area (Fig. 3.9), consists of lower Oligocene strata. The section is further characterised by unconformities separating lower and upper Oligocene, and upper Oligocene and middle Miocene strata. Although early Miocene microfaunas were identified in the well, they appear to be largely reworked into the middle Miocene sediments. An intra-Langhian unconformity correlates with reflector A in the north Hebridean region; this is not inconsistent with the data from borehole 94/1 which also suggest a mid-Miocene, albeit slightly younger, age for reflector A on the western flank of the trough. Such diachroneity in the age of the reflector would not be surprising given the likely lateral variability of bottom-current activity and strength over such a large area.

In the Hebridean region adjacent to the study area, Oligocene to Miocene deposits occur as a partly eroded wedge of sediment, locally unconnected to the basinal unit (Figs. 3.3 & 3.20). Three unconformity-bounded subunits have been identified on high-resolution seismic profiles on the upper Hebrides Slope off north-west Lewis, consisting predominantly of lower Oligocene sediments unconformably overlain by a thin wedge of upper Oligocene and middle to lower upper Miocene strata (Fig. 3.8). The lower Oligocene sediments consist of shallow-marine carbonates recovered in a short core (44) from the Geikie Escarpment (Jones *et al.*, 1986), whilst upper Oligocene calcareous mudstones and middle to lower upper Miocene glauconitic sandstones were proved by BGS borehole 88/7,7A, landward of this escarpment (Stoker *et al.,* 1994). The bulk of the Miocene section is of mid-Miocene age, deposited at about 16Ma (intra-Langhian), comparable with the section in well 164/25-2. However, no obvious unconformity equivalent to reflector A - intra-mid-Miocene - was recorded in the borehole, and the erosion surface at the top of the seismically-defined wedge is related to a younger event within the overlying middle Miocene to Holocene sequence (Fig. 3.8). Moreover, the apparent diachroneity of mid-Miocene events, as already demonstrated within the Rockall Trough, makes it difficult to assign unambiguously the middle Miocene section in borehole 88/7,7A to the Oligocene to middle Miocene unit as defined in the basin. The erosion on the upper Hebrides Slope is known to have locally re-excavated a mid-Oligocene surface in the vicinity of the Geikie Escarpment (Stoker *et al.*, 1994). Consequently, the unconformity surface at the top of the wedge is the product of at least two phases of upper slope erosion. This aptly demonstrates the problem of accurately dating sequence boundaries between deep-water basins and the adjacent margins.

In the Hatton-Rockall Basin, DSDP site 116 proved lower Oligocene limestones unconformably overlain by upper Oligocene and younger calcareous oozes (Laughton *et al.*, 1972); the break in sedimentation spans biozones NP23-24 (Berggren and Schnitker, 1983). However, upper Oligocene limestones (NP24-25) were recovered at DSDP site 117 on the eastern margin of the basin. Although the Neogene section at site 116 appears relatively complete at the drillsite, seismic data indicate a prominent unconformity within this section on the flank of the basin, with complex, current-moulded bedforms onlapped by acoustically-layered and flat-lying deposits (Fig. 3.17). When traced to the drillsite, this unconformity occurs within uppermost lower Miocene strata, above which modern-day, deep-water, benthonic foraminifera became established (Berggren and Schnitker, 1983). The implication is that the upper Oligocene to uppermost lower Miocene sediments were deposited under a more vigorous bottom-current regime than the overlying sediments, which reflect the more-stable, modern, current regime. Reflector A clearly represents, in part, a response to a latest early Miocene oceanographic event. This transition is also preserved farther west on the south-west Rockall Plateau, where a fragmented and locally condensed record of Oligocene to middle Miocene carbonate sedimentation is blanketed beneath a widespread cover of younger deposits (cf. Stoker and Gillespie, 1994).

3.2.5. Middle Miocene to Holocene

This sequence is present over the whole study area including the tops of the Rockall and George Bligh banks and axial seamounts (Fig. 3.23). In the Rockall Trough, the sequence is mostly between 50 and 100ms thick, but this increases greatly towards the Barra Fan where it locally exceeds 500ms in thickness. On the western flank of the trough, the sequence is much thinner and is largely preserved as a veneer, below the level of seismic resolution but proved to be present by shallow cores and boreholes. This veneer extends onto the banks and seamounts, and localised accumulations may exceed 20ms in thickness. The overall geometry of the sequence displays a marked east-west asymmetry across the trough (Fig. 3.2). The Hatton-Rockall Basin preserves a thicker (locally >600ms), more-uniformly distributed succession which onlaps and thins onto the surrounding banks (Figs. 3.2 & 3.17).

In the basins, the base of the sequence (where seismically resolvable) is marked by reflector A; its top is everywhere represented by the sea bed. As previously discussed, reflector A is a mid-Miocene unconformity surface which mostly onlaps onto the basin margins (Figs. 3.2 & 3.3). In the Rockall Trough, erosion of the older strata is a basin-wide phenomenon, whilst in the Hatton-Rockall Basin, reflector A is a distinct onlap surface on the eastern flank of the basin. On the adjacent slopes, banks/shelves and tops of seamounts, no equivalent surface has been identified, and the base of the sequence is commonly a composite erosion surface overlying a variety of older sequences (Fig. 3.2). On the Hebrides Slope, the Plio-Pleistocene section was sub-divided during the BGS reconnaissance mapping programme into a number of regionally mappable, informal seismic-stratigraphical units, including the Lower MacLeod, Upper MacLeod, Gwaelo and MacAuley sequences (Fig. 3.1). Although these units are not considered further in this report, they do provide an indication of the high-resolution stratigraphical sub-division that is achievable (Stoker *et al.,* 1993).

The sequence has been sampled in numerous boreholes and shallow cores across the area (Figs. 3.4, 3.6, 3.7 & 3.23). In the Rockall Trough, the limitations of the shallow sampling technique restricted most of the sampling to the upper (Pliocene to Holocene) part of the sequence. However, on the flanks of the trough and on the tops of the seamounts, the proven record extends back into the Miocene. These data compliment the more-complete sections recovered in well 164/25-2 in the north Hebridean region (Fig. 3.8), DSDP site 610 at the southern end of the Rockall Trough (Fig. 1.1), and DSDP site 116 in the Hatton-Rockall Basin (Fig. 3.17).

In the Rockall Trough, the acoustic character of the sequence is well-layered over most of the area, although a more-chaotic reflection configuration becomes predominant adjacent to the Hebrides Slope. The acoustically well-layered sediments are largely associated with several types of bottom-current-influenced depositional features which include: 1) broad-domed, sheetform sediment drifts, up to several tens of kilometres across on the basin floor; 2) narrower, elongate drifts, commomly <10km wide, developed along the basin margin and around the base of seamounts, and with marginal erosional moats; and, 3) localised fields of deep-water sediment waves (Figs. 3.3, 3.23 & 3.24). The variable thickness of the sediments in the basin north and west of Anton Dohrn seamount (Fig. 3.23) is largely a function of bottom-current-controlled sedimentation. The basinal succession has been locally disturbed by faulting (Figs. 2.12 & 3.3h,i,l).

Comparable depositional features from the north-east Rockall Trough have been proved to consist, in the uppermost part of the section, of Pleistocene to Holocene, interbedded, bioturbated, sands and muds deposited mainly by bottom-currents reworking material supplied to the basin-floor by hemipelagic and glaciomarine (ice-rafting) processes (Howe *et al.*, 1994). The interbedded nature of the sediments reflects a variable current-strength. Similar lithofacies have been recovered from Pliocene to Holocene sediments in numerous shallow cores from the basinal area and western flank of the trough in the study area, including cores 57-12/33 (S27), 58-11/2 (S45) and 57-13/76 (S48) (Fig. 3.7), and are interpreted to reflect deep-marine contouritic and hemipelagic sedimentation processes in the basin. A mix of terrigenous and carbonate material comprise the sediments; the terrigenous fraction, in part, reflects a glacially derived component in sediments younger than about 2.48 Ma, which marked the onset of mid-latitude glaciation in this area (Stoker *et al.*, 1994). In older deposits, carbonate material tends to dominate in sediments distal to the Hebridean region (cf. Stoker and Gillespie, 1994); this is consistent with core 57-12/33 (S27) which recovered middle Pliocene chalk (Fig. 3.7)

On the eastern side of the Rockall Trough, middle Miocene to Holocene sediments display upslope-accretion onto the Hebrides Slope (Fig. 3.2). This contrasts with the western side of the trough where the Feni Ridge drift accumulated very little sediment during this interval. Although collectively boreholes 94/1 and 94/4, together with several shallow cores including 56-14/10, 13 (S24) and 57-14/48 (S21), proved a middle Miocene to Holocene sandy veneer (Fig. 3.7), the western margin of the trough appears to have been largely a zone of net erosion. The high-energy setting is consistent with the predominance of sandy and gravelly sediments recovered from the slope flanking Rockall Bank (Figs. 3.6 & 3.7). The gravelly sediments, in particular, probably represent gravel-lag contourites from which most of the finer-grade material has been winnowed away. This contrasts with the southern end of the

Feni Ridge, in deeper water at the mouth of the Rockall Trough (Fig. 1.1), where sedimentation persisted throughout this interval; DSDP site 610 proving several hundred metres of middle Miocene to Holocene pelagic nannofossil chalk and ooze, with glacially-derived terrigenous material at the top of the section (Kidd and Hill, 1987).

The chaotic reflection configuration is most thickly developed in the area of the Barra Fan, on the eastern margin of the trough, where the Hebrides Slope has prograded basinward by the accumulation of a thick succession of debris flows on the slope apron. The chaotic seismic texture is typical of the acoustic response of debris-flow deposits, which also display a hummocky, mounded form. The fan deposits consist of several major packages of debris flows, tens of milliseconds thick (Fig. 3.25), which individually represent an amalgamation of numerous smaller flows. Ponded, highly reflective turbidites are locally interbedded with the debris flows, particularly at the distal-edge of the fan; higher-up on the fan, debris flows predominate. Although this part of the sequence has not been sampled in the study area, shallow cores from a similar build-out (Sula Sgeir Fan) on the northern Hebrides Slope have recovered Pleistocene debris-flow diamictons with thin, interbedded turbidite sands and muds from the uppermost part of the section (Stoker, 1989; Stoker *et al.*, 1993). The seismically resolvable, basinward limit of the debris flows associated with the Barra Fan is well-defined and relatively sharp on seismic profiles (Fig. 3.25). On the Hebrides Slope north of the Barra Fan, debris flows and acoustically layered drift deposits become interbedded (Fig. 3.23). Episodic reworking of the drift deposits by bottom currents may have been partly responsible for generating the interbedded debris flows in this area.

A fragmented record of Miocene to Holocene sedimentation is preserved on the axial seamounts, and on the highs bordering the Rockall Trough. Middle to upper Miocene (NN7-9) bioclastic sandstones with sporadic thin beds of chalk/ooze have been proved in boreholes 90/15,15A and 90/18 from, respectively, Anton Dohrn and Rosemary Bank (Fig. 3.7). These partly correlate with upper Miocene sandstones sampled in several boreholes on the Hebrides Shelf and Slope, including 88/7,7A (Fig. 3.8) (Stoker *et al.*, 1993, 1994). In all of these locations, the Miocene strata are unconformably overlain by Plio-Pleistocene sands and muds. On the Hebrides Slope, Pleistocene glacigenic sediments may locally form at least 50% of the middle Miocene to Holocene sequence (Stoker *et al.*, 1993). The reworking of middle to upper Miocene microfossils into Pleistocene strata on the northern Hebrides Shelf (Stoker *et al.*, 1993) and on the Rockall Bank (cf. Borehole 94/5 in Appendix 1), implies a formerly more-extensive cover of these sediments on the shelves and banks flanking the Rockall Trough.

On the western side of the Rockall Trough, Quaternary sands, gravelly sands and gravels were predominant in shallow cores and boreholes from the veneer on top of Rockall and George Bligh banks (Fig. 3.6). Borehole 94/3 recovered shallow-marine muddy sands associated with a wave-cut terrace or platform on the eastern edge of the Rockall Bank; this is one of several terraces/platforms recognised along the edge of the bank (Figs. 3.3a-d,f & 3.23). Higher on the bank, borehole 94/5 sampled shallow-marine sands from a sand-bar or ridge. These features were probably formed during a Quaternary lowstand of sea-level, the timing of which remains uncertain. At the present day, carbonate debris forms a significant component of the sea-bed layer on Rockall Bank, which can be classed as an isolated, temperate-water, carbonate platform (Scoffin *et al.*, 1980). Similar conditions may also have prevailed on the bank at intervals during the past; lower Pliocene (NN12-15) bioclastic limestone was proved from the upper slope of Rockall Bank in core 58-14/32 (S12), whilst thin-bedded, white, chalky muds of Plio-Pleistocene age were sampled in borehole 94/6 on the northern edge of the bank (Fig. 3.6). A similar bioclastic limestone was also cored in 58-14/56 (S50) from a knoll-like feature on the top of George Bligh Bank, and has been tentatively assigned a Pliocene age.

In the Hatton-Rockall Basin, the middle Miocene to Holocene sequence is acoustically well-layered with sub-horizontal reflections in the eastern half of the basin giving way to more complex, current-moulded bedforms and erosional scours in the west as the sequence onlaps Hatton Bank (Fig. 3.17). The sequence in the main part of the basin is commonly faulted, with faults locally extending up to the sea bed (Figs. 2.14, 2.15 & 3.17). DSDP site 116 proved in excess of 500m of middle Miocene to Holocene calcareous oozes, with an increased terrigenous (ice-rafted) component in the upper Pliocene to Pleistocene section, reflecting mid-latitude glaciation (Laughton *et al.*, 1972). A similar carbonate succession capped with a mixed glacial/interglacial section accumulated on the south-west Rockall Plateau (cf. Stoker and Gillespie, 1994).

4. VOLCANICITY

Extrusive early Tertiary igneous rocks are widespread in the Rockall Trough and on the adjacent shallow-water banks. They are mainly basic in composition (see below) and hence are generally referred to as basalts. However within the vicinity of Rockall Island granite, syenite, dolerite, microgabbro and basalt have all been reported (Jones *et al.*, 1972; Roberts and Eden, 1973; Roberts *et al.* 1974). Unusual ultra-potassic rocks have also been recovered from Rosemary Bank.

4.1. Distribution of lavas

The basalt distribution has been mapped using both high-resolution and multichannel seismic data acquired for this study (Fig. 4.1). In order to depth convert the data, interval velocities of 1480m/s and 2000m/s were used for the water and sediments above the basalts respectively. These figures are consistent with those used for other published BGS maps on the Hebrides Shelf. However the figure for the sediments is undoubtedly a simplification of the real velocitiy for which there is very little control. Hence the contours best represent the form of the 'Top Basalt' surface rather than an accurate depth map. Where contours are absent on the tops of the banks, the basalts are at, or close to, sea bed.

Figure 4.1 confirms the existence across much of the Rockall Trough of large 'window' areas where the basalt is absent or thin (below the limit of seismic resolution). This is compatible with the 'minimalist' school of thought for the extent of the basalts (Ziegler, 1988; Smythe, 1989; Joppen and White, 1990; Boldreel and Andersen, 1993). Window areas to the north and east of Rosemary Bank have also been advocated by Wood *et al.* (1987, 1988). However Keser Neish (1993) suggests that, just south of the main survey area, a distinct layer of Tertiary volcanic rocks with a thickness varying from 1.5-2.0km extends across the Rockall Trough. This volcanic unit has 'the apparent form of interleaved basalt flows of varying velocities rather than dykes and sills intruded into sediments'(Keser Neish, 1993, p.1050). The interval velocities used by Keser Neish for this unit (4.35-4.82km/s) are similar to those used by Roberts *et al.* (1988) (approximately 4.5-4.7km/s) for a layer extending across the width of the Rockall Trough, within the main survey area, and postulated to be 'basalt and/or early

Mesozoic sediments'.

Most lavas were probably erupted subaerially. However there are some indications for submarine eruption. The amount of alteration of the lavas in DSDP 117 (Hatton-Rockall Basin) suggests these lavas may be submarine. Boldreel and Andersen (1993, their figure 2) suggest that most of the basalts in the Rockall Trough between the northern end of Rockall Bank and Rosemary Bank were erupted into a submarine environment, but do not state their reasons. Pillow lavas were drilled below 207.94m in BGS borehole 94/3 (Appendix 1) and have also been described at DSDP site 555 at the south-western end of Hatton Bank. The petrography of sample 57-13/54, collected from the eastern margin of Rockall Bank, suggests it may have formed through the submarine breakup of an extrusive flow.

4.1.1. Sources

The volcanic rocks in the area have been derived from a variety of locations. Potential sources for the basalts on the Hebrides Shelf include the Geikie and St Kilda Tertiary igneous centres. Other, as yet unrecognized, centres and fissures may also have contributed. The eastern boundary fault of the Rockall Trough may also have acted as a conduit enabling lavas to reach the contemporary surface.

George Bligh Bank is a continental fragment which became detached from the Hebrides Shelf during the initial formation of the Rockall Trough. It is therefore not a volcanic seamount comparable to Rosemary Bank and Anton Dohrn. However gravity and magnetic modelling for this study have shown that George Bligh Bank is intruded by two magnetic bodies of contrasting size and density (Edwards and Hitchen, 1994). The smaller body may be a basic intrusion which appears to reach the surface of the bank. Hence this may be a source for the early Tertiary basalts on top of George Bligh Bank. The larger intrusion may be an anatectic granite.

Apart from the Rockall centre, other possible centres may have been recognized on Rockall Bank by Roberts and Jones (1978). In this study, a positive gravity anomaly was discovered on the eastern margin of Rockall Bank, centred at 57° 22'N, 13° 2'W, although this is not well constrained by the data coverage. High-resolution seismic data on the eastern side of the bank commonly image dipping reflectors thought to represent the original attitude of lavas. The dips are generally easterly, implying a source to the west on the top of Rockall Bank.

In the centre of the Rockall Trough obvious sources for lavas are Rosemary Bank, Anton Dohrn and Hebrides Terrace. However fissures (transfer faults) associated with Cretaceous rifting may also have provided conduits to the surface.

4.2. Age of lavas

The most recent compilation of igneous rock ages to the north and west of Scotland was by Hitchen and Ritchie (1993). This paper was included as Appendix 2 in Hitchen and Stoker (1993a); the timescale used was that of Harland *et al.* (1990). The same data have also been plotted by Ritchie and Hitchen (In press) using the updated timescale of Cande and Kent (in press). Data from the present study have been amalgamated into the Hitchen and Ritchie (1993) compilation and an updated age correlation chart is presented as Fig. 4.2.

Carboniferous and Early Permian volcanicity was widespread in mainland Scotland (Francis, 1991). Furthermore, a Permian volcanic centre has been reported from Northern Ireland (Penn *et al.*, 1983) and Permo-Triassic volcaniclastics from wells offshore western Ireland are noted by Tate and Dobson (1989a). Hence the possibility that the oldest lavas in the Rockall Trough may be Carboniferous to Triassic in age cannot be excluded. Joppen and White (1990) suggested that some seismic layering in the bottom of the Rockall Trough may represent interbedded sediments and syn-rift lavas. As the Rockall Trough probably opened in the mid-Cretaceous, some lavas of this age may be present. However no samples from this layered sequence have been obtained. The proven oldest volcanic rocks in the trough are from Anton Dohrn and Rosemary Bank (see below).

4.2.1. Hebrides Shelf

The basalts on the shelf have yielded apparent ages ranging from 63-43 Ma. This wide timespan is geologically implausible and is probably due to argon loss in weathered samples causing excessively 'young' ages to be determined by the K-Ar (whole rock) dating technique. The precise age of these lavas remains unconfirmed.

4.2.2. Darwin (well 163/6-1A)

Well 163/6-1A was drilled on the north-west flank of the Darwin igneous complex. Beneath a Tertiary succession the well encountered 689m of basalt overlying at least 356m of dacite, after which the well was terminated without penetrating through the lava pile (Morton *et al.*, 1988; Abraham and Ritchie, 1991). Isotopic dating of the lavas has yielded a wide range in ages. However the older (mainly Cretaceous) ages are considered to be the result of excess argon from incompletely-degassed, potassium-rich sediments being assimilated into the lavas (Morton *et al.*, 1991). Most of the other ages fall into the range 58-51 Ma, with the average being 55 Ma.

4.2.3. Rosemary Bank

BGS borehole 90/18, drilled on the top of Rosemary Bank, terminated after penetrating nearly 17m of basalts overlain by 1.53m of bioclastic limestone. An upper Maastrichtian nannofossil assemblage was recovered from the limestone and hence the lavas must be older. K-Ar (whole rock) ages increase systematically downhole but are all Tertiary and considered unreliable in view of the nannofossil age. Palaeomagnetic studies suggest that the bulk of Rosemary Bank formed during a period of reversed polarity (Miles and Roberts, 1981). Hence the best conclusion for the age of Rosemary Bank is that it formed no later than 70-68 Ma (during magnetochron 31R) (Hitchen and Ritchie, 1993).

Sample 59-11/12, collected from the top of Rosemary Bank for this study, comprises several lava flows with thin, interbedded limestones. Unfortunately no microfossils were recovered from the interbeds so the age of the basalts cannot be confirmed from this sample.

4.2.4. Anton Dohrn

Rockdrill sample 57-12/18, comprising volcanic clasts in a carbonate matrix, was collected from the top of Anton Dohrn for this study. Forams from the matrix are mid- to late Eocene (NP17-19) in age and hence the clasts must be older. Previously, Jones *et al.* (1974) reported a late Maastrichtian nannofossil assemblage from chalk adhering to volcanic blocks dredged from the eastern side of Anton Dohrn. As the lavas had not altered the chalk they must pre-date it, and hence must be Maastrichtian or older. This is the main evidence for a Cretaceous age for Anton Dohrn.

4.2.5. Hebrides Terrace

Ages of 67-60 Ma have been determined by Omran (1990). As Hebrides Terrace is reversely magnetized this range can be slightly constrained to a reversal between 65.5 and 60 Ma.

4.2.6. George Bligh Bank

The basalts recovered from George Bligh Bank have not been dated isotopically and hence their age has to be estimated from biostratigraphical evidence using samples recovered from the top and flanks of the bank, and subsamples from borehole 94/7. A proven, but undifferentiated, Paleocene age has been obtained from the matrix of a volcanic conglomerate on the top of the bank (samples 58-14/42 and 57). Evidence from other nearby sea-bed samples (58-14/10,11 and 43) suggests a pre-NP6 age for this conglomerate. Hence the lavas on which the conglomerate rests must be mid-Paleocene or older.

4.2.7. Rockall Bank

Isotopic age dating and magnetostratigraphy suggest an age of 55-54 Ma, close to the Paleocene-Eocene boundary (C24R), for the Rockall central complex (Ritchie and Hitchen, in press). A Late Cretaceous age (83 ± 3 Ma) has also been obtained from Helen's Reef (3km ENE of Rockall Island), although the low potassium content of the sample means that this age must be treated with some caution.

Four boreholes (94/2, 3, 5 and 6) and one sea-bed sample (57-14/53) penetrated *in situ* lavas on the top of Rockall Bank (Appendix 1). None of the lavas penetrated by the boreholes (all basalts) has been isotopically dated. Lavas were proven at two levels in borehole 94/3; the sediments containing the upper lava have been biostratigraphically dated at NP13-14 (latest early Eocene to early mid-Eocene, approximately 51-49 Ma). Hence this lava records a late event in the volcanic history of this margin. Similar, and even younger ages, up to late mid-Eocene, have been recorded for tuffaceous deposits in DSDP boreholes drilled on the extreme south-western edge of the Rockall Plateau (Stoker and Gillespie, 1994, their figures 1 and 2). Lavas penetrated at the base of the 1994 boreholes on Rockall Bank are late Paleocene to early Eocene in age. A K-Ar (whole rock) age of 57.8±1.6 Ma has been obtained from a trachyte lava (sample 57-14/53). The high potassium content and fresh nature of the rock suggest this age may be fairly reliable.

4.3. Geochemistry

Geochemical data have been collated from a variety of sources including DGU, academia, commercial wells and published information. However the vast majority of the data have been derived from material collected and analysed by BGS, either from previous work or specifically for this project. Apart from a single deep-water site in the northern Rockall Trough (well 163/6-1A), most of the material has been gathered from the Hebrides Shelf, George Bligh and Rockall Banks, and the mid-trough seamounts. The locations from where geochemical data have been obtained are shown in Fig. 4.3.

Where the material is suitable, major, trace, rare-earth element and lead isotope data have been determined. This allows the derivation, evolution and contamination of an igneous rock to be characterised (Tables 4.1, 4.2 and 4.3).

Appendix 1 of Hitchen and Stoker (1993a), written by A C Morton, contained a review of the existing knowledge of the petrography, geochemistry and isotope geochemistry of the Late Cretaceous to early Tertiary igneous rocks of the western margin of the UK south of the Wyville-Thomson Ridge. Appendix 3 of this report contains a similar review of all the igneous rocks collected for this study during field operations in 1994. These two reviews comprise the most comprehensive regional geochemical account so far produced for the offshore igneous rocks west of Scotland.

To the west of Scotland the vast majority of igneous rocks from which samples have been obtained are extrusive in origin and basic in composition. Although intrusive rocks are clearly widespread and are imaged on seismic data, none has been sampled for this study. They have, however, been penetrated in The Minch and the Sea of Hebrides by sampling and shallow drilling, and west of Shetland in commercial deep wells.

Most igneous rocks in the area are derived from a North Atlantic asthenopheric mantle (NAAM) source, which has been modified by the Iceland plume. Consequently, many of the rocks cannot be described as true mid ocean ridge basalts (MORB). Variations in geochemistry may be due to the depth at which this material was produced. Most rocks have also suffered some alteration in their geochemistry en-route to the surface due to processes such as assimilation, differentiation or fractional crystallisation. There is a small number of examples where the original magmatic source material is not NAAM-like, such as at Rosemary Bank, well 163/6-1A (dacites) and Rockall Island. These and other locations are discussed below.

4.3.1. Hebrides Shelf

All the basalts on the shelf are derived from a NAAM source although those in the north (85/7, 90/4 and 88/10) appear to be more alkaline than those farther south (85/5B 90/7 and 90/10). Isotope data from well 164/25-1 and boreholes 88/10, 90/7 and 90/10 (see Table 4.1) provide strong evidence that Lewisian basement has been assimilated into the melt during ascent of the magma from the upper mantle. Lead isotope data from one sample from borehole 85/7 suggests that pre-Tertiary sediments are present beneath the basalts at this location.

4.3.2. Darwin (well 163/6-1A)

Three cores have been cut from the basalt interval in this well (cores 4, 5 and 6). Petrographic and geochemical data show differences between the basalts of core 4 and cores 5-6. The core 4 basalts are more alkaline and can be described as 'within-plate' tholeiites. Basalts from cores 5-6 are more typically N-type MORB. The differences can be explained by the earlier basalts representing greater degrees of partial melting. Lead isotope data from a single sample taken from core 6 indicate some contamination by subcontinental lithospheric material, indicating the presence of continental crust in the northern Rockall Trough.

The geochemistry of the dacites in well 163/6-1A is indicative of (?Mesozoic) black shales having been incorporated into the melt (Morton *et al.*, 1988; Hitchen and Stoker, 1993a, Appendix 1). The process is one of anatectic melting of carbonaceous shales by large volumes of basic magma ponded within the sedimentary pile. Similar rock types have been recognized, and similar processes invoked, for the Erlend dacites north of Shetland (Kanaris-Sotiriou *et al.*, 1993), and those drilled at DSDP site 642 on the Voring Plateau.

4.3.3. Rosemary Bank

Rock types from Rosemary Bank fall into two categories. Sub-alkaline basalts from a NAAM-like source have been recovered from the foot of the bank by dredging (Dietrich and Jones, 1980) and from the top of the bank by shallow drilling (BGS borehole 90/18). Lead isotope data from the dredged sample suggest that the melt assimilated some upper crustal sedimentary rocks during its ascent to the surface.

In contrast, highly alkaline, ultra-potassic rocks have also been recovered from the top of the bank. Dredge samples of lapilli tuffs were reported by Waagstein *et al.* (1989). The tuffs may represent vent material during a late stage event in the history of Rosemary Bank. Sample 59-11/12, collected for this study, comprises several phono-tephrite lava flows with similar geochemistry to the tuffs. Both these occurrences are considered to be derived from the partial melting of subcontinental lithospheric material, indicating that continental crust is present in the northern Rockall Trough in the vicinity of Rosemary Bank.

4.3.4. Anton Dohrn

Material from Anton Dohrn is available from a dredge site on the eastern slope of the seamount (Jones *et al.* 1974; 1994) and from sample 57-12/18, recovered for this study from the top of Anton Dohrn. The dredge comprises four, variously weathered, basaltic blocks, whereas the sample is a carbonate which includes volcanic clasts.

All the recovered material is basaltic in composition. That from the dredge is 'within-plate' in character, plots within the North Atlantic MORB field on a lead isotope diagram, and is distinct from basalts in well 163/6-1A and Rosemary Bank. None of the material shows significant evidence for crustal contamination. The age, location and geochemical data from Anton Dohrn suggest it formed earlier than the main Iceland plume, in an area of highly stretched, very thin crust possibly on a terrane boundary.

4.3.5. Hebrides Terrace

Two samples have previously been recovered from Hebrides Terrace. Both are sub-alkaline in character and comprise typical N-type MORB material. The lead isotope data suggest that the magma has assimilated some continental crustal material en-route to the contemporary surface. The trends are not compatible with contamination by Lewisian basement but are more indicative of Islay terrane material. Hence, although the conclusion is based on a very limited data set, it appears that Hebrides Terrace lies south of the Lewisian/Islay terrane boundary.

4.3.6. George Bligh Bank

All the volcanic rocks recovered from George Bligh Bank are alkali-basalts. Those from borehole 94/7 may be termed hawaiite; those from sample 58-14/42 as trachyandesite or benmoreite. The dredge samples can be classified as 'within-plate'. The rare-earth data show that the George Bligh Bank basalts were generated by lower degrees of partial melting than those of Rockall Bank to the south. Furthermore, the George Bligh Bank basalts are all contaminated, to a greater or lesser degree, by granulite-facies continental basement. This contamination is unlike that of Rockall Bank (see below) but appears to be caused by Lewisian basement. This implies that the Lewisian/Islay (Rockall) terrane boundary is located between the northern part of Rockall Bank and George Bligh Bank.

4.3.7. Rockall Bank

Most of the igneous rocks recovered from Rockall Bank are basaltic and sub-alkaline in composition. Differences in silica saturation and light rare-earth enrichment indicate that variations are due to differences in the degree of partial melting. Many basalts have also been contaminated by other lithologies, mainly Islay terrane (Rockall Bank) material. This includes both amphibolite (eg borehole 94/5) and granulite (borehole 94/6) facies metamorphic rocks. However sample 57-13/66, from the eastern flank of the bank, appears to represent uncontaminated, mantle-derived, asthenopheric material and plots firmly in the MORB field. The petrography of the basaltic agglomerate recovered in sample 57-13/54 suggests that it was formed by the breakup of a submarine flow. The upper and lower basalt flows in borehole 94/3 are similar in composition, although the upper one is at least 9 My younger and contaminated by Rockall basement. However a basalt pebble from coarse-grained sandstones, at a stratigraphical level between the flows in the same borehole, is petrographically and mineralogically different from the flows and is clearly exotic.

Rockall Island is granitic in composition and derived from the melting of subcontinental lithospheric material. The trachytes (samples 57-14/53 and 58-14/51) are differentiates, through fractional crystallisation, of the same parent magma which was responsible for the basaltic outpourings. However sample 57-14/53 may have been derived from a slightly more alkaline source and is more contaminated by Rockall Bank basement. Borehole 94/3 contains several vitric tuffs which may be the result of andesitic lavas flowing into water which caused rapid cooling, degassing and fragmentation of the lava. Although of similar age, the tuffs bear no resemblance to the Balder Formation, either in terms of texture or composition, and are therefore probably of local origin.

5. PROSPECTIVITY

No commercial hydrocarbon exploration wells have been drilled in the Rockall Trough. Prior to this study therefore, the perceived prospectivity of the trough was based mainly on circumstantial evidence by extrapolating the known geology from west of Shetland, the Hebrides and western Ireland (Erris, Slyne and Porcupine basins). A limited number of seismic reflection and refraction profiles have been interpreted (see Chapter 2: Structure) and some palaeogeographic reconstructions had been published (eg Ziegler 1988; 1990).

This chapter concentrates on two principal factors which affect the prospectivity of the Rockall Trough: (1) the presence, or otherwise, of a source rock, and (2) possible hydrocarbon-trapping structures. Figure 5.1 locates the possible hydrocarbon-related features identified by this study.

5.1. Source rocks

Carboniferous, Mesozoic (principally Jurassic) and Tertiary source rocks may all be present in the Rockall Trough.

5.1.1. Carboniferous

The oldest likely source rocks in the Rockall Trough are Carboniferous in age, although evidence for their presence is circumstantial. Thick coal-bearing sequences are known onshore in central Scotland and Ireland, and have been proved offshore in the Donegal Basin where Irish well 13/3-1 included up to 50 coal horizons (Tate and Dobson, 1989). However, although Stein (1988) postulated Carboniferous rocks to be present in the North Minch Basin, well 156/17-1 proved Triassic rocks to rest directly on Torridonian (Fyfe *et al.,* 1993).

In the eastern Rockall Trough, between Anton Dohrn and Hebrides Terrace seamounts, Roberts *et al.* (1988) identified a refraction layer with an interval velocity of 5.3km/s. Farther south in the Irish sector, Shannon *et al.* (1994) identified a 4.5km/s interval-velocity layer which extends across the width of the trough. West of the present main study area, Keser

Neish (1993) has reported resolved velocities of 5.1-5.3km/s for dipping strata on Hatton Bank. All these authors suggest that late Palaeozoic or Carboniferous rocks comprise at least part of these layers.

A study of reworked palynomorphs undertaken by Riding (1995) has shown that the thermally mature Carboniferous spore *Lycospora* has been reworked into Eocene, shelf-margin, sediments at three sites south-east of George Bligh Bank (samples 58-14/53, 59-14/4,5,6 and 59-14/8). Bearing in mind the easterly progradation of this shelf-margin succession (see Chapter 3: Stratigraphy), the most obvious source for these sediments is likely to have been from the west, implying an available Carboniferous source at this time. This may have been Hatton Bank (see Keser Neish, above), or possibly East Greenland where continental-facies Carboniferous rocks have been mapped in Jameson Land.

The evidence for widespread occurrence of Carbonifeous rocks on the western margin of the British Isles, possibly farther west on Hatton Bank, and in East Greenland, implies that rocks of this age may be present in the deeper parts of the Rockall Trough. The lithology cannot be accurately predicted but is likely to be continental in aspect.

5.1.2. Mesozoic

The presence of Mesozoic source rocks is probably crucial if prospectivity of the Rockall Trough is to be good. Upper Jurassic to Lower Cretaceous rocks (the Kimmeridge Clay Formation equivalent) are responsible for the oil and gas accumulations west of Shetland (Bailey *et al.,* 1987). Mesozoic source rocks may also have been the source for the gas shows in the Lopra-1 borehole, on Suduroy, Faeroe Islands, implying a marine source rock beneath the basalt cover (Jacobsen and Laier, 1984).

Farther south, potentially very rich source rocks have been proved beneath the northern Hebrides Shelf in the West Lewis and West Flannan Basins (Hitchen and Stoker, 1993b). Ryazanian shales have been proved in both basins (BGS boreholes 90/5 and 90/9), with those in the West Lewis Basin having with TOC values up to 14.50%. Bathonian source rocks, with TOC values up to 6.28%, have been proved by BGS boreholes 88/1 and 90/2 in the West

Lewis Basin. Although immature where drilled on the shelf, both the Bathonian and Ryazanian shales have excellent oil source-rock potential and, if present in the northern Rockall Trough, may have generated large amounts of hydrocarbons (Hitchen and Stoker, 1993b).

Information from Irish well 27/13-1 shows that source rocks at two stratigraphical levels in the Jurassic are also present in the Slyne Trough, offshore western Ireland (Trueblood, 1992). In this well the Sinemurian-Pliensbachian strata ascribed to the Pabba Shale Formation has TOC values up to 4.04% whereas the Toarcian Portree Shale Formation has values up to 7.15%. The higher shales are only marginally mature, but the lower have R_0=0.70%. The Upper Jurassic Kimmeridge Clay Formation is also present on the western Irish Shelf, and has sourced the Connemara oilfield in the North Porcupine Basin. The presence of any of these Jurassic sources in the Rockall Trough would greatly enhance its prospectivity.

Evidence for possible source rocks in the deeper parts of the Rockall Trough - Faeroe-Shetland rift axis can also be derived from the study of the acidic volcanic rocks in the Erlend (wells 209/4-1A and 209/9-1) and Darwin (well 163/6-1A) central igneous complexes. In both cases, highly peraluminous, cordierite-bearing dacites have been proved by drilling. The geochemistry of the dacites, especially the presence of graphite in the Erlend wells, implies that they may have been derived by the anatexis of carbonaceous black shales (Morton *et al.*, 1988; Kanaris-Sotiriou *et al.*, 1993). Regional considerations suggest that these shales are likely to be Jurassic or Cretaceous in age.

The three southernmost boreholes drilled for this study have yielded Mesozoic palynomorphs reworked into the Eocene. In boreholes 94/1 and 94/3 the Lower Cretaceous spore *Cicatricosisporites* was identified whereas in borehole 94/2 two Jurassic/Cretaceous miospores were found. In all cases the colouration of the palynomorphs was indicative of thermally mature sediments. The boreholes penetrated sediments which appear to be sourced from the west (see Chapter 3: Stratigraphy). Jurassic and Cretaceous sediments are present in the East Greenland basins in Jameson Land and the area to the north.

5.1.3. Tertiary

Borehole 94/1 was drilled just east of the western basin-bounding fault of the Rockall Trough. Beneath a Neogene-Quaternary succession the borehole penetrated 25.03m of Middle Eocene silty mudstone overlying 6.52m of sandstone, after which the borehole was terminated (see Appendix 1). The mudstones are waxy and greasy and have an aromatic smell.

Three samples from borehole 94/1 were tested for hydrocarbon source potential (see Volume 4, Appendix 3, section 5.6). TOC values range from 1.1-1.3% and S2 values from 0.29-0.31mg/g. Vitrinite reflectance values range from 0.22-0.25, and Tmax from 386-389°C. Hence the mudstones may be considered a potential source rock, although immature where drilled. The high oxygen index compared with the low hydrogen index shows that the mudstones are probably gas-prone, but even if present in the central part of the Rockall Trough the mudstones are unlikely to be thermally mature. No other potential Tertiary source has been identified.

5.1.4. Evidence for fluid migration

In the area between Rockall and George Bligh banks, the high-resolution airgun data have imaged possible gas-charged sediments within the Eocene interval at one location (Fig. 5.2), and the underlying reflector D (Top Basalt) is acoustically masked.

East of Rockall Bank a possible fluid-escape chimney was recognized on sparker data (Fig. 5.3). On deep seismic lines D6 and D19, with their intersection over the feature, it can be seen that the fluid was not derived from the near surface, although whether the fluid is water or gas cannot be determined. A gravity core (sample 57-13/34) for geochemical analysis was taken on the feature; total n-alkanes from the lower sub-sample were relatively high and the TSF data show a significant fluorescence maximum in the oil/condensate region of the spectrum. However this may not be indicative of a thermogenic source (see Volume 4, Appendix 3).

Other structures which are possibly indicative of fluid migration have been imaged on both the high-resolution and conventional multichannel data. Figure 5.4 illustrates a typical structure where the mainly Eocene interval between reflectors D and C is deformed. Similar structures, which have developed further so that the sea bed is deformed, have been explained by Hovland (1990) as being the result of gas migrating upwards into a plastic clay layer causing instability and deformation due to differential buoyancy. These possible fluid migration structures, which have also been identified on the multichannel data, appear to be more common in the middle and and western parts of the Rockall Trough. Some have also been observed in the Hatton-Rockall Basin.

A headspace gas analysis from sea-bed sample 58-14/54, obtained from the top of the diapir south-east of George Bligh Bank (Fig. 2.12), contained 2.3% methane. The $\delta^{13}C$ of the methane was determined by mass spectrometry to be on the boundary between thermogenic and biogenic sources. The methane may be thermally derived therefore but could have been altered or diluted during migration. Figure 3 of Appendix 3 shows the distribution of methane concentrations across the Rockall Trough. The higher values are all on the western side of the trough, an observation which requires further investigation.

5.2. Styles for hydrocarbon traps

Three principal styles of potential hydrocarbon trap are envisaged for the Rockall Trough. Two are structural; one is stratigraphic.

5.2.1 Tilted fault blocks

These have been imaged on multichannel seismic data on the western margin of the Rockall Trough (Fig. 2.9). Joppen and White (1990) illustrated tilted fault blocks at a very shallow level in Irish waters; these are described in more detail in section 2.5.3. The blocks do not appear to be covered by lavas, but neither is there a significant sedimentary cover containing a possible seal. Seismic profile 93/02-D3, acquired for this study, shows a tilted block in UK waters where lavas may be present in a thin sedimentary sequence over this block in approximately 1700m of water. Interpretation of seismic reflection and refraction data suggests that fault blocks may be present along the whole eastern margin of Rockall Bank, although they are not definitively imaged perhaps due to the basalt cover.

5.2.2. Fault-scarp fans

In view of the occurrence of major faults on the margins of both the Rockall Trough and Hatton-Rockall Basin there is the possibility of syn-rift mid- to Late Cretaceous fault-scarp fans. However, lavas extend across these areas and no fans of this age have been imaged on the seismic data.

In the Hatton-Rockall Basin a post-lava fault-scarp fan has been recognized adjacent to the north-west basin-bounding fault (Figs. 2.14 and 5.5). It immediately overlies reflector D and hence is likely to be latest Paleocene to early Eocene in age. Interpretation of the seismic data shows that the fan extends for nearly 6km into the basin before losing its identity. The vertical displacement of the basalt horizon is approximately 800ms TWT. Nothing of a similar style and age has been detected along the western margin of the Rockall Trough.

5.2.3. Lowstand fans

After the high sea levels of the Late Cretaceous, the early Tertiary was a time of regression caused by uplift and associated volcanism. Although the Rockall Trough may have remained a deep-water area throughout the Tertiary, the Scottish mainland was an area of potential sediment supply for the adjacent shelf and the trough. In times of low sea level the shelf may have been sub-aerially exposed or else covered by such shallow water that it was completely by-passed as an area of sediment accumulation. Hence, early Tertiary slope fan or basin floor sandstones may exist adjacent to the margins of the Rockall Trough. These are schematically represented in Fig. 5.6. Such fans may be more likely on the eastern side of the trough than the west as the sediment supply was probably greater here.

5.3. Summary

The results of this study show that the western side of the Rockall Trough has more indications of potential source rocks (gas blanking, fluid migration structures, methane concentrations) than the east, although the presence of a thermogenic source rock has not been demonstrated. Source rocks of Carboniferous, Mesozoic and Tertiary age have been drilled around the margins of the Rockall Trough but cannot be proved in the trough itself without deep drilling. Tilted fault blocks have been imaged close to the western margin of the Rockall Trough in both UK and Irish waters.

6. SUMMARY AND CONCLUSIONS

The widespread distribution of Upper Cretaceous to lower Palaeogene volcanic rocks continues to hinder the investigation of the geology and resource potential of the Rockall Continental Margin. Nevertheless, this project has accumulated a wealth of new data from across the margin, which has greatly improved our understanding of its geological development. The interpretation of these data, and their integration with existing information from within and beyond the study area, provides a number of key observations about the geological framework and potential prospectivity of the Rockall Continental Margin which are summarised below:

6.1. Geological framework

- Rockall Bank is part of the Islay structural terrane. The continental basement on the bank includes granulite gneiss dated at 1914Ma. The boundary between the Islay and Lewisian terranes is aligned between Rockall and George Bligh banks, through Anton Dohrn Seamount and to the north of the Hebrides Terrace Seamount.

- The Rockall Trough is underlain by highly stretched, thinned, continental crust heavily intruded by igneous material. The positive gravity anomaly north of Anton Dohrn Seamount suggests that here the crust came close to complete separation.

- The Rockall Trough is defined by major basin-bounding faults on its eastern and western margins.

- A tilted fault block has been imaged on the eastern flank of Rockall Bank, similar to that previously reported in the Irish sector. However, structures within the UK area remain largely obscured on seismic data by the widespread volcanics.

- Widespread shallow faulting has been imaged on the high-resolution seismic data. Some of the faults affect the sea bed. This is especially apparent in the Hatton-Rockall Basin. Minor compressional structures have also been recognised.

- The major rifting episode in the Rockall Trough was probably during mid-Cretaceous time. Syn-rift lavas may be present in the deeper parts of the Rockall Trough, whereas Upper Cretaceous lavas, volcaniclastic sediments and conglomerates have been proven from the axial seamounts of Rosemary Bank and Anton Dohrn. The lavas from Rosemary Bank show evidence for a subcontinental lithospheric source.

- The following ages have been suggested in the literature for pre-major rift sediments in the bottom of the Rockall Trough: Torridonian, Carboniferous, Permo-Triassic, Jurassic or Early Cretaceous. The bulk of the sediments preserved in the trough are Late Cretaceous and Tertiary in age.

- A unified seismic stratigraphy has been established, for the first time, for the uppermost Mesozoic and Cenozoic succession in the central and northern Rockall Trough. This is based on various BGS and commercial seismic reflection data, BGS borehole and shallow sample results, and commercial well data, Correlation with DSDP sites in the Hatton-Rockall Basin reveals broadly comparable Cenozoic basin histories for these two major depocentres.

- Volcanic rocks form acoustic basement over much of the Rockall Continental Margin. Lavas cover much of Rockall Bank, George Bligh Bank and the Hebrides Shelf, and probably underlie most of the Hatton-Rockall Basin. Although lavas are absent from a large part of the Rockall Trough, sills are widespread in this basin. Most of the lavas are late Paleocene to early Eocene in age and were extruded in the build-up to sea-floor spreading in the Iceland Basin. They are largely basaltic in composition.

- Late Paleocene to early late Eocene sedimentation reflects tectonic instability across the Rockall Continental Margin following the onset of sea-floor spreading west of the Rockall Plateau. A prograding shelf-margin sequence on the western margin of the Rockall Trough preserves a fluctuating record of alluvial to shallow-marine sedimentation, punctuated by phases of uplift, erosion and sporadic volcanism. Such instability may be responsible for the development of rotational slides and diapiric structures within the rapidly accumulating sediment wedge. The Rockall Trough may have been actively subsiding during this interval; shallow-marine sediments on top of Anton Dohrn Seamount indicates that it was submerged by early Eocene time.

- Late Eocene differential subsidence within the Rockall Trough and Hatton-Rockall Basin provided the tilted, basin-margin, unconformity surface onto which upper Eocene to middle Miocene sediments onlap. Unconformities within this sequence suggest further sporadic tectonism during the late Eocene to mid-Miocene interval, as both basins developed their maximum basinal expression. Current-moulded, deep-water sedimentation, and the initiation of the Feni Ridge sediment drift on the western margin of the Rockall Trough, indicate that strong deep-sea current systems had become established in the deep-water basins around the time of the Eocene/Oligocene boundary. This style of sedimentation generally dominates the late Eocene to mid-Miocene interval, although a phase of late Eocene to earliest Oligocene deep-water fan deposition, sourced from the Rockall Bank, resulted from a tectonically controlled change in relative sea level.

- Middle Miocene to Holocene sedimentation was preceded by a phase of uplift and/or change in regional palaeoceanography, which resulted in the development of a widespread unconformity, and the initiation of the Barra Fan on the eastern margin of the Rockall Trough. The latter accumulated a thick succession of debris flows, including glacially derived material during the mid- to late Pleistocene. In the central and western part of the Rockall Trough bottom-current deposition dominated, although the sequence is relatively thin, and an erosional regime prevailed on the western margin of the trough. This variation in sediment accumulation has resulted in a marked asymmetry in depositional sequence architecture across the Rockall Trough. The Hatton-Rockall Basin accumulated a thick succession of calcareous oozes deposited by bottom-current processes, although erosional processes prevailed on the eastern margin of the basin.

6.2. Prospectivity

- Circumstantial evidence suggests that Carboniferous, Mesozoic or lower Tertiary source rocks may be present in the Rockall Trough, but a definite thermogenic source has not been proved.

- Possible hydrocarbon indications (gas blanking, fluid migration structures, higher methane concentrations in surface sediments) are more common in the western Rockall Trough than in the east.

- Potential hydrocarbon traps include tilted fault blocks, fault-scarp fans and lowstand slope-apron or basin-floor fans.

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8. SEPARATE LISTING OF ALL ROCKALL PROJECT REPORTS

(to April 1995)

8. SEPARATE LISTING OF ALL ROCKALL PROJECT REPORTS

NOTES: *1. Listed in chronological order (to April 1995)*
*2. * not routinely distributed to consortium members*

<u>1990</u>

STOKER, M S, ABRAHAM, D A, EVANS, D, LONG, D, ARDUS, D A, and DOBINSON, A. 1990. The Rockall continental margin: a review of existing data and recommendations for a 10-year regional survey programme. *British Geological Survey Technical Report* WB/90/5.

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In preparation or planned:

*Simon Petroleum Technology. 1995. Processing report for 1993 seismic survey. Grid and transects.

*Simon Petroleum Technology. 1995. Processing report for purchased Mobil seismic data.

9. FIGURES AND TABLES

(In chapter order)

Figs. 1.2, 1.3, 1.4, 3.2, 3.3, 3.4, and 4.1 in plastic wallets at back of this volume

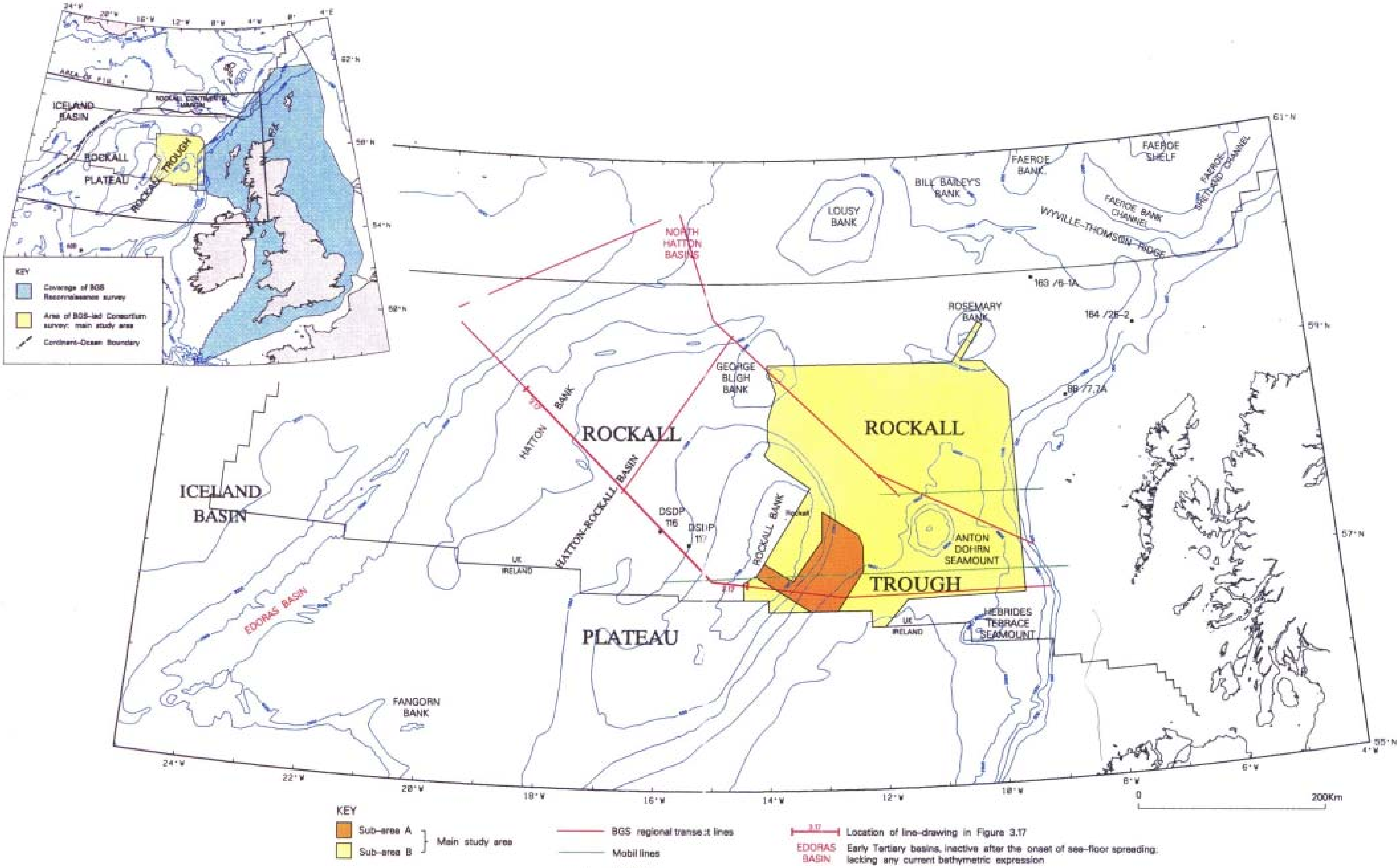


Fig. 1.1 Location of main study area and regional transect lines, together with boreholes and early Tertiary basins outside of the study area but referred to in the text. Inset shows the study area in the overall context of the Rockall Continental Margin, and in relation to BGS seismic coverage on the inner margin: location of DSDP site 610 also indicated to the south of the area. Bathymetric contours in metres.

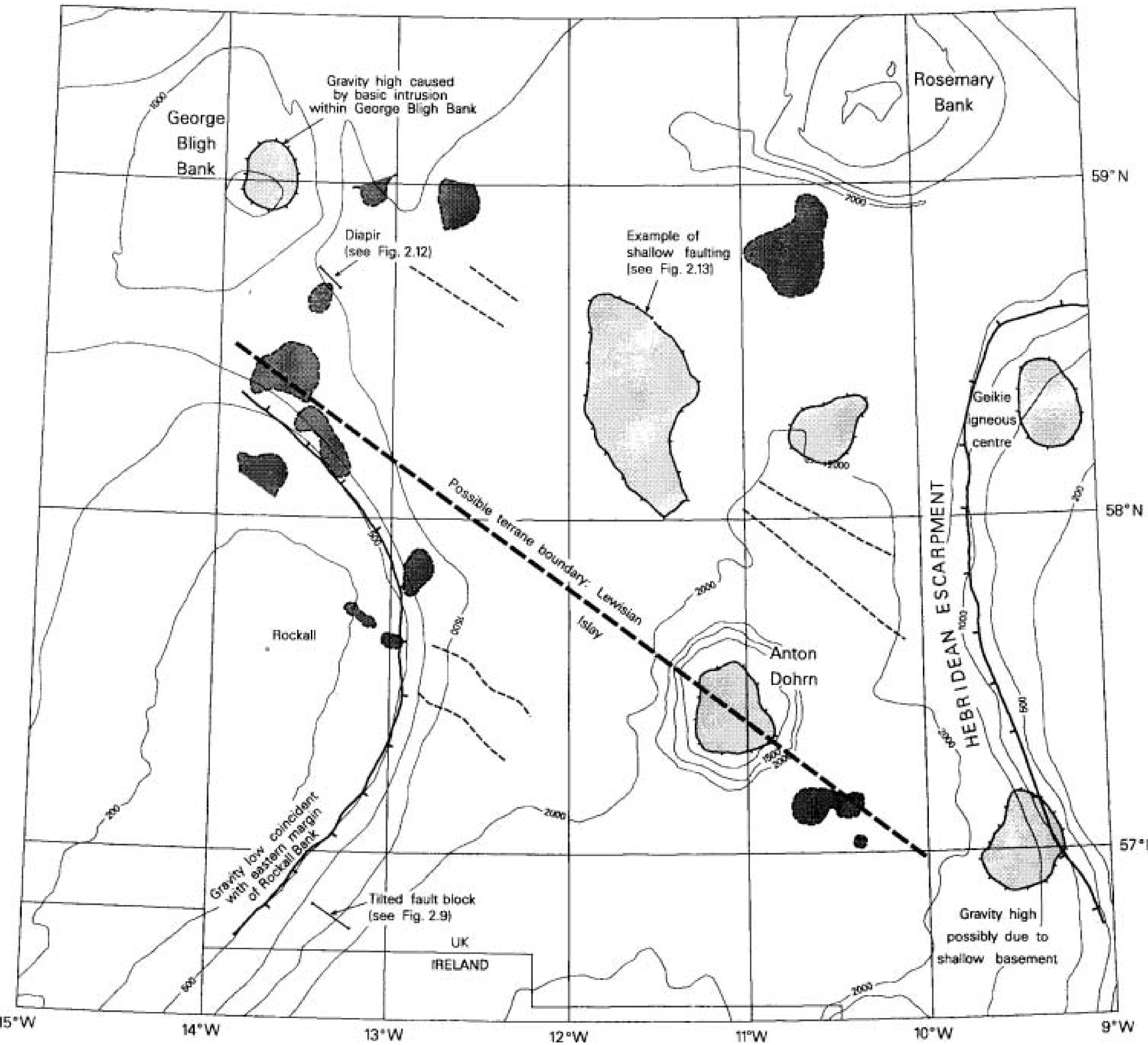


Figure 2.1
Synoptic structure map based on seismic, gravity and magnetic data.

KEY

200 Bathymetry in metres

Magnetic trends or highs

Top basalt escarpment

Positive gravity anomaly

High magnetic anomaly

0 40km

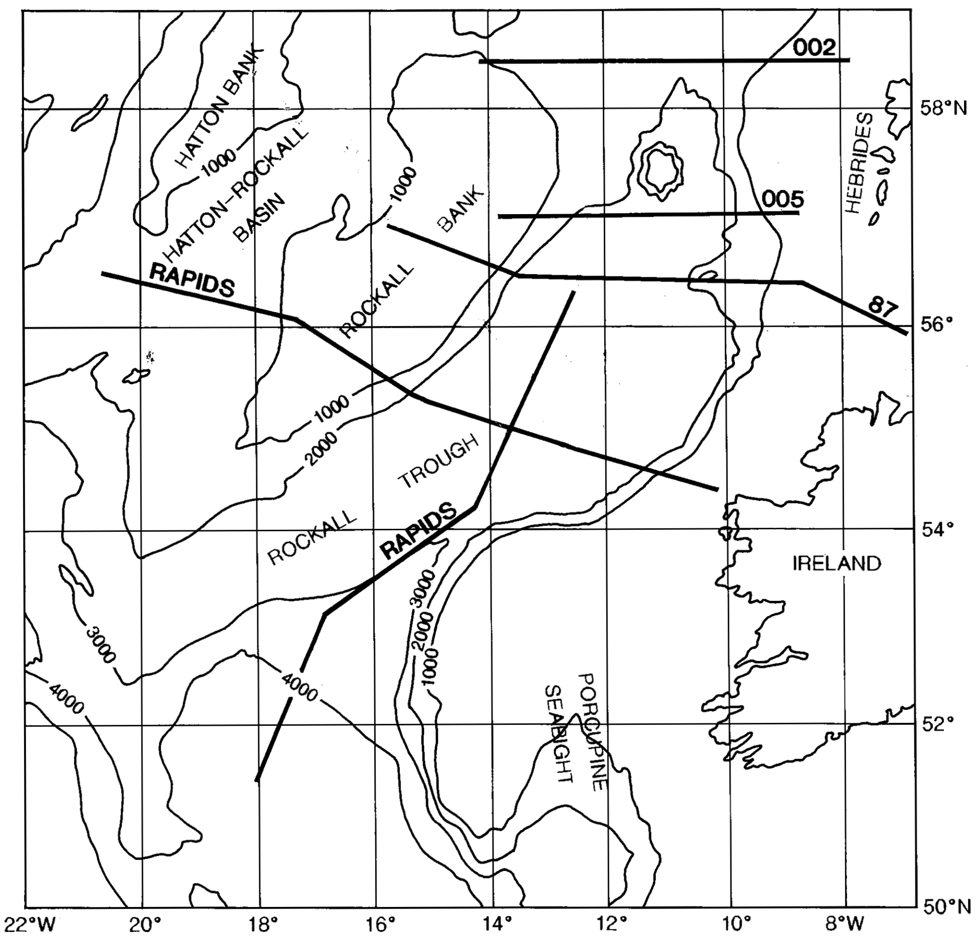


Fig. 2.2 Location of crustal structure profiles across the Rockall Trough

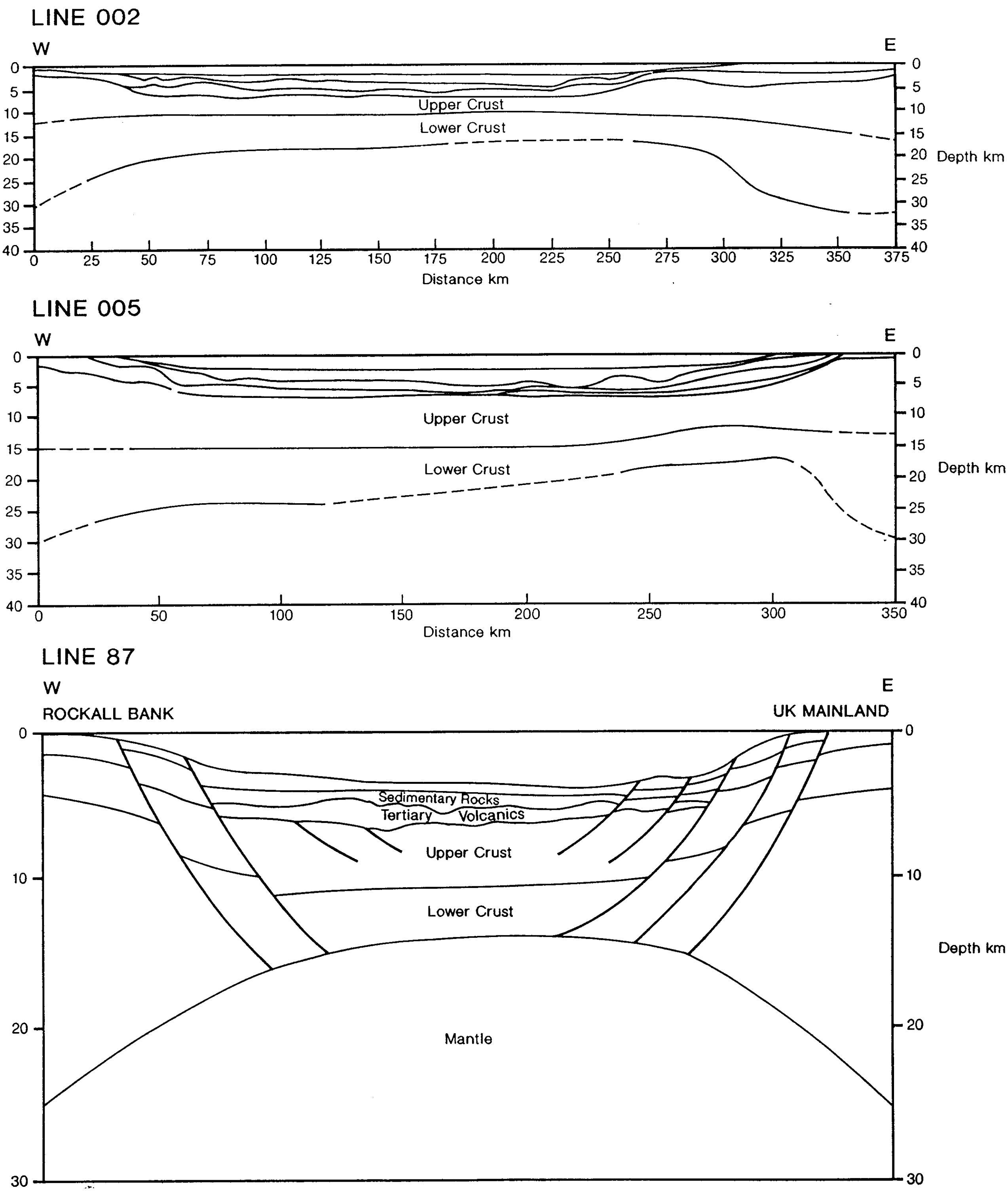


Fig. 2.3 Crustal profiles across the Rockall Trough. Lines 002 and 005 from Roberts et al. (1988). Line 87 from Keser Neish (1993).

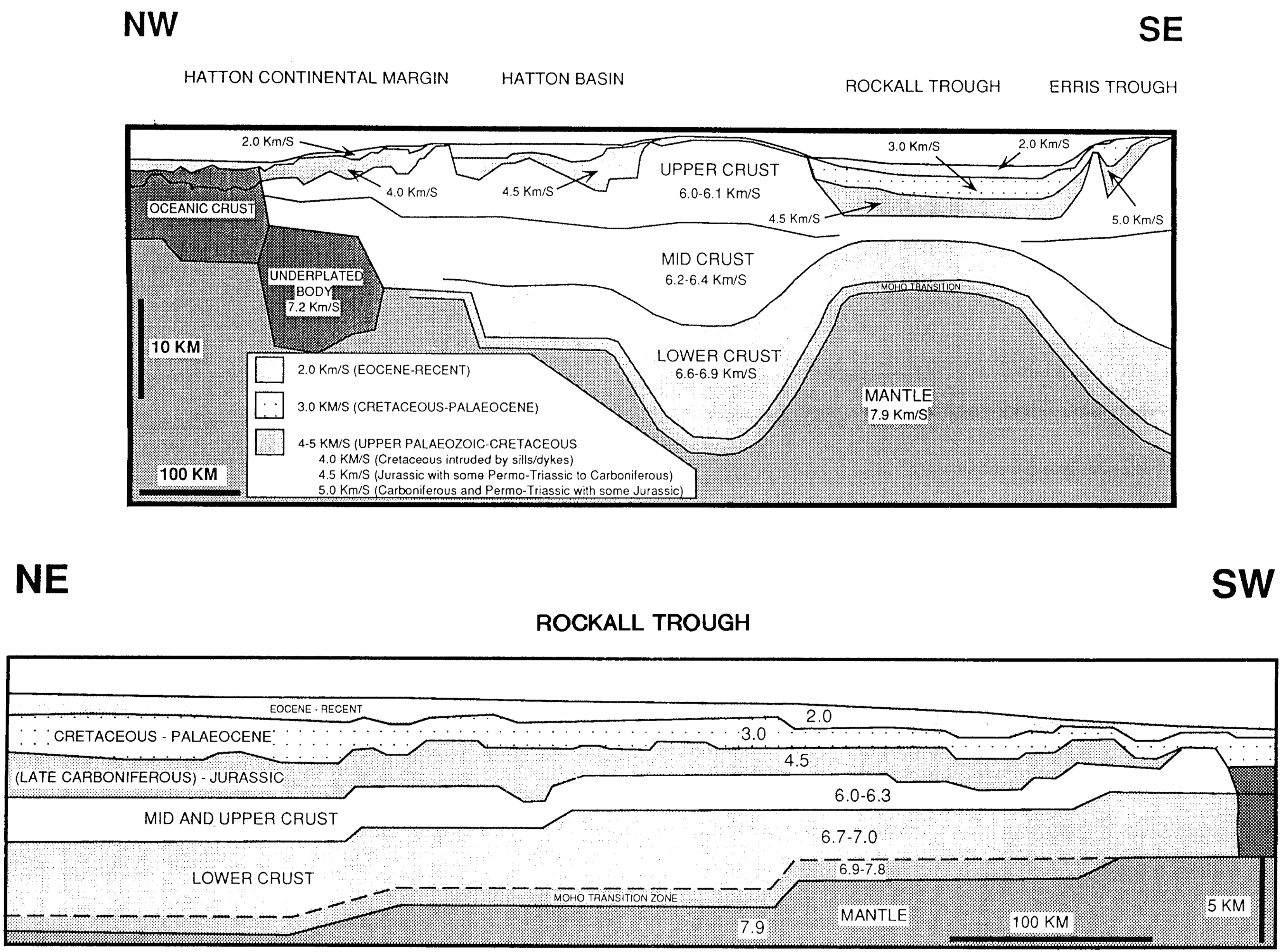


Fig. 2.4 Transverse and axial profiles of the Rockall Trough based on the RAPIDS data (from Shannon et al. 1994). Numbers are refraction velocities (km/s) for each layer.

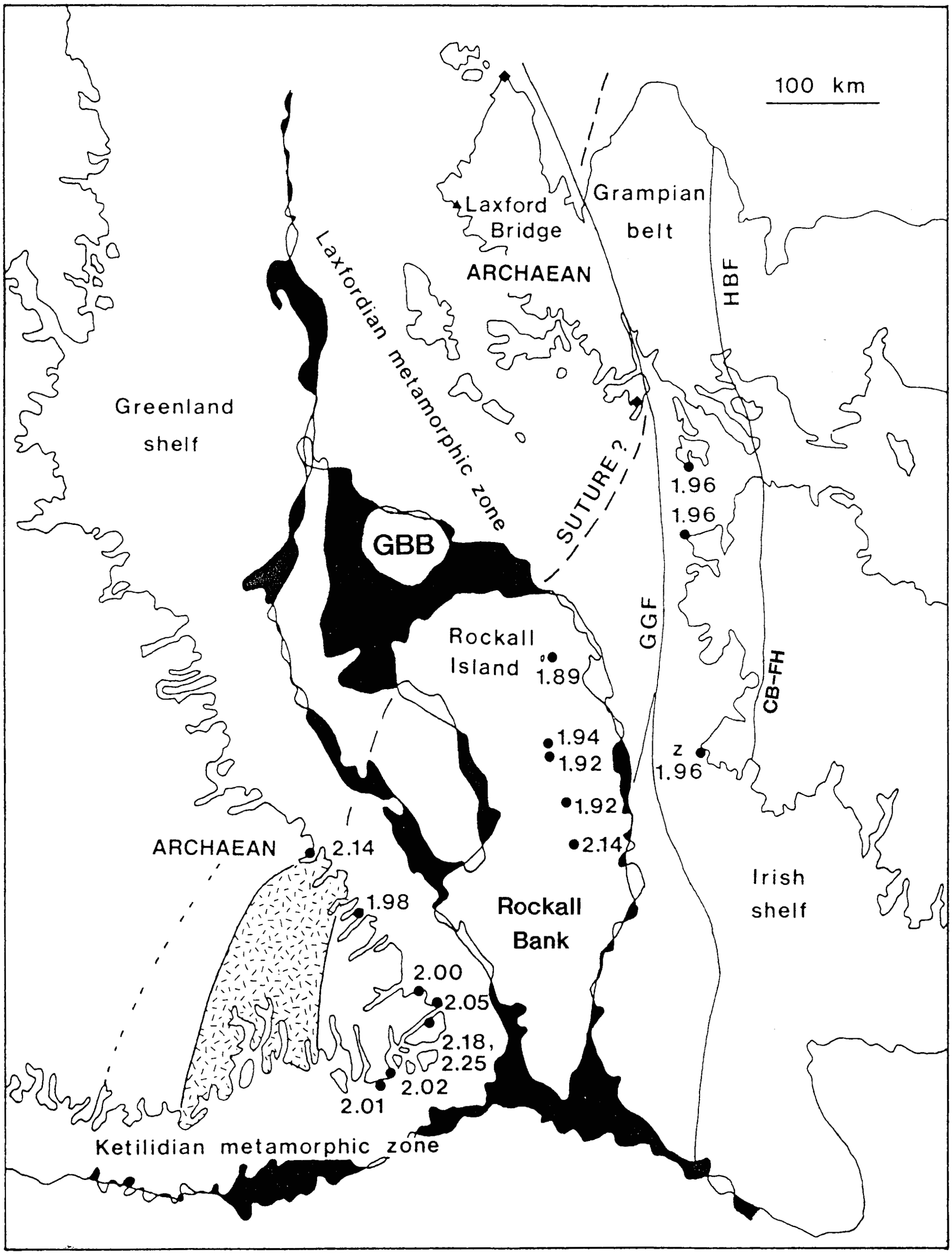


Fig. 2.5 Reconstruction of North Atlantic region before Atlantic opening, showing location of possible suture separating the Lewisian terrane (to the north) from the Islay Terrane (to the south). Numbers are ages in Ga. From Dickin (1992).

HBF: Highland Boundary Fault
GCF: Great Glen Fault
CB-FH: Clew Bay-Fairhead Line
GBB: George Bligh Bank

HB	Hatton Bank	WTR	Wyville-Thomson Ridge	I	Inishtrahull
LB	Lousy Bank	RB	Rosemary Bank	HBF	Highland Boundary Fault
FB	Faeroe Bank	AD	Anton Dohrn	GGF	Great Glen Fault
FS	Faeroe Shelf	HT	Hebrides Terrace		

Islay Terrane

Lewisian Terrane

Fig. 2.6 Possible extent of Lewisian and Islay terranes relative to present day features

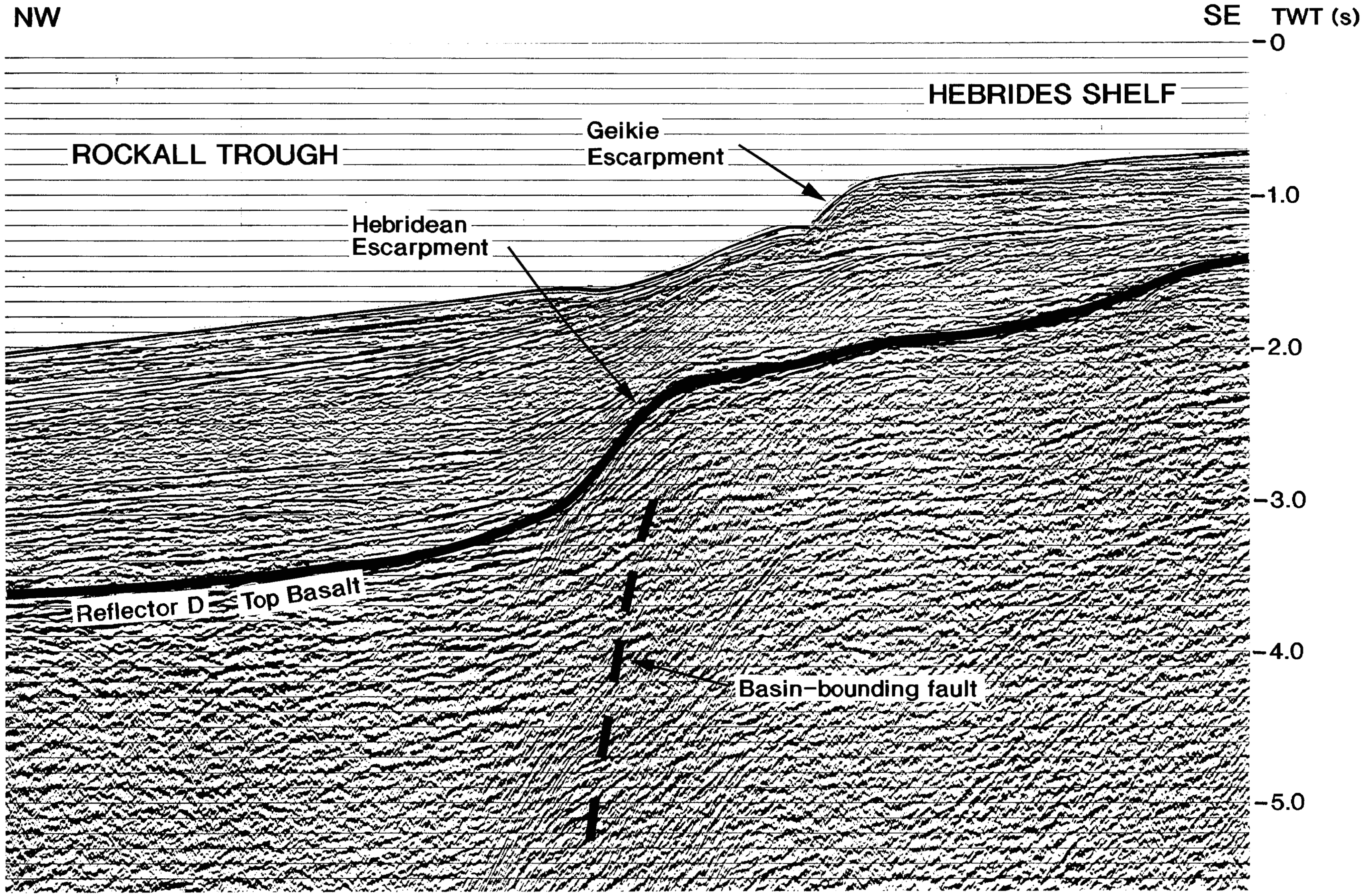


Fig. 2.7 The eastern basin-bounding fault of the Rockall Trough is inferred to occur beneath the buried, basaltic Hebridean Escarpment. From Evans et al. (1989).

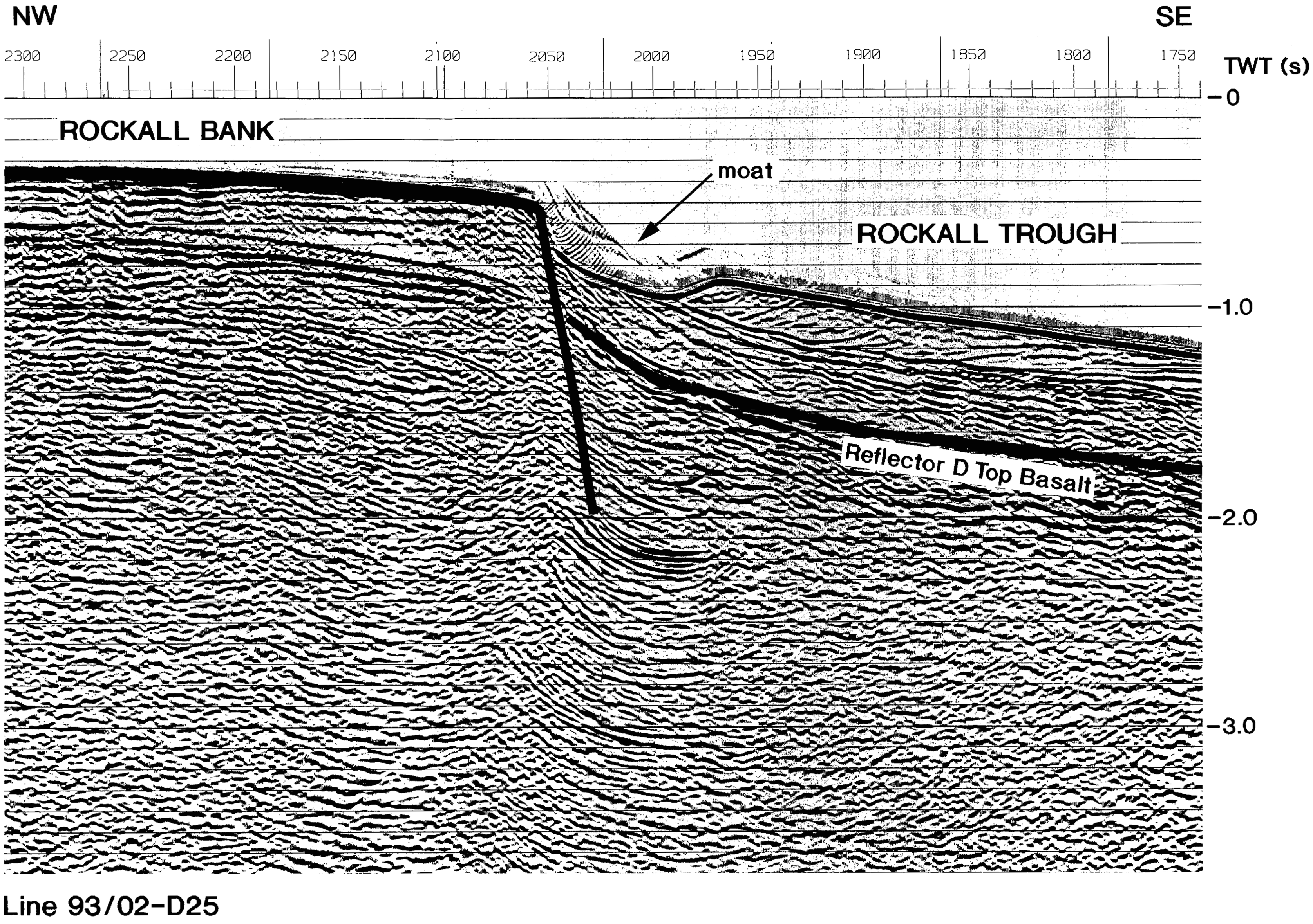
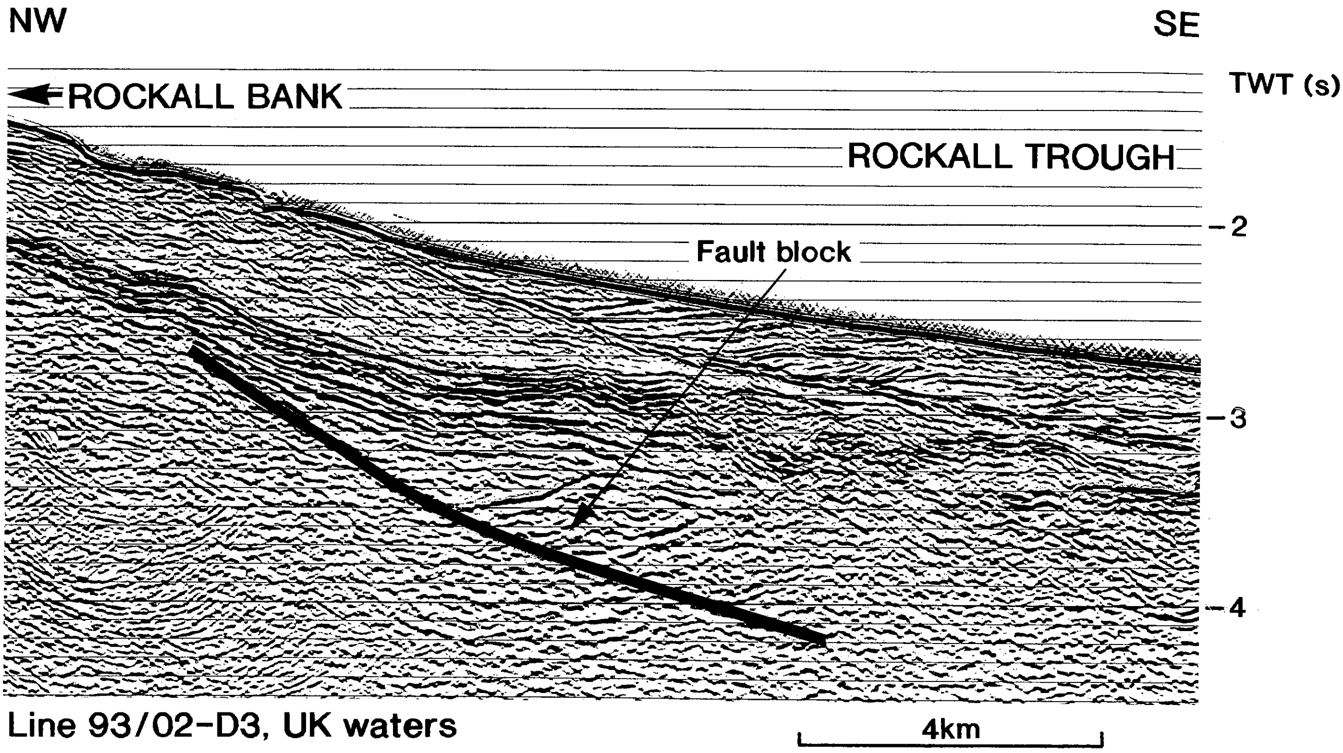


Fig. 2.8 The western basin-bounding fault of the Rockall Trough



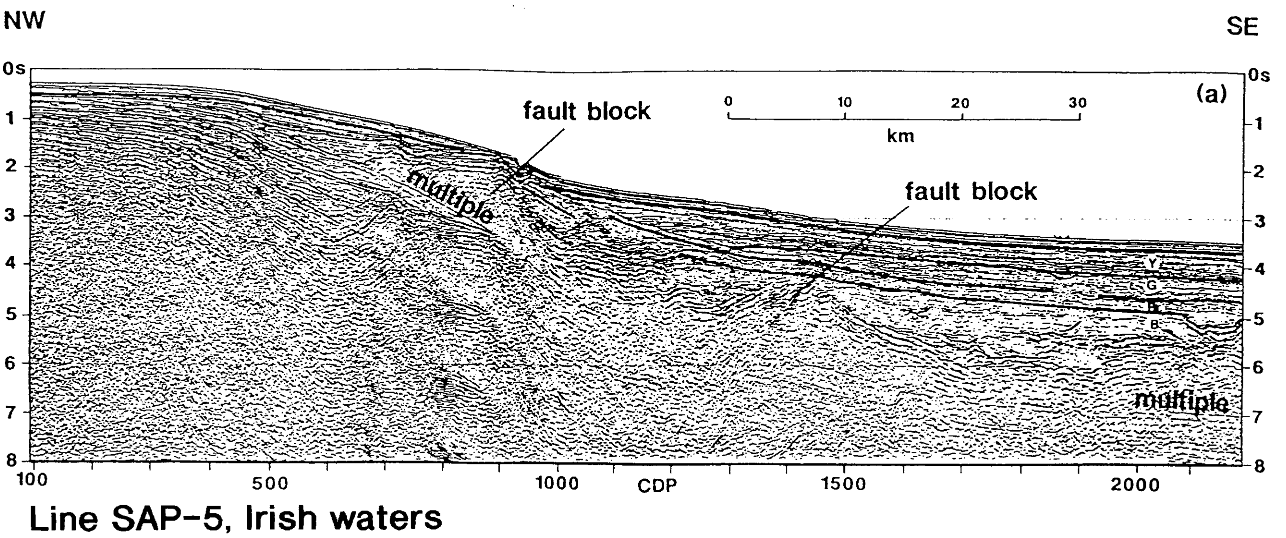


Fig. 2.9 Tilted fault block structures on the western margin of Rockall Trough
Line 93/02-D3 acquired for this study (UK waters).
Line SAP-5 from Joppen and White (1990) (Irish waters)

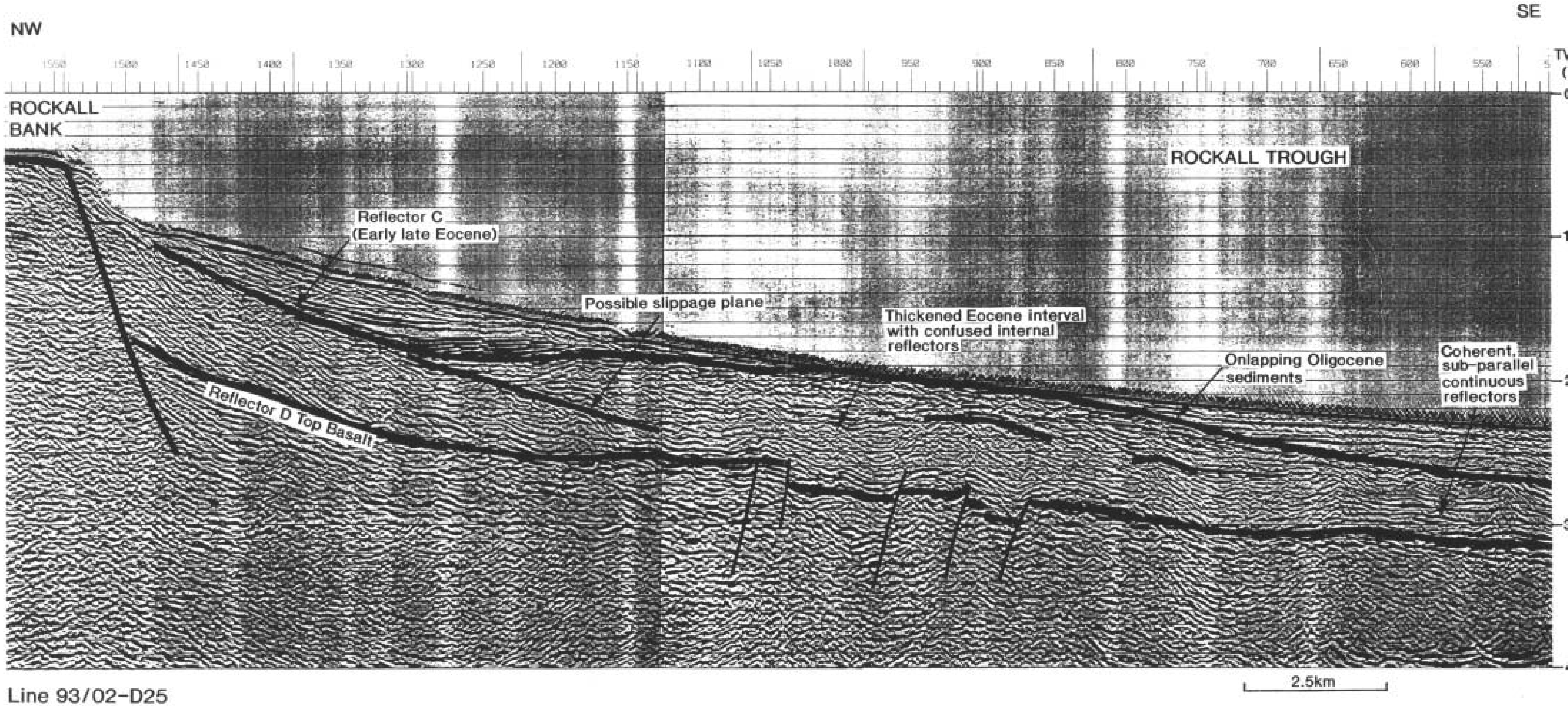


Fig. 2.10 Detail of the western margin of the Rockall Trough. Increased thickness of the reflector D-C interval (mainly Eocene) partially caused by internal faulting

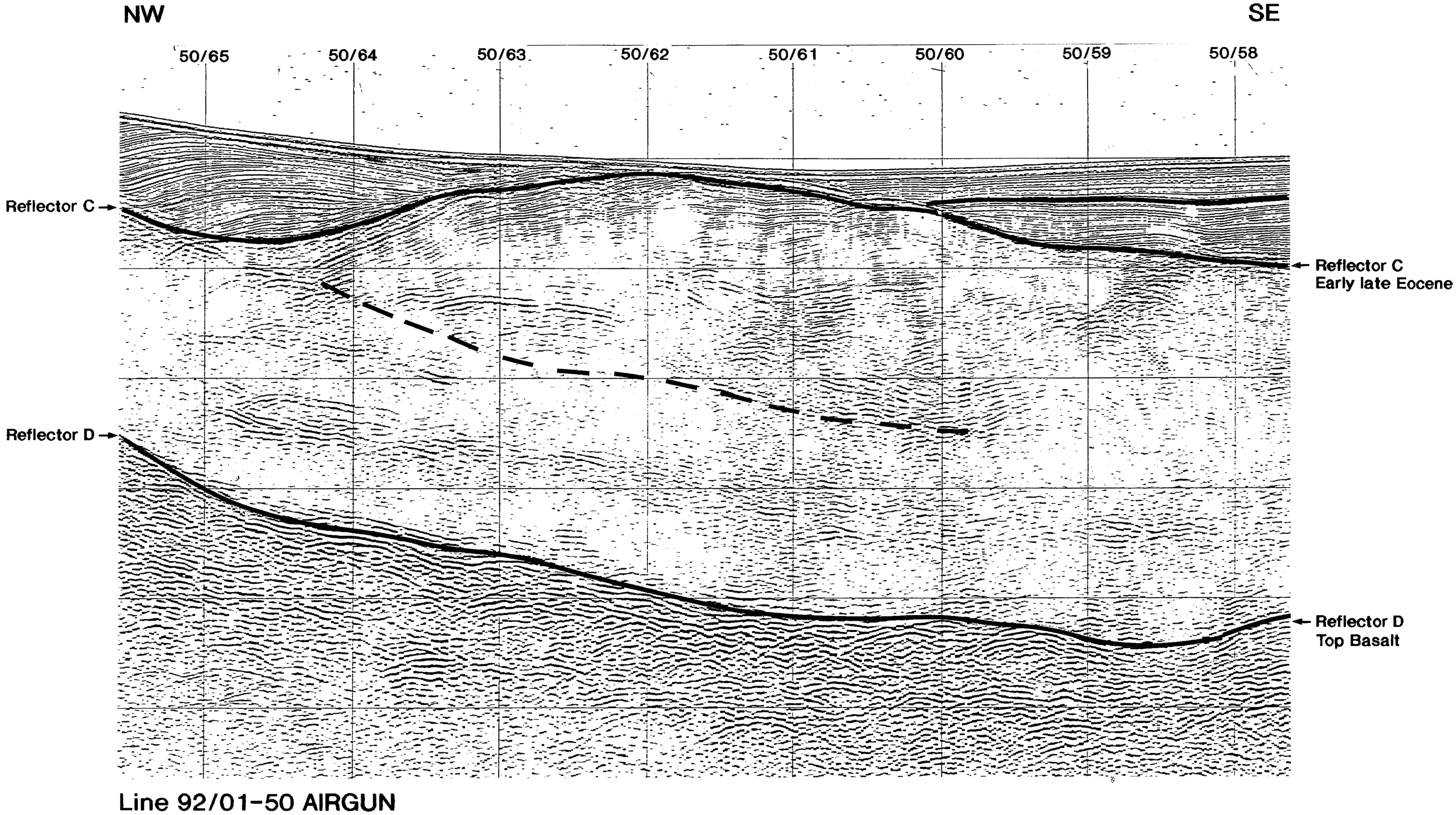


Fig. 2.11 Thickening of reflector D-C interval (mainly Eocene) due to faulting and the creation of a rollover structure

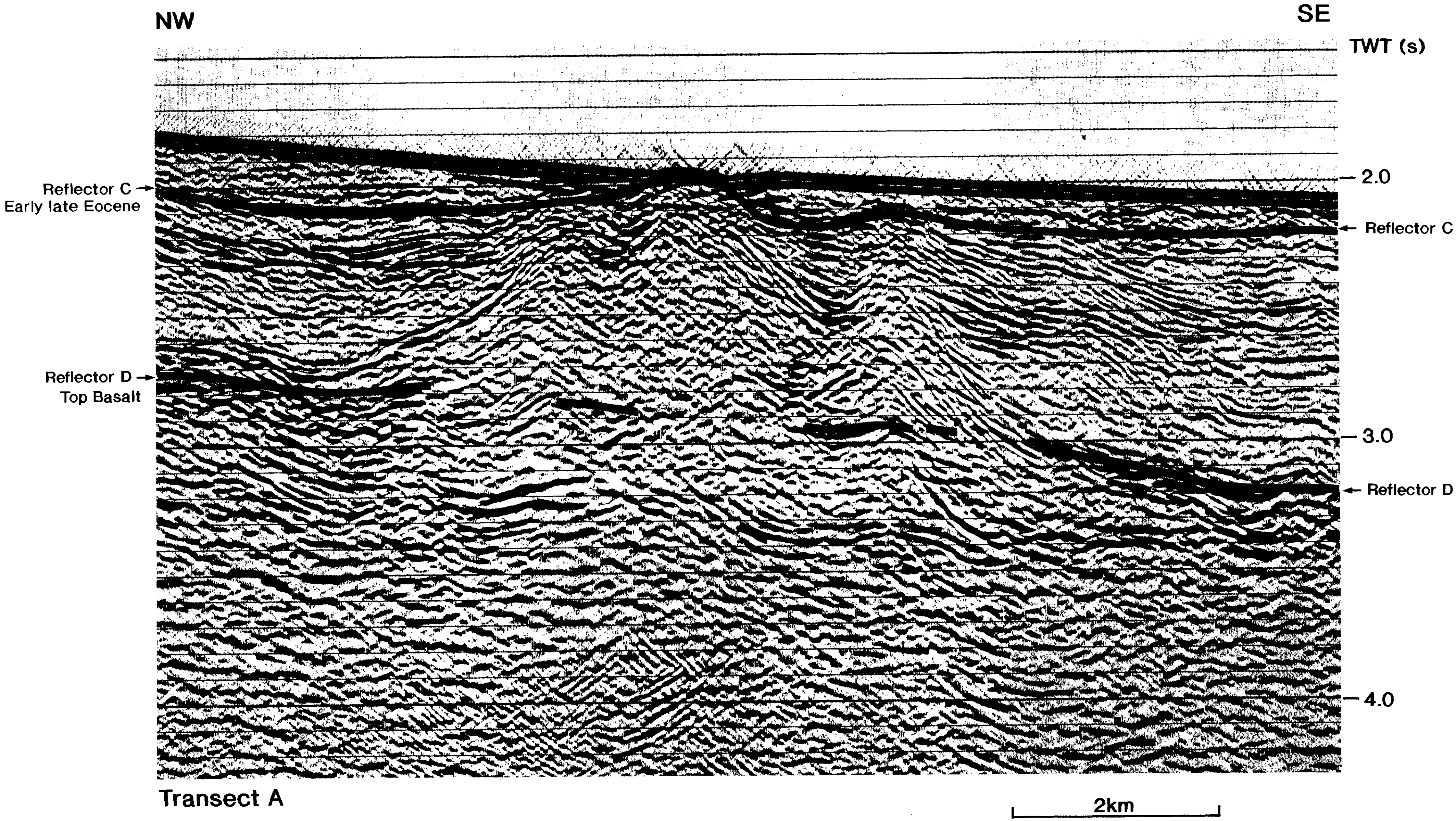


Fig. 2.12 Diapiric structure south-east of George Bligh Bank

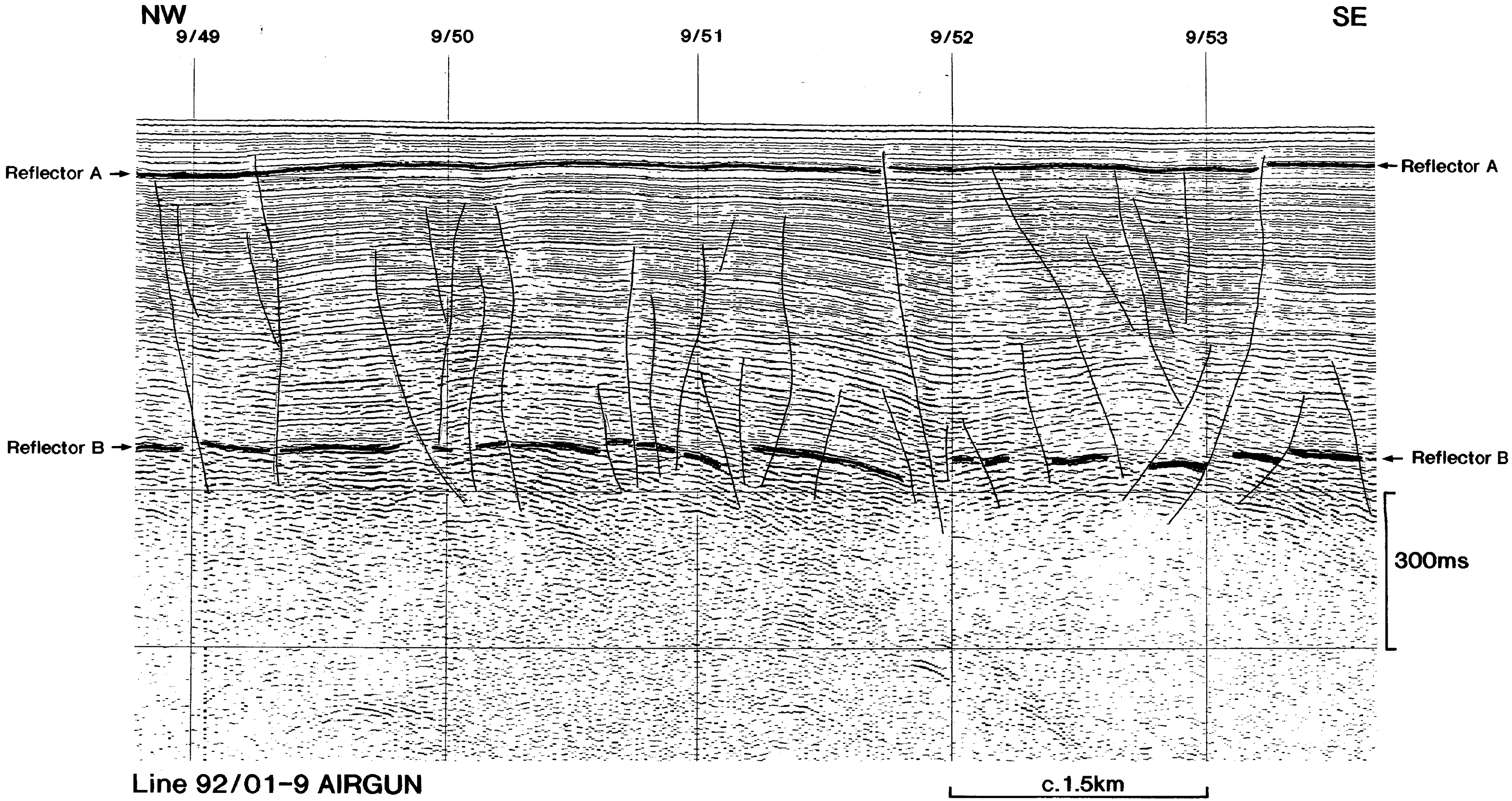


Fig. 2.13 Shallow faulting affecting the reflector B-A interval (latest Eocene to mid Miocene) in the northern Rockall Trough.

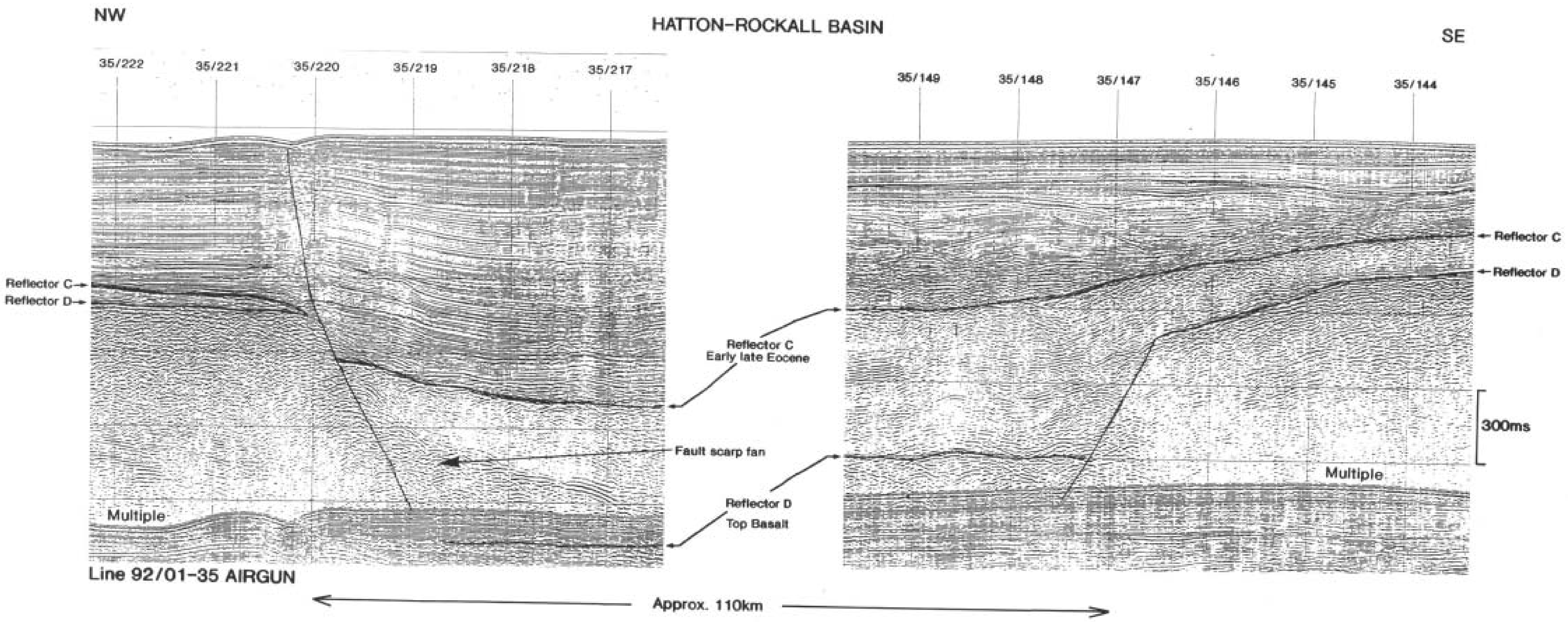


Fig. 2.14 The basin-bounding faults of the Hatton-Rockall Basin. The south-eastern fault is clearly inactive whereas the north-western fault has moved later and may have acted as a conduit for fluids moving to the surface.

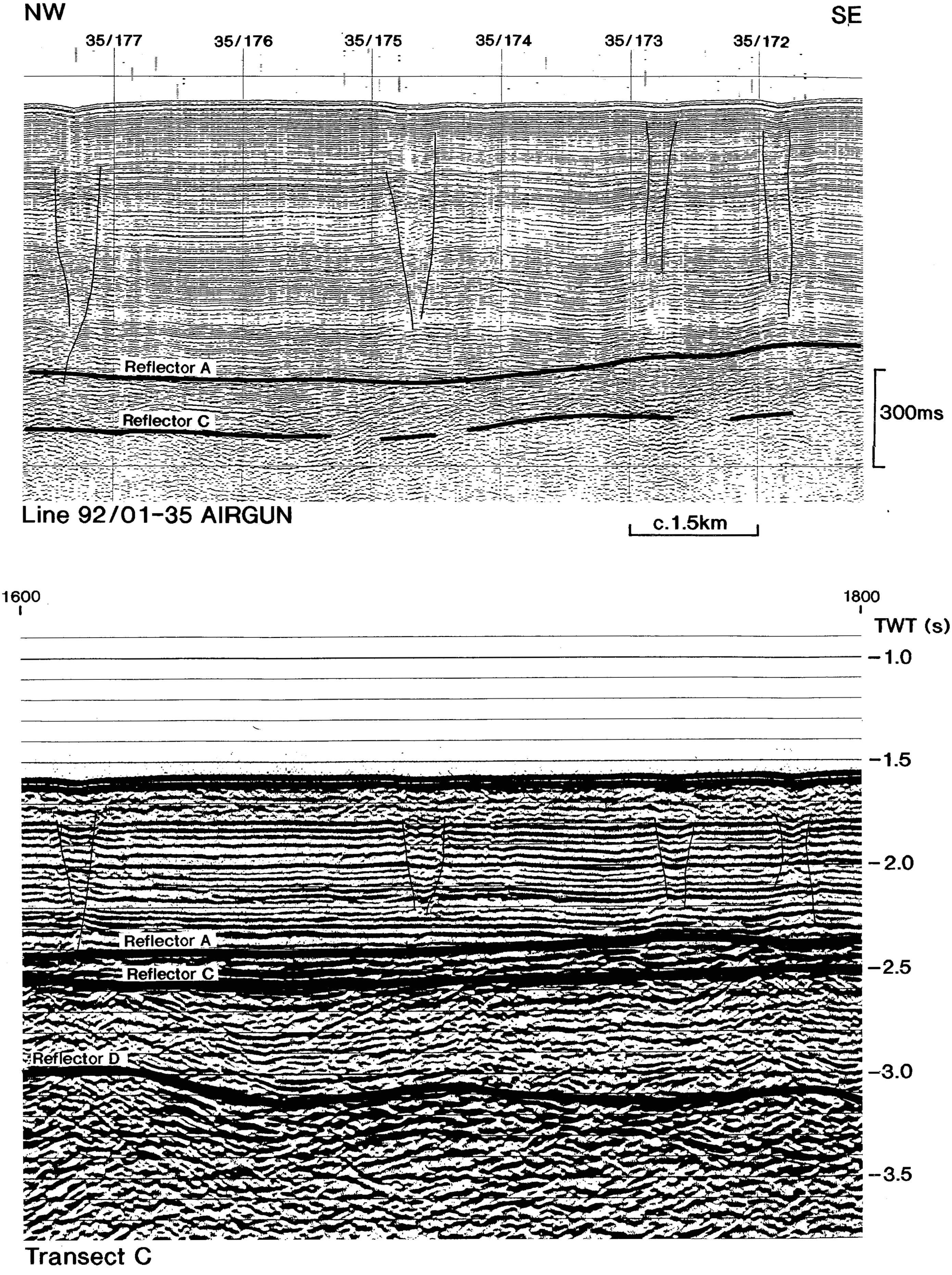


Fig. 2.15 Coincident high-resolution (top) and multichannel (bottom) seismic data showing the shallow faulting in the Hatton-Rockall Basin. The faults are clearly affecting the sea bed. There is a marked difference in style from the northern Rockall Trough (compare Fig. 2.13).

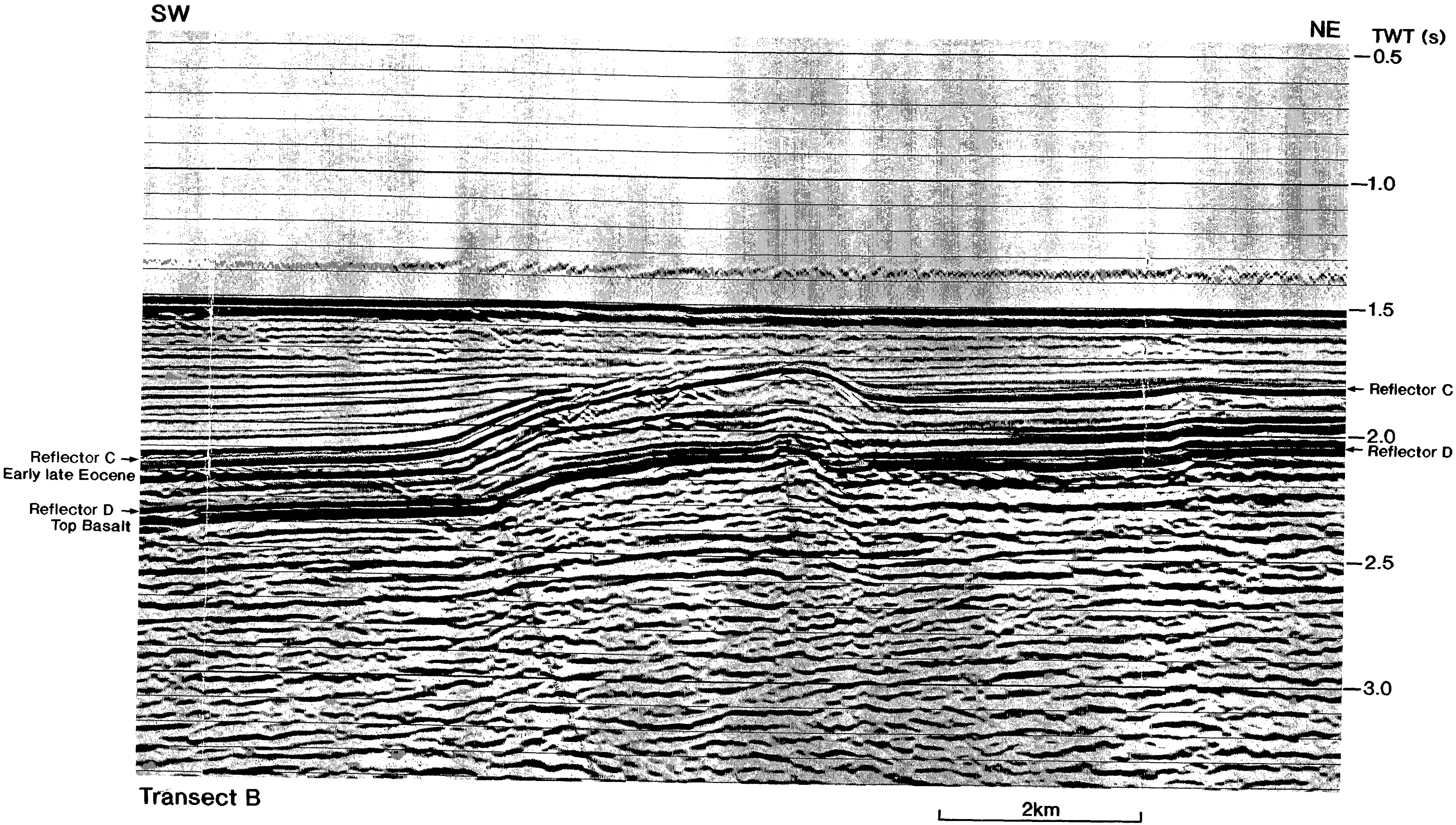


Fig. 2.16 Compressional feature in the north-east of Hatton-Rockall Basin. Latest Eocene and Oligocene reflectors downlap onto Reflector C.

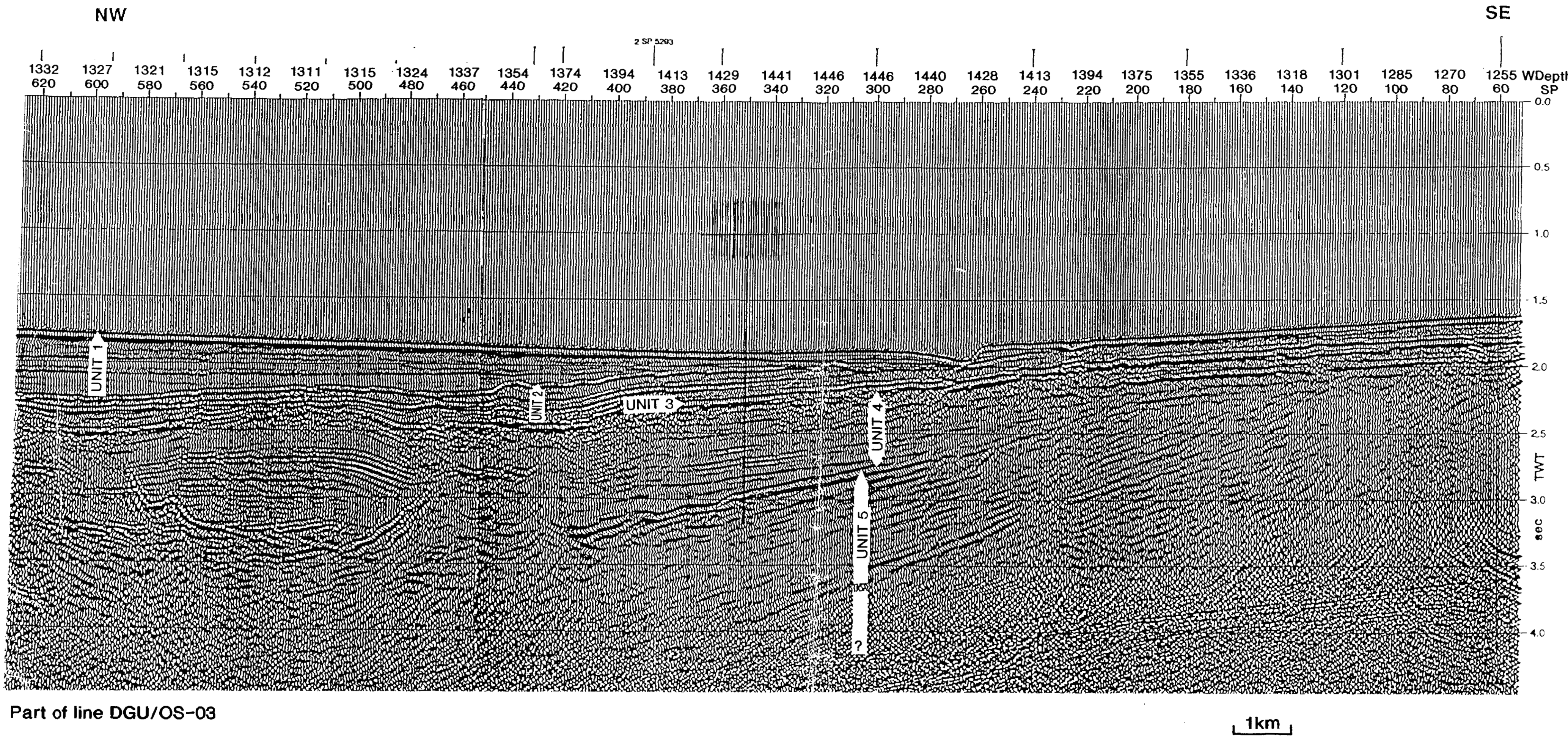
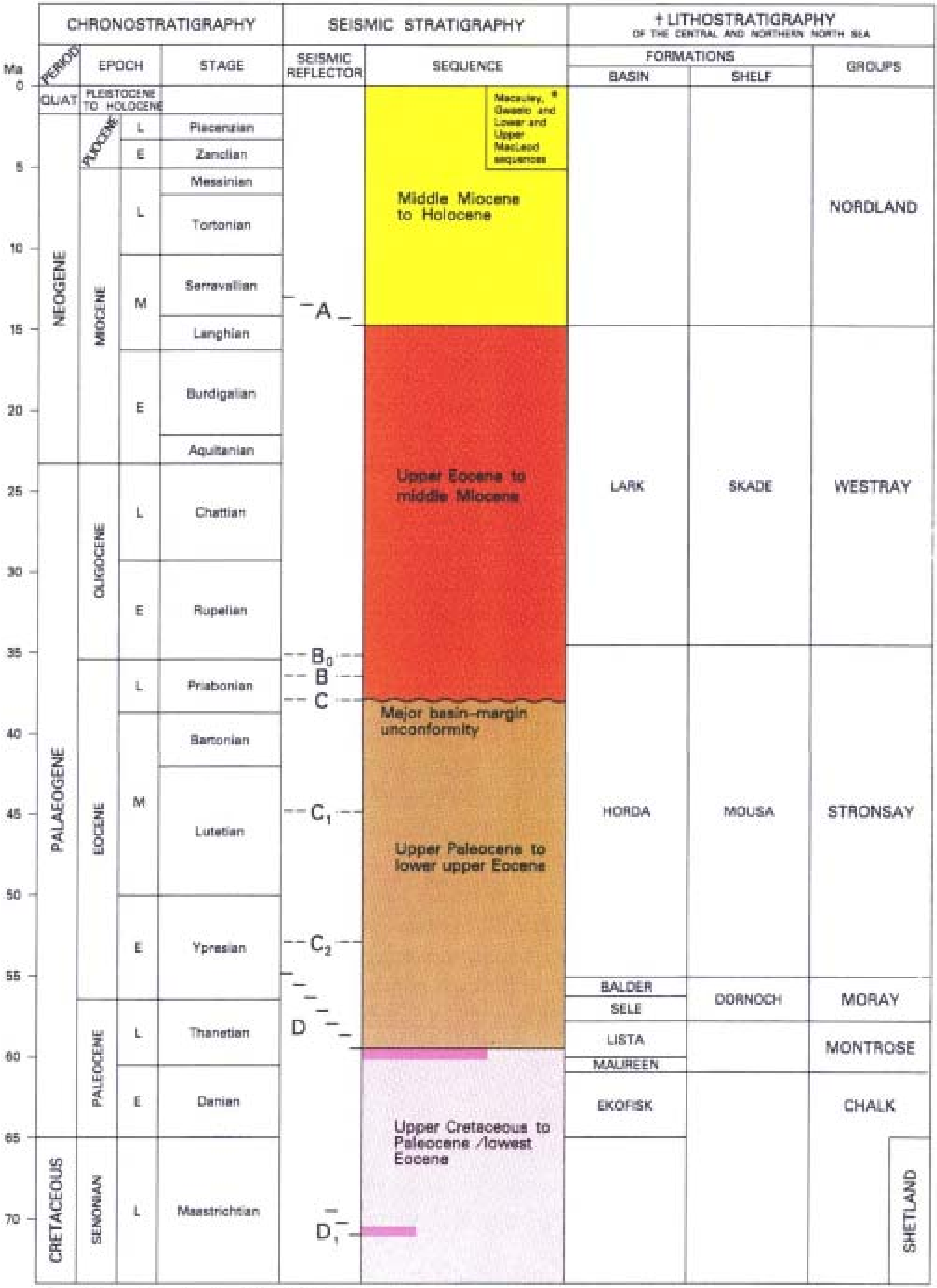


Fig. 2.17 Seismic line from the Irish sector of the Hatton-Rockall Basin. Unit 3 is probably a thin volcanic layer, equivalent to reflector D of this study. Units 4 and 5 show that a significant sedimentary thickness is present beneath the volcanics. (Taken from an ODP drilling proposal).



* BGS seismic stratigraphy, Hebridean margin

† After Knox and Cordey (1992)

Fig. 3.1 Generalised latest Mesozoic and Cenozoic stratigraphy of the central and northern Rockall Trough. Timescale after Harland et al. (1990).

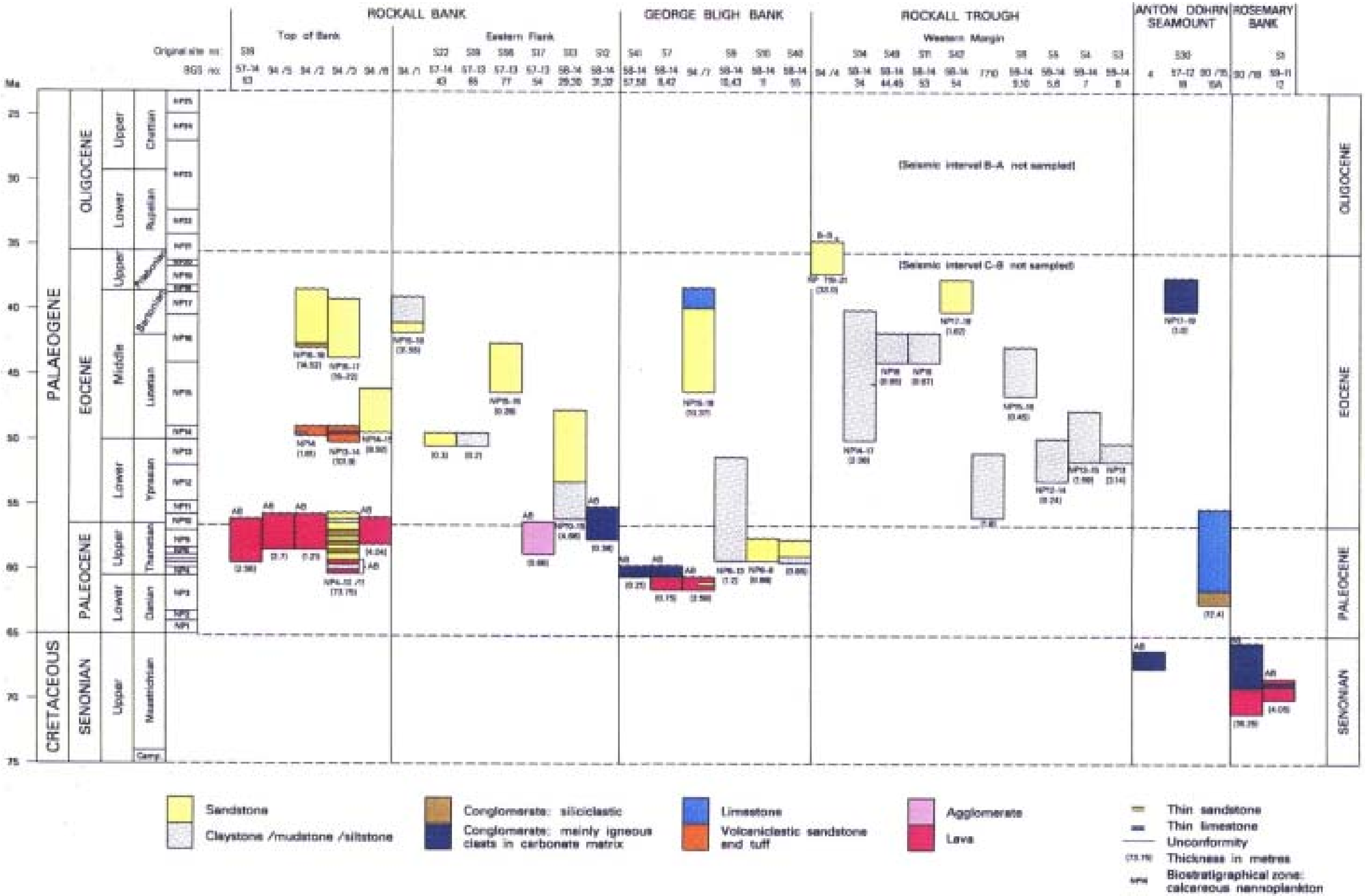


Fig. 3.5 Stratigraphical-range chart, thickness and generalised lithology (not to scale) of the uppermost Cretaceous and Palaeogene rocks recovered in BGS boreholes and shallow cores, excepting sites 7710 (Ferragne et al., 1984) and 4 (Jones et al., 1974). All samples recovered from seismic interval D/D, –C, except where otherwise indicated (i.e. B–B_0; AB = acoustic basement). Timescale after Harland et al. (1990).

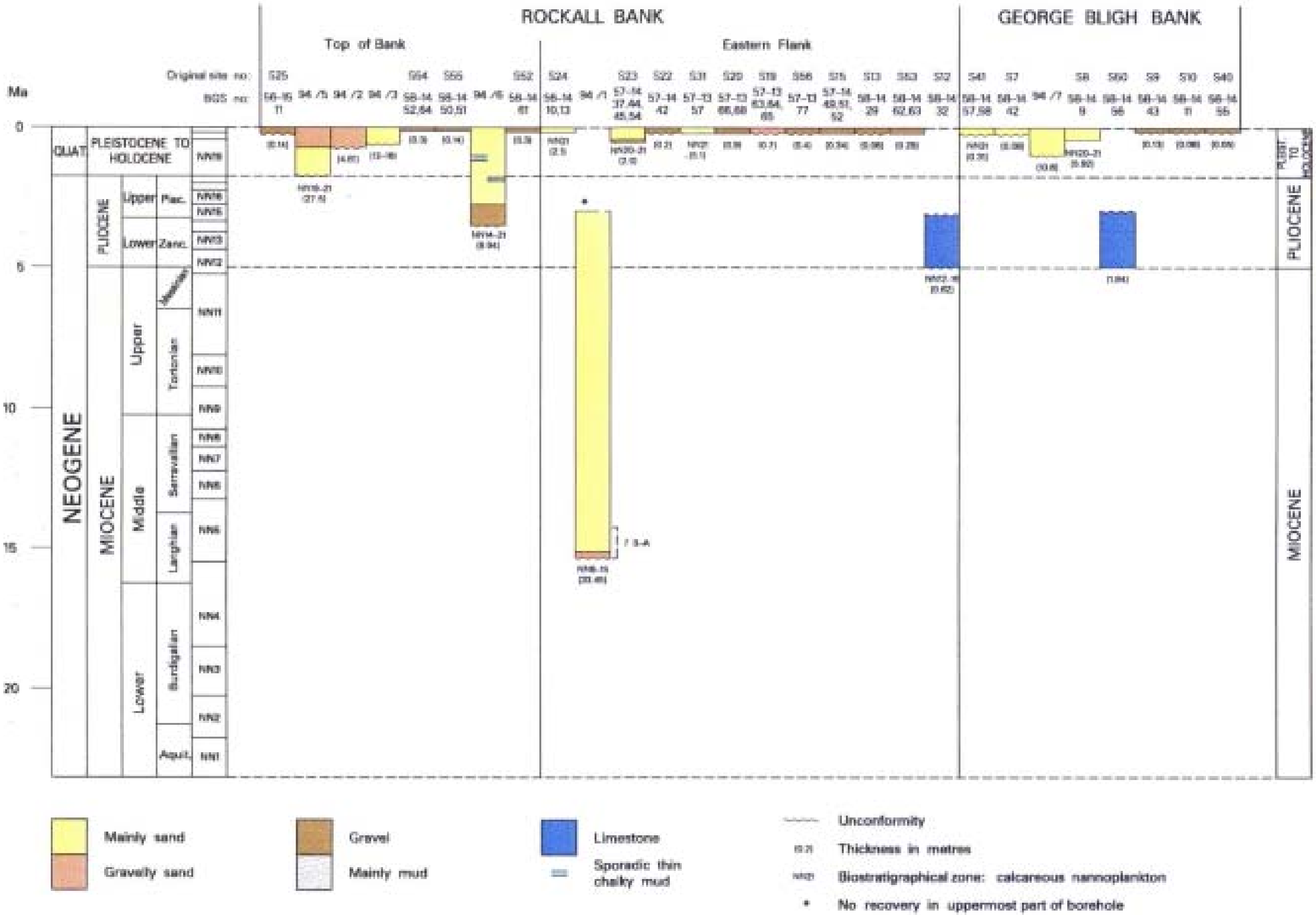


Fig. 3.6 Stratigraphical–range chart, thickness and generalised lithology (not to scale) of the Neogene and Quaternary sediments recovered in BGS boreholes and shallow cores from Rockall and George Bligh banks. All samples recovered from seismic interval A–sea bed except where indicated (i.e. B–A). Timescale after Harland et al. (1990).

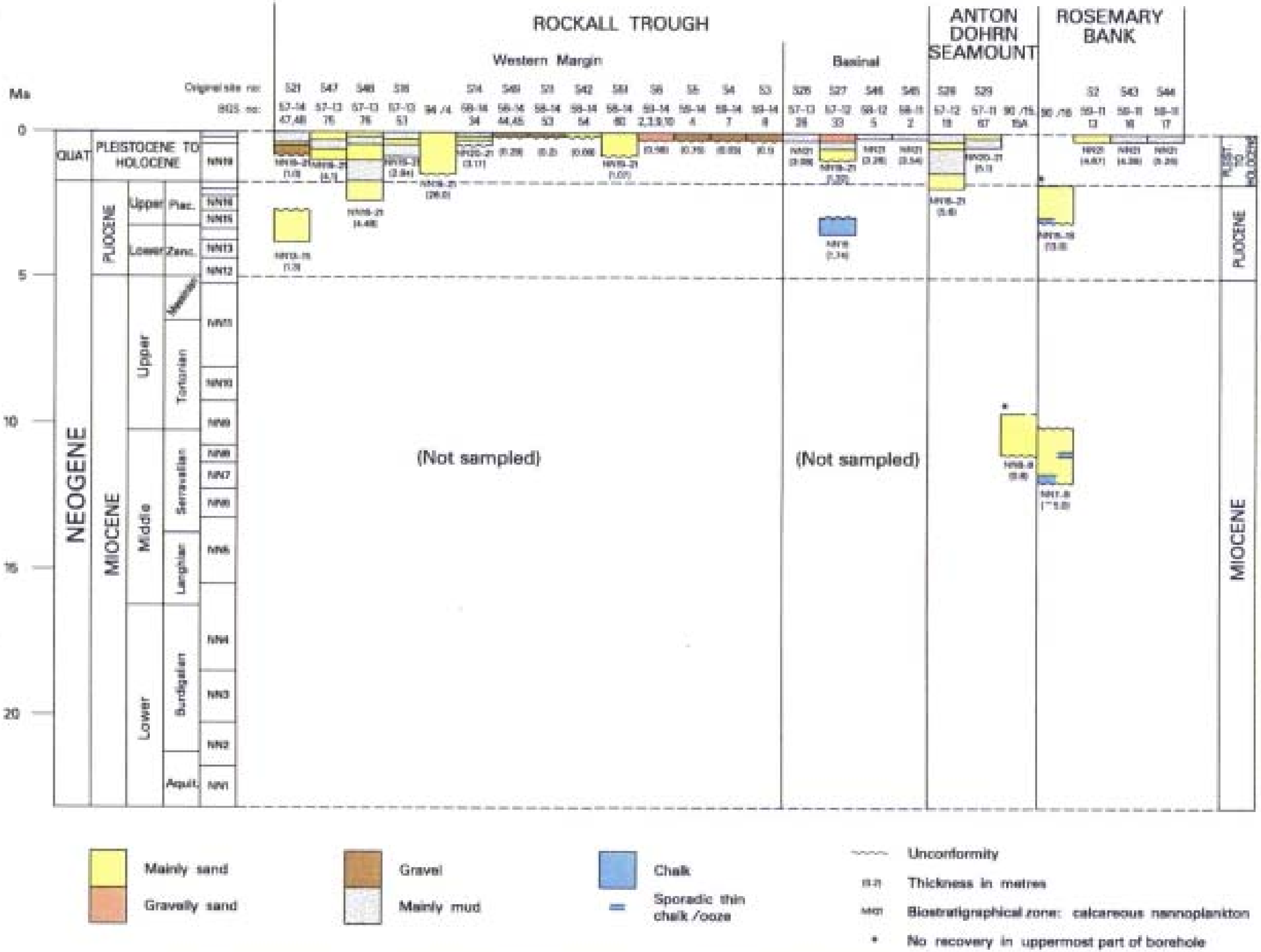


Fig. 3.7 Stratigraphical-range chart, thickness and generalised lithology (not to scale) of the Neogene and Quaternary sediments recovered in BGS boreholes and shallow cores from the Rockall Trough and Anton Dohrn and Rosemary Bank seamounts. All samples recovered from seismic interval A–sea bed. Timescale after Harland et al. (1990).

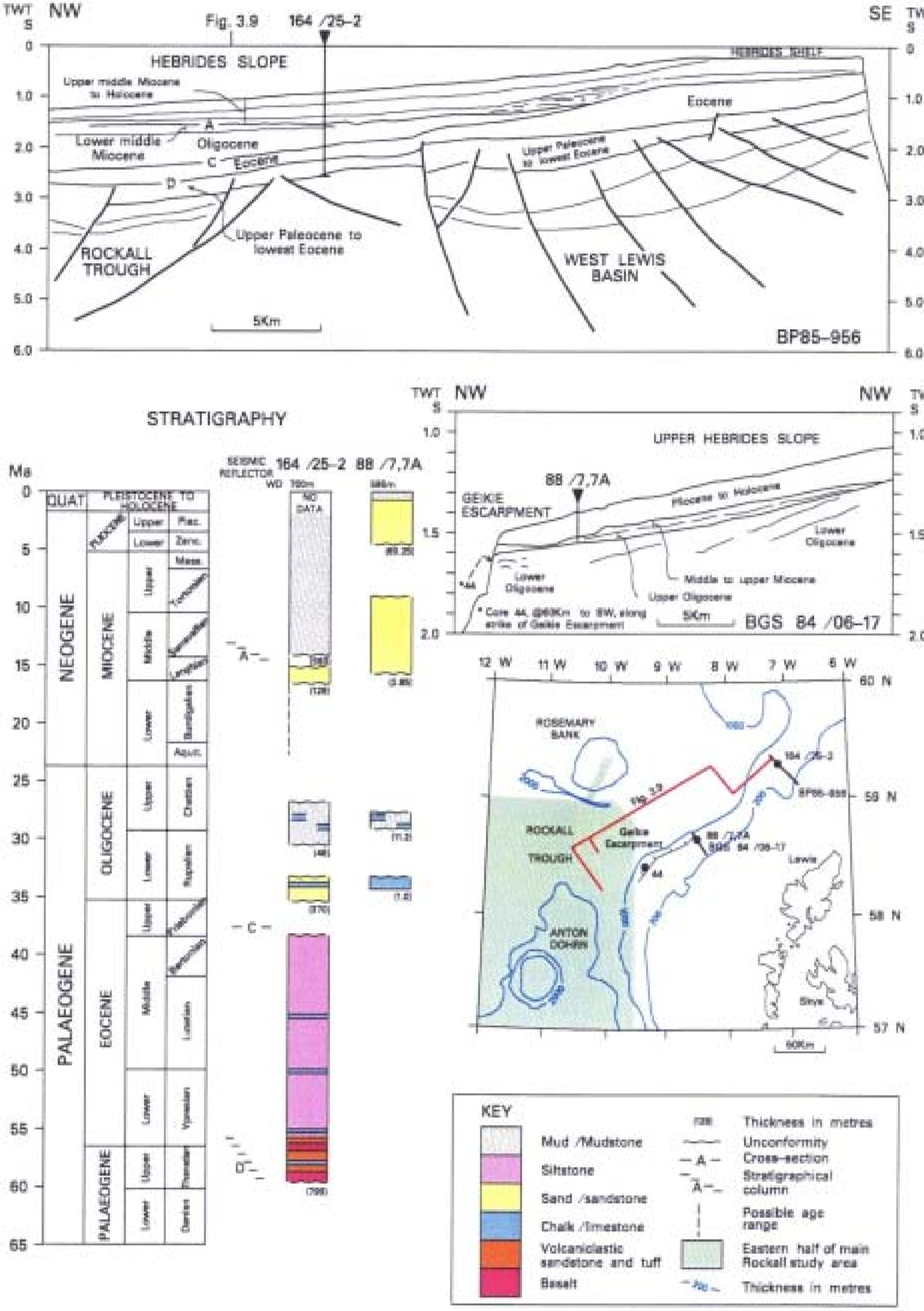


Fig. 3.8 Simplified logs and seismic-stratigraphical setting of Cenozoic strata recovered in well 164/25-2, borehole 88 /7,7A and shallow core 44 (Jones et al., 1988), and their relations to regional seismic reflectors A, C and D of this report. Timescale after Harland et al. (1990). Permission to utilise well 164 /25-2 and profile BP85-956 courtesy of BP.

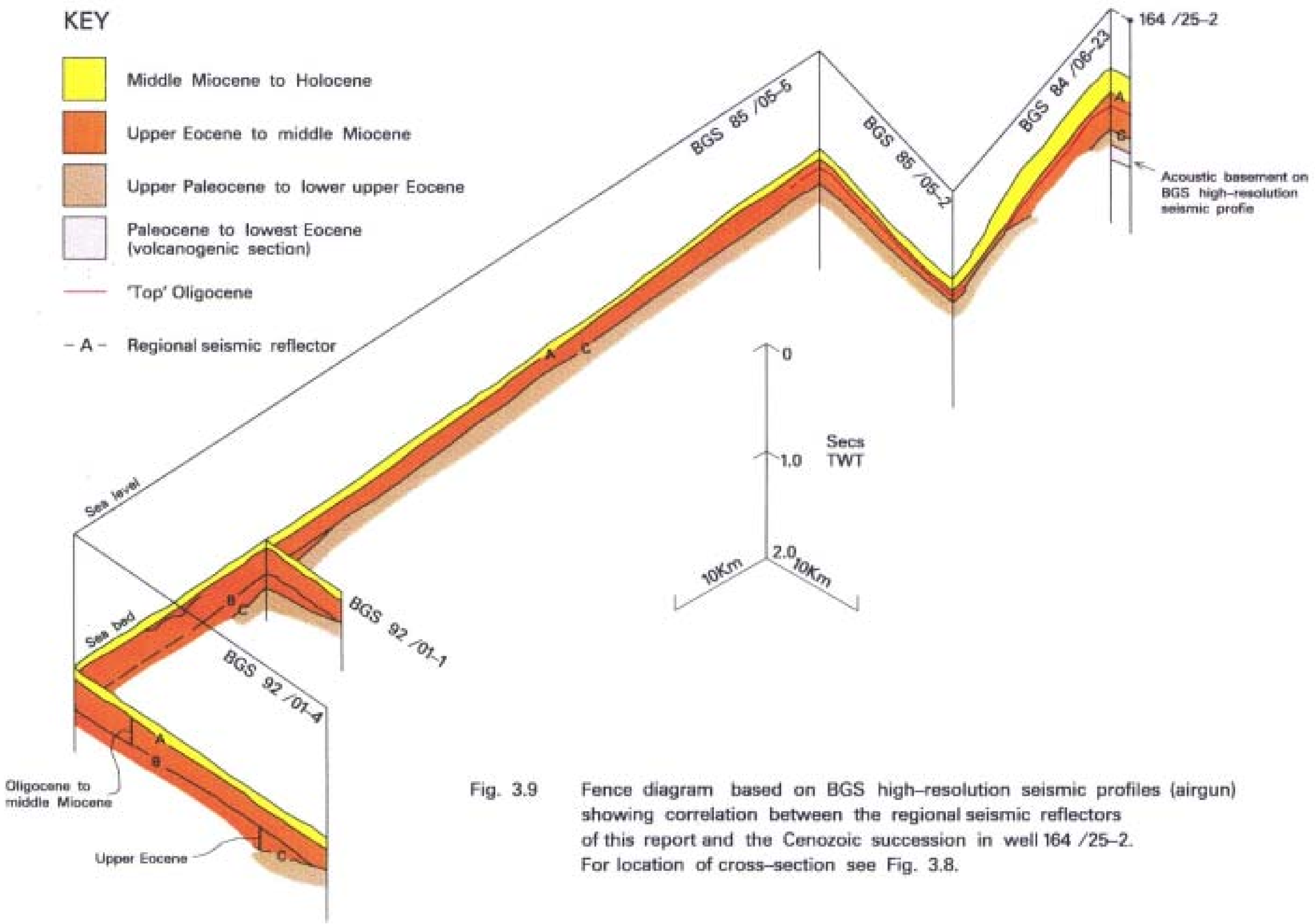


Fig. 3.9 Fence diagram based on BGS high-resolution seismic profiles (airgun) showing correlation between the regional seismic reflectors of this report and the Cenozoic succession in well 164 /25-2. For location of cross-section see Fig. 3.8.

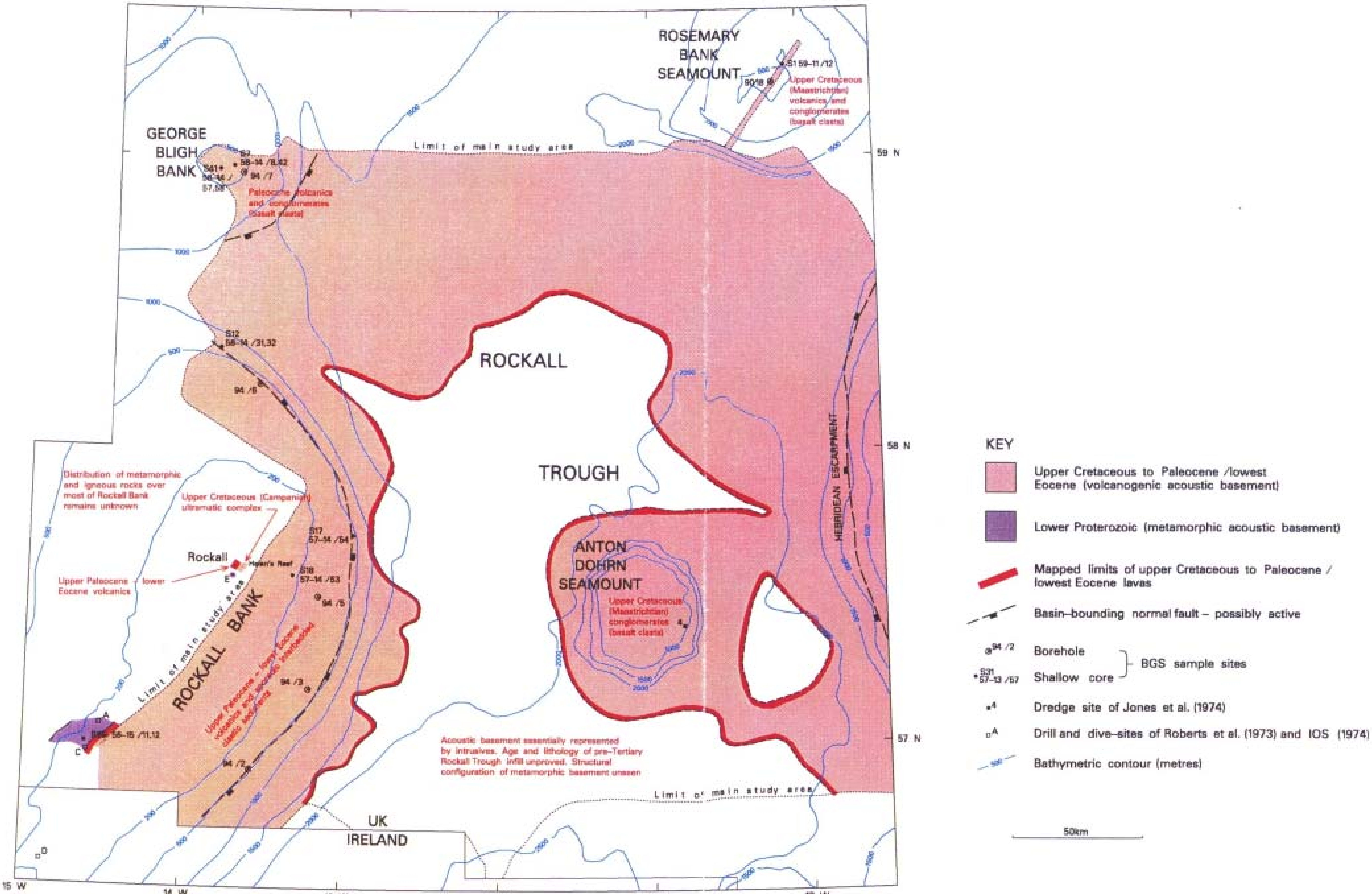


Fig. 3.10 Distribution and nature of acoustic basement

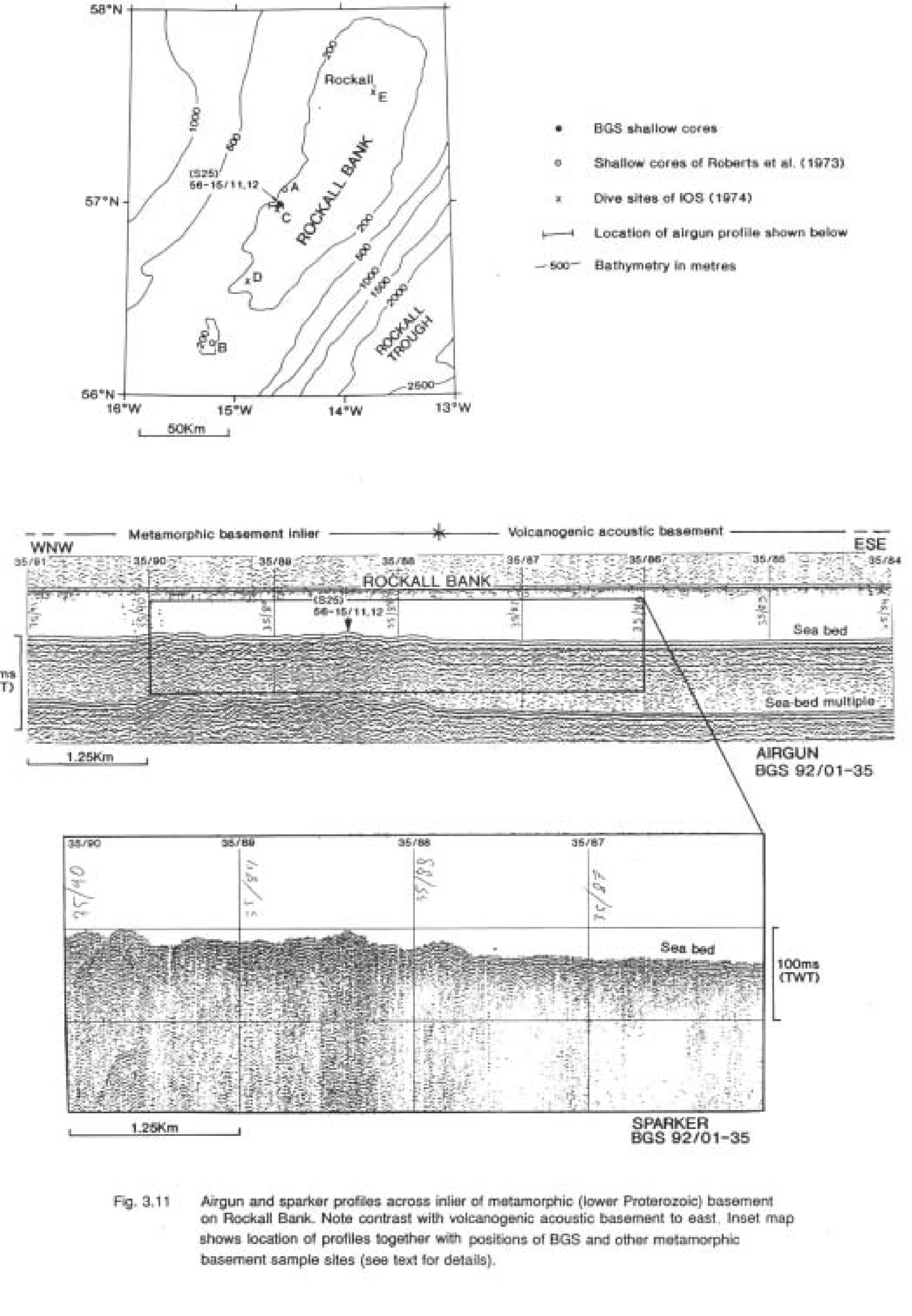


Fig. 3.11 Airgun and sparker profiles across inlier of metamorphic (lower Proterozoic) basement on Rockall Bank. Note contrast with volcanogenic acoustic basement to east. Inset map shows location of profiles together with positions of BGS and other metamorphic basement sample sites (see text for details).

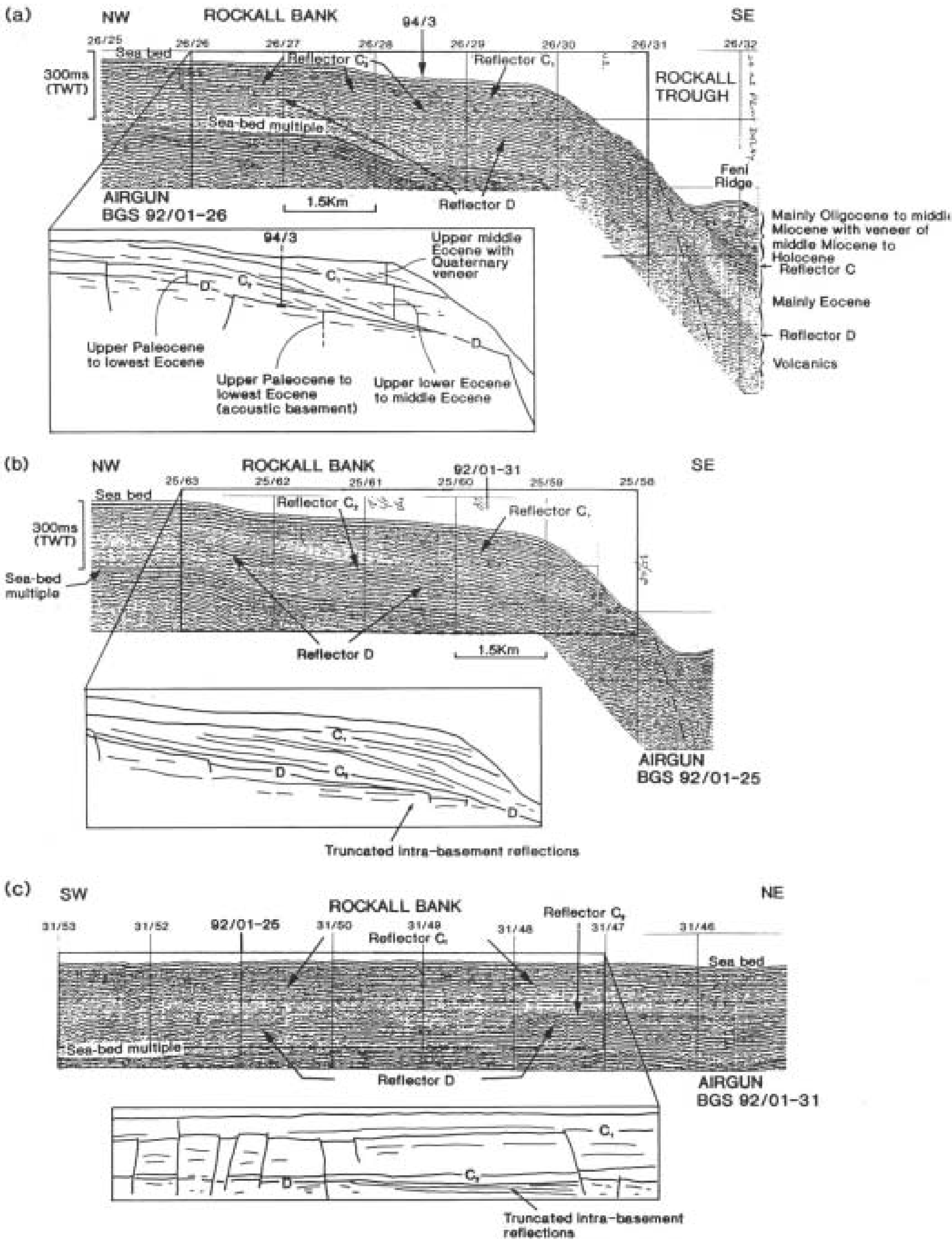


Fig. 3.12 Airgun profiles with interpreted line drawings illustrating the seismic-stratigraphical characteristics of, and relations between, the acoustic basement and overlying sediment-wedge on the eastern flank of Rockall Bank (see text for details). Profiles located in Figure 3.14.

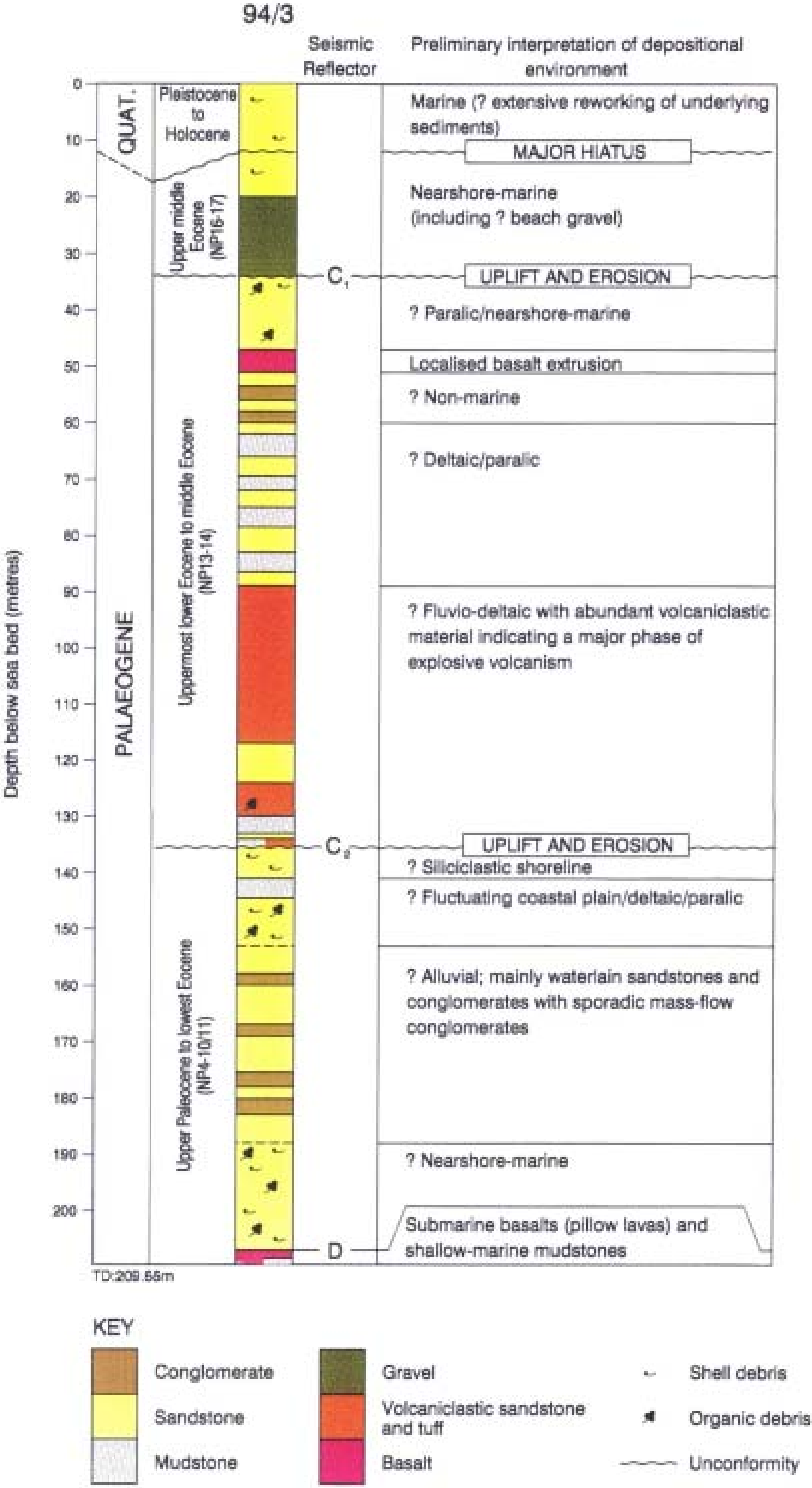


Fig. 3.13 Simplified log of the Cenozoic succession in borehole 94/3 (see text and Appendix 1 for details). For location se Fig. 3.14.

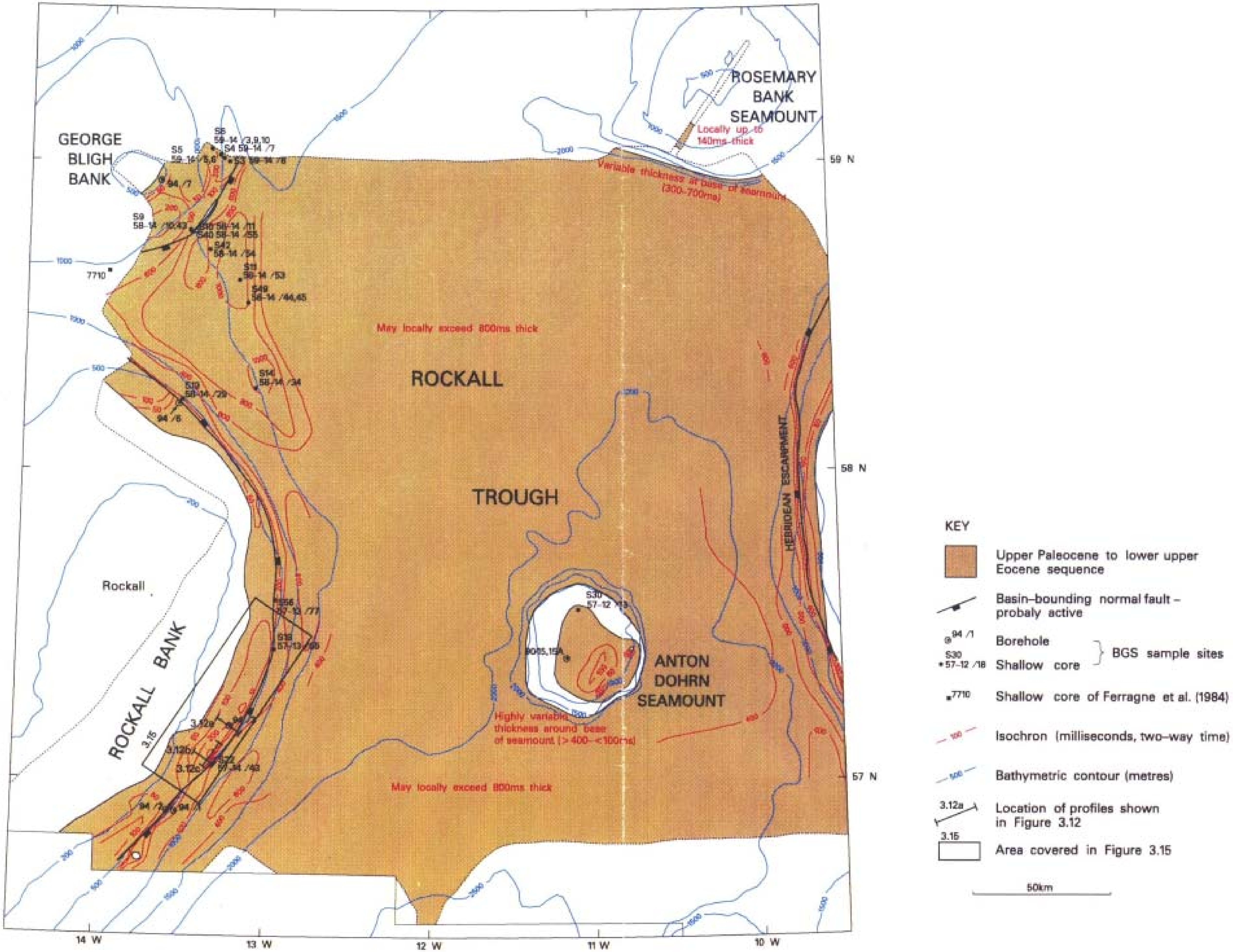


Fig. 3.14 Distribution of upper Paleocene to lower upper Eocene sequence (seismic interval D–C)

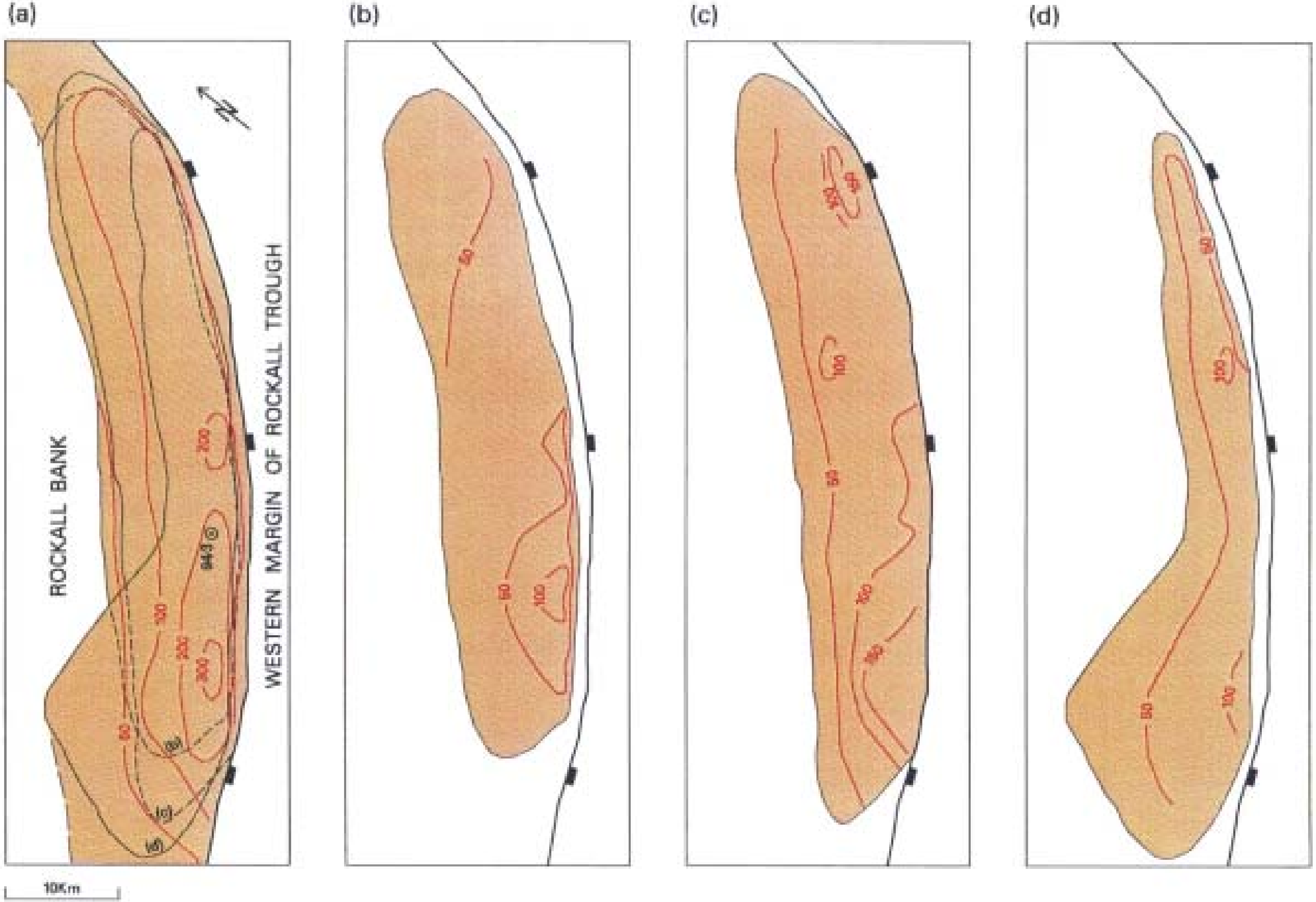


Fig. 3.15 Subdivision of the upper Paleocene to upper middle Eocene sediment-wedge on the eastern flank of Rockall Bank, in the area of borehole 94/3. (a) Total distribution and thickness of sediment-wedge on the bank, with superimposed boundaries of sub-units clarified in (b) to (d); (b) Distribution and thickness of upper Paleocene to lowest Eocene section (NP4–10/11); (c) Distribution and thickness of uppermost lower Eocene to middle Eocene section (NP13–14); (d) Distribution and thickness of the upper middle Eocene section (NP16–17). Boxed area located in Fig. 3.14.

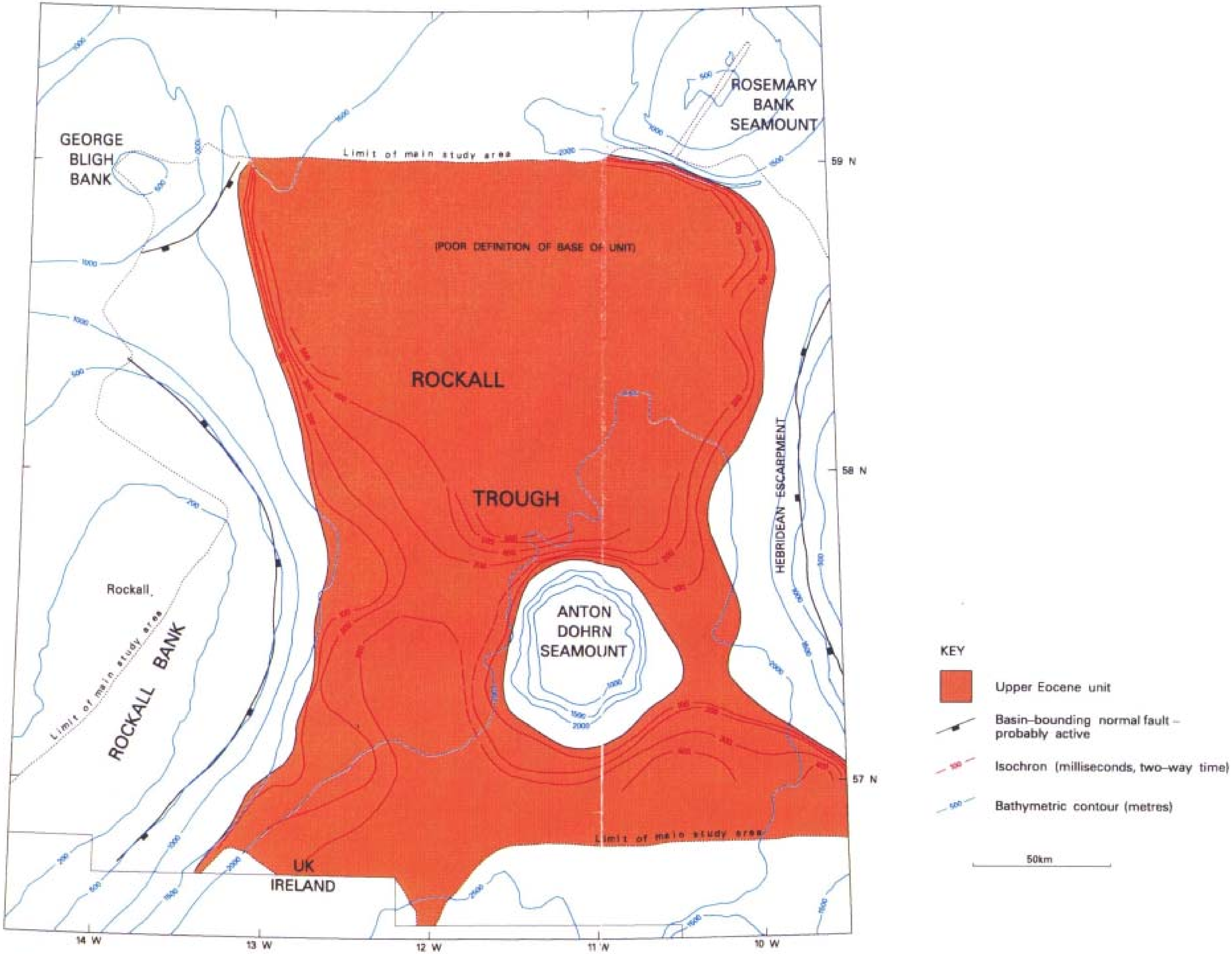


Fig. 3.16 Distribution of upper Eocene unit (seismic interval C–B); lower part of the upper Eocene to middle Miocene sequence (seismic interval C–A)

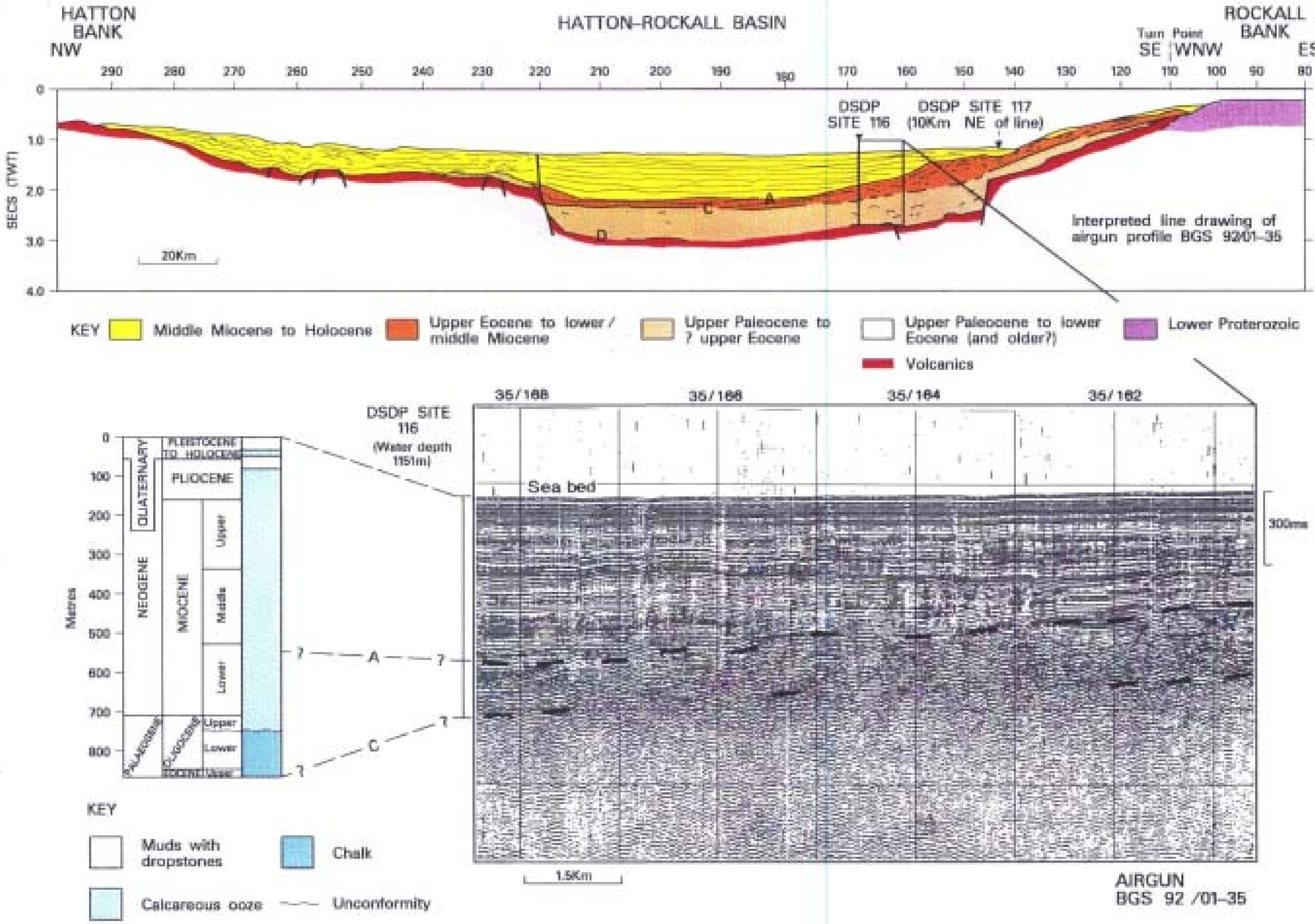


Fig. 3.17 Generalised stratigraphical framework of the Hatton–Rockall Basin: section located in Figure 1.1. Despite the uncertainty in the accurate correlation of regional seismic reflectors A and C with DSDP 116, the stratigraphical scheme appears to be broadly comparable with the Rockall Trough (see text for details). Note the faulting in the acoustically-layered section above reflector A; several faults appear to extend to the sea bed.

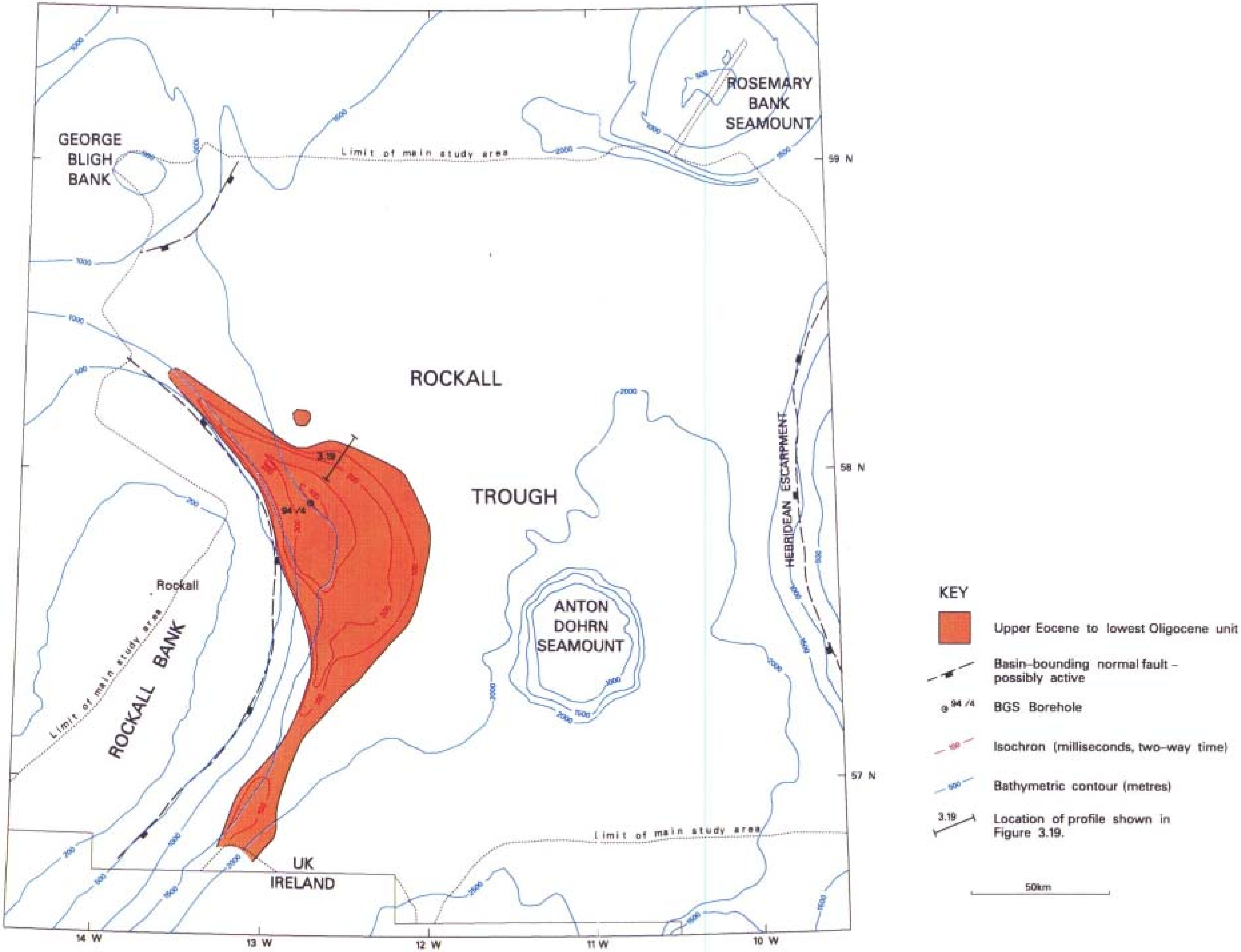


Fig. 3.18 Distribution of upper Eocene to lowest Oligocene unit (seismic interval C /B–B$_0$); part of upper Eocene to middle Miocene sequence (seismic interval C–A)

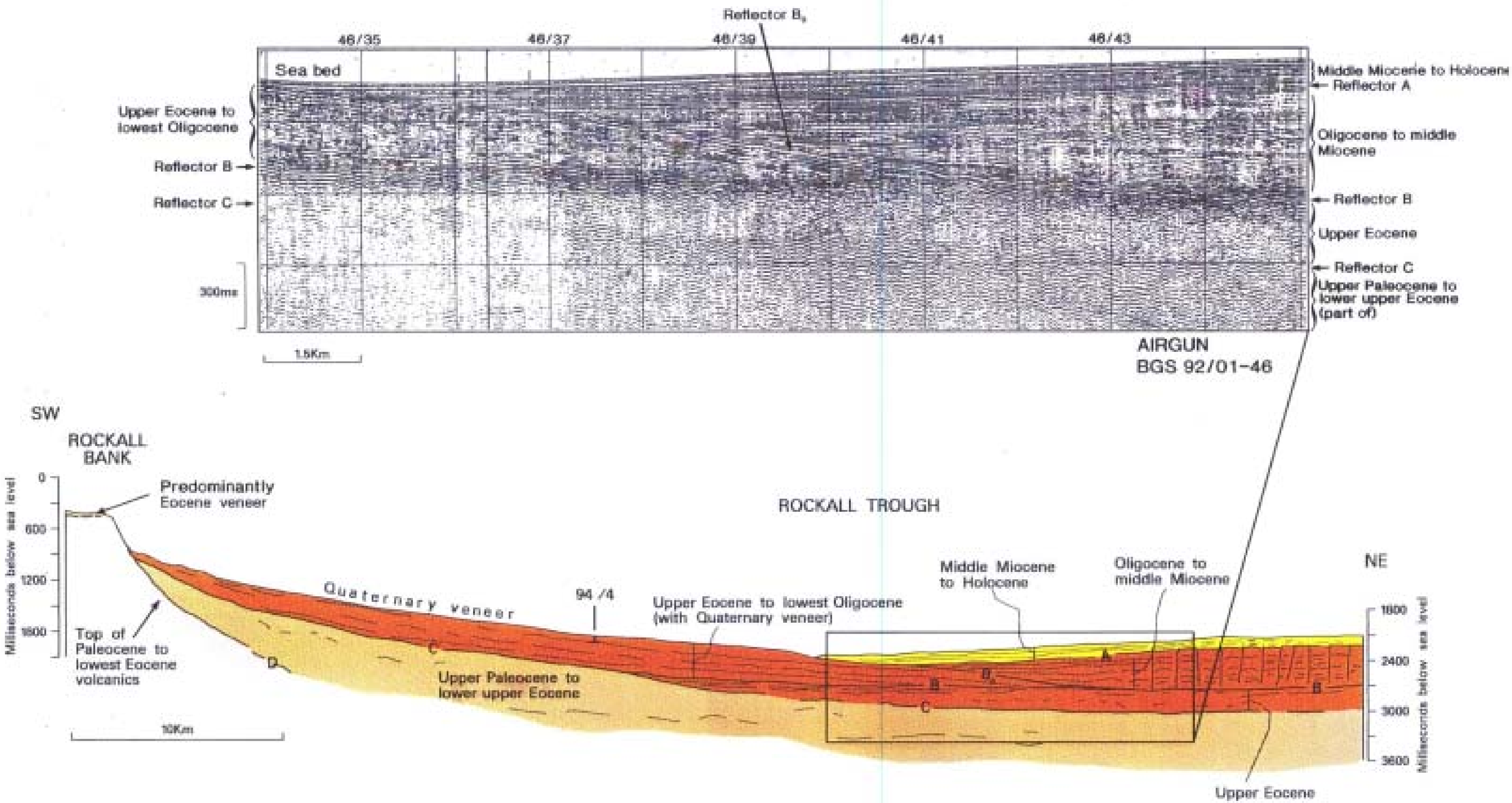


Fig. 3.19 Interpreted line-drawing of airgun profile showing seismic-stratigraphical characteristics of the upper Eocene to lowest Oligocene (seismic interval C /B–B_s) fan-like deposits preserved on the western margin of the Rockall Trough: profile located in Figure 3.18. Inset illustrates acoustic character and seismic-stratigraphical relations at the distal-end of the fan (see text for details).

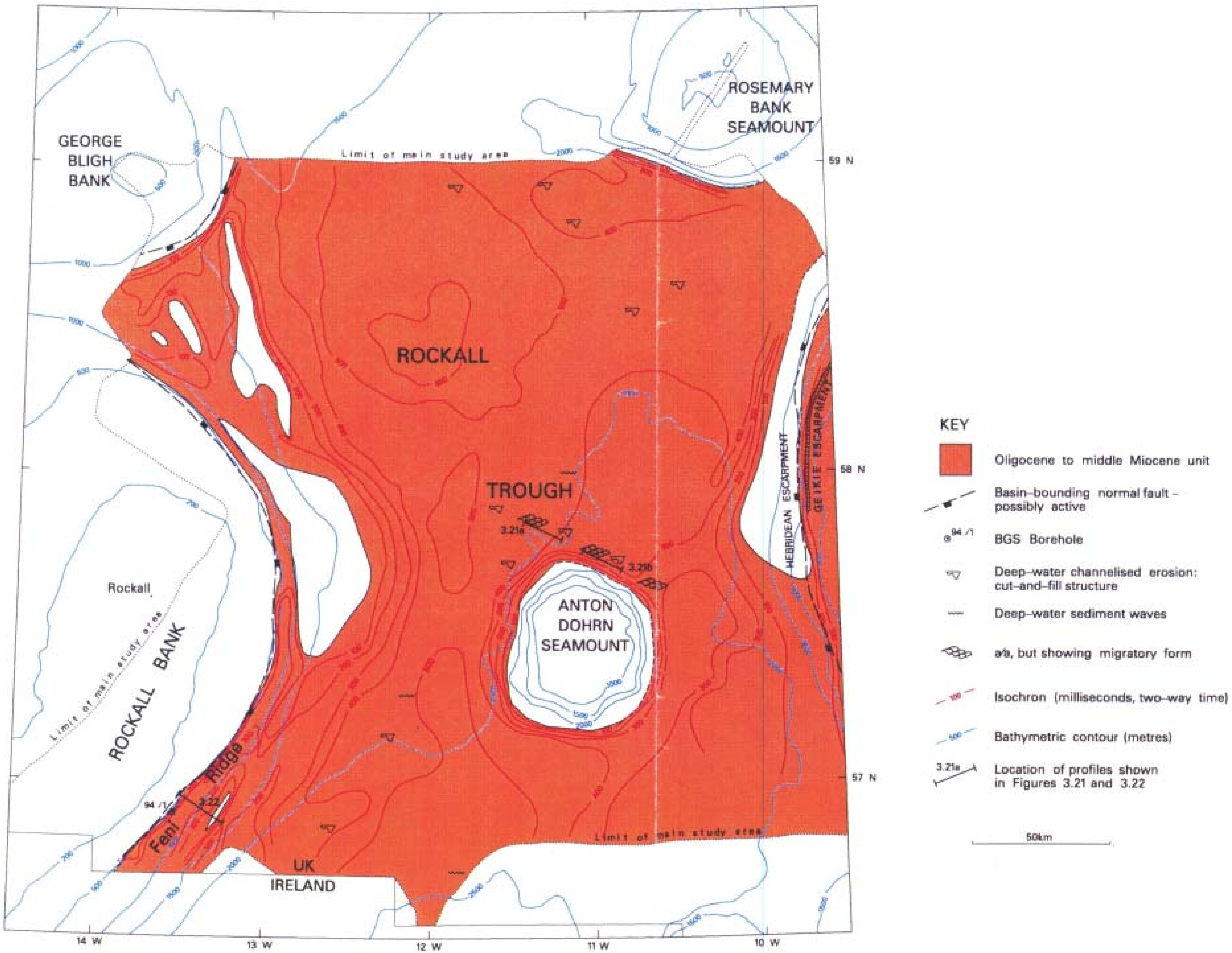


Fig. 3.20 Distribution of Oligocene to middle Miocene unit (seismic interval B–A); upper part of upper Eocene to middle Miocene sequence (seismic interval C–A)

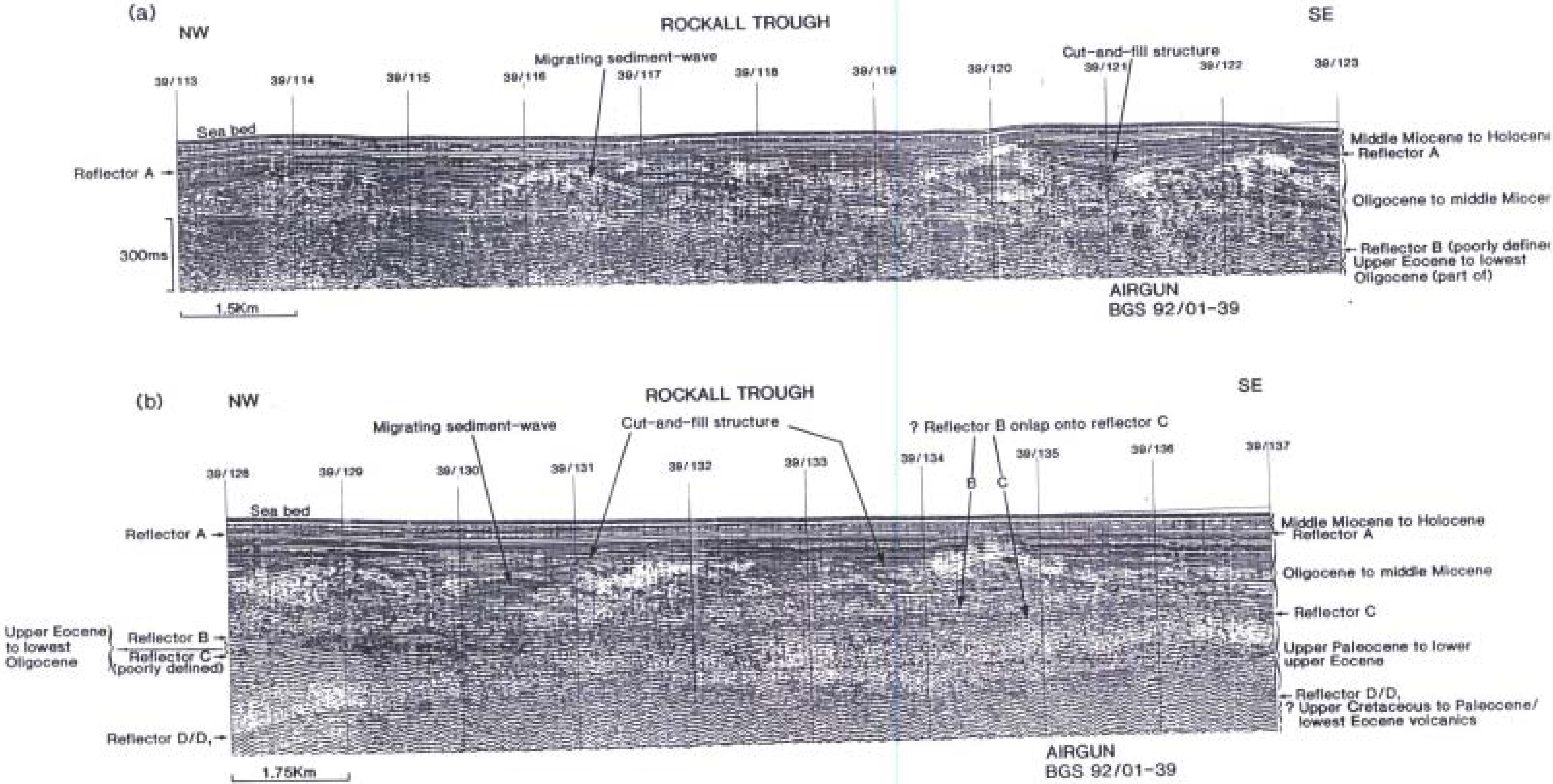


Fig. 3.21 Airgun profiles from the Rockall Trough, adjacent to the northern flank of the Anton Dohrn seamount, showing complex, large-scale, deep-water, current-moulded bedforms preserved in the Oligocene to middle Miocene section (seismic interval B-A): profiles located in Figure 3.20. At the top of the section, reflector A is a locally well-defined angular unconformity.

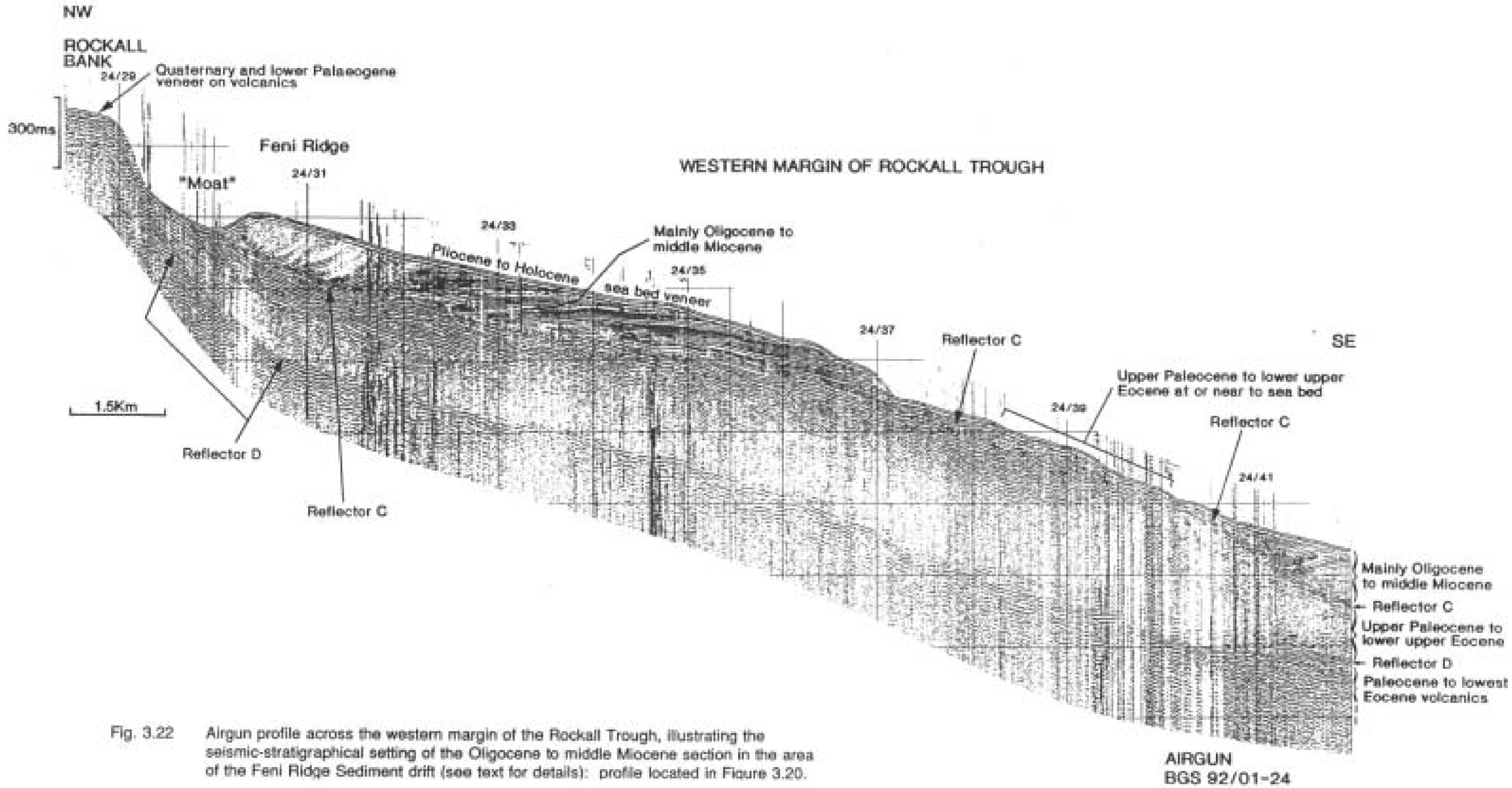


Fig. 3.22 Airgun profile across the western margin of the Rockall Trough, illustrating the seismic-stratigraphical setting of the Oligocene to middle Miocene section in the area of the Feni Ridge Sediment drift (see text for details): profile located in Figure 3.20.

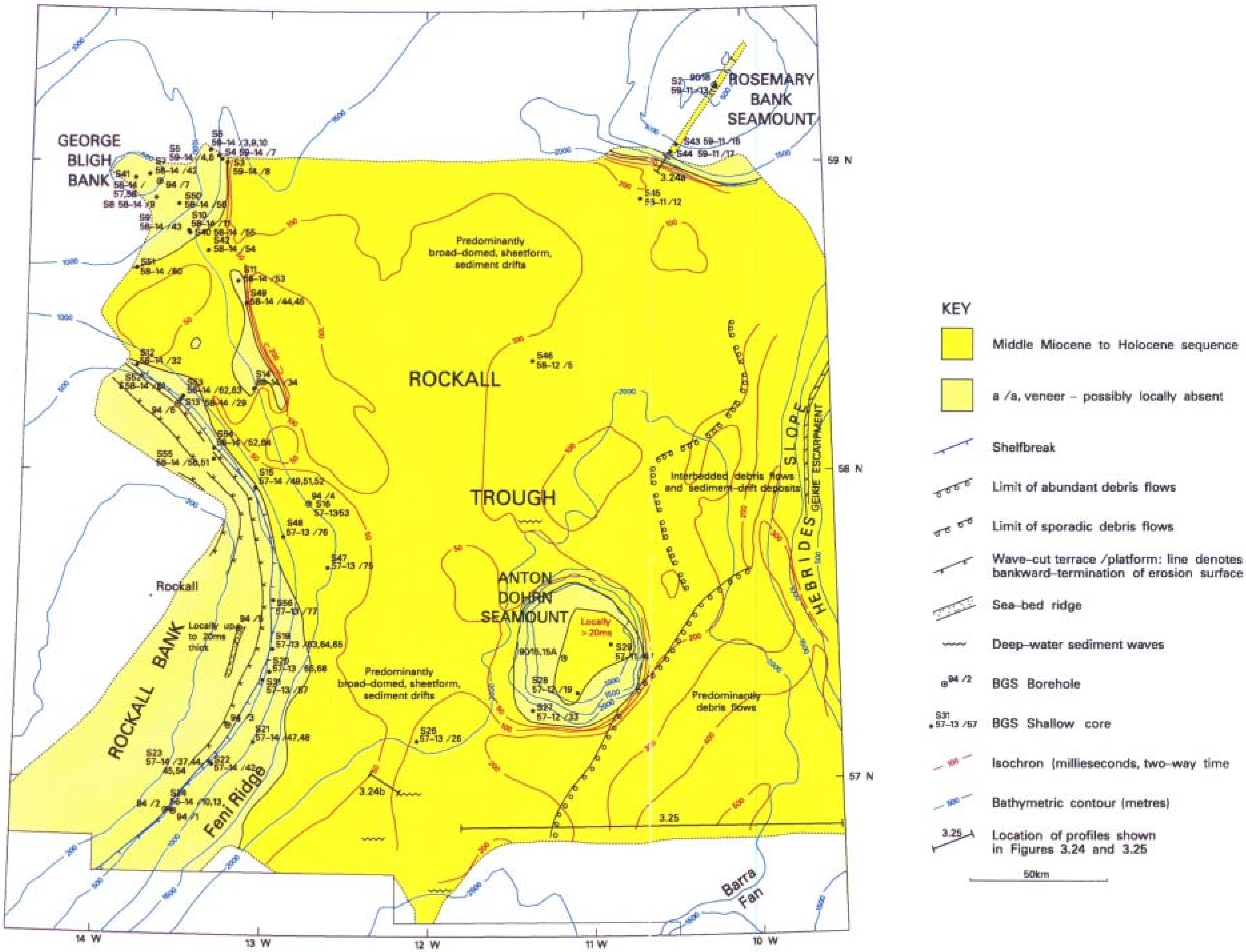
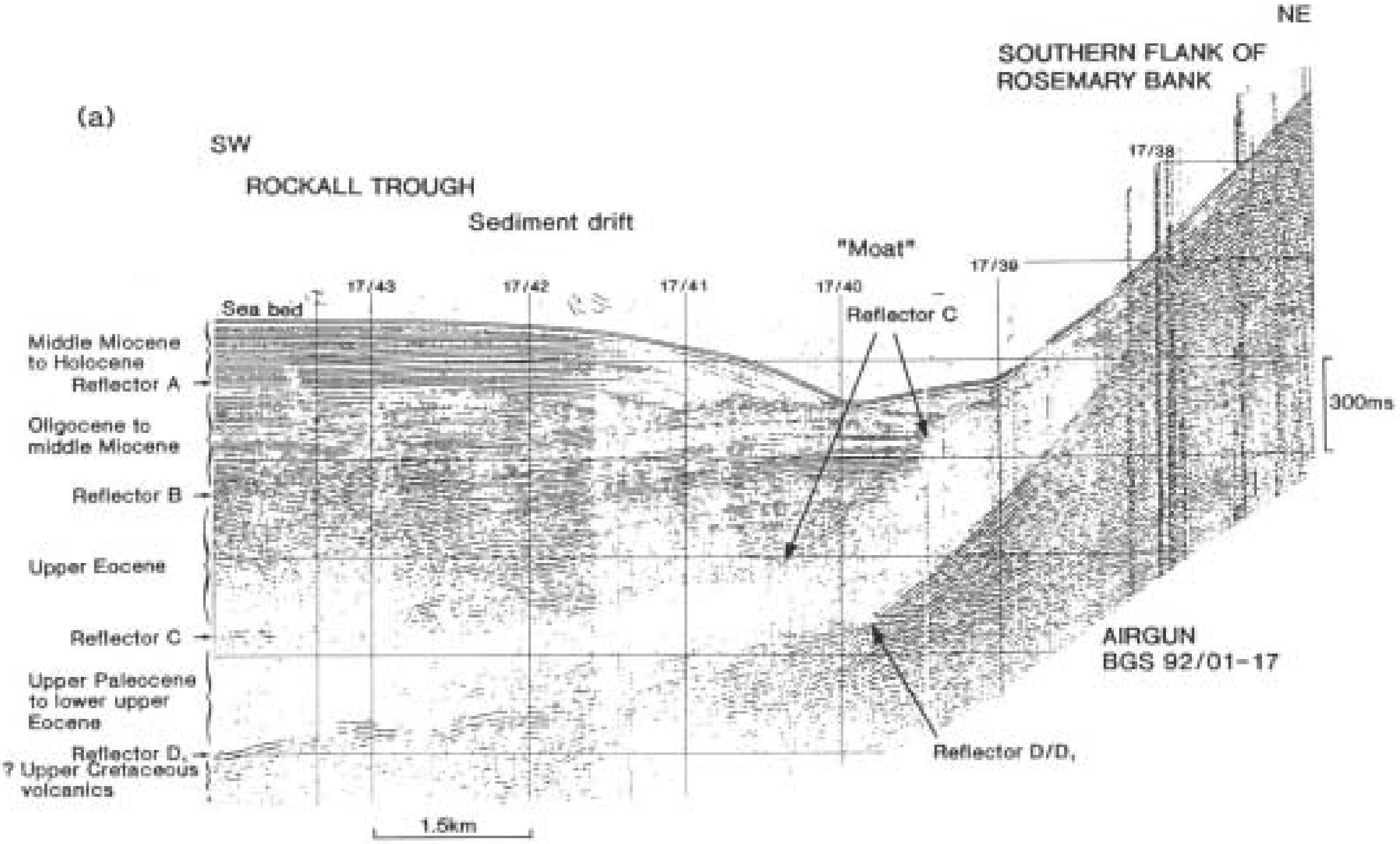


Fig. 3.23 Distribution of middle Miocene to Holocene sequence (seismic interval A-sea bed)



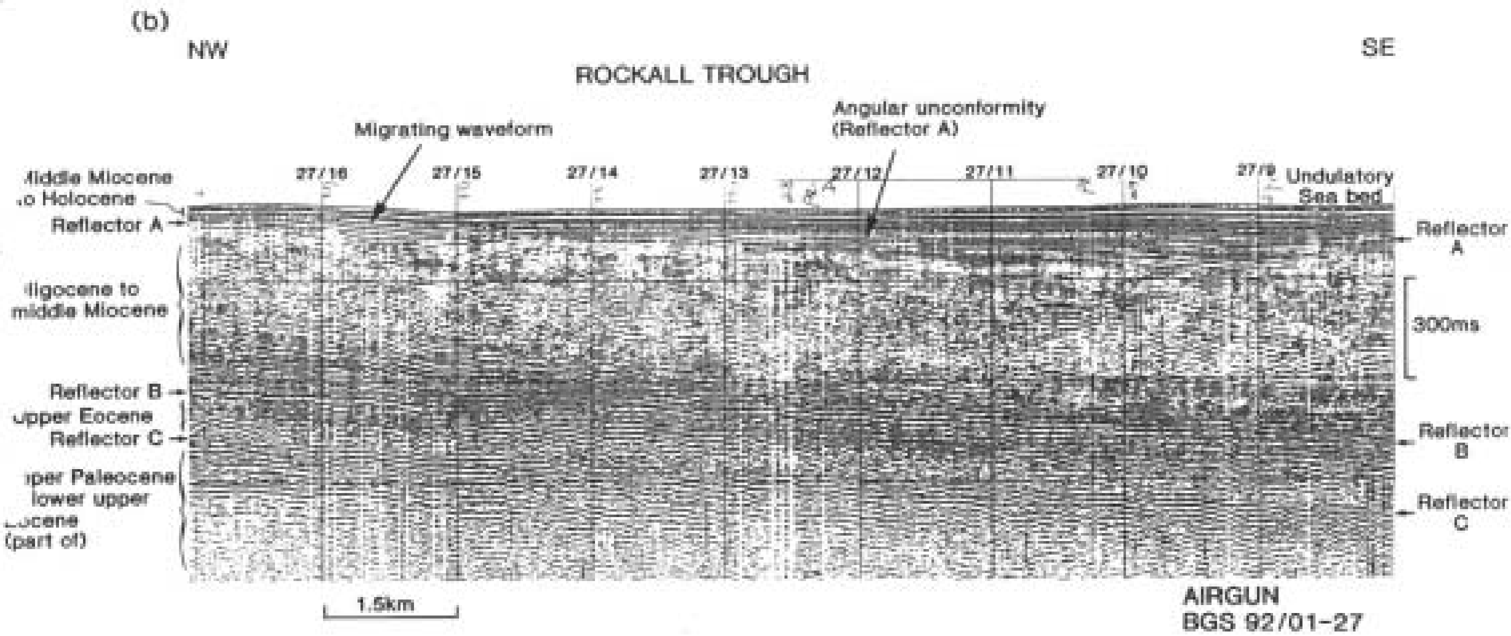


Fig. 3.24 Airgun profiles from the Rockall Trough showing large-scale, deep-water, current-moulded bedforms associated with the middle Miocene to Holocene section (seismic interval A-sea bed): profiles located in Figure 3.23. In (b), the sediment-waves impart an undulatory character to the sea bed. See text for details.

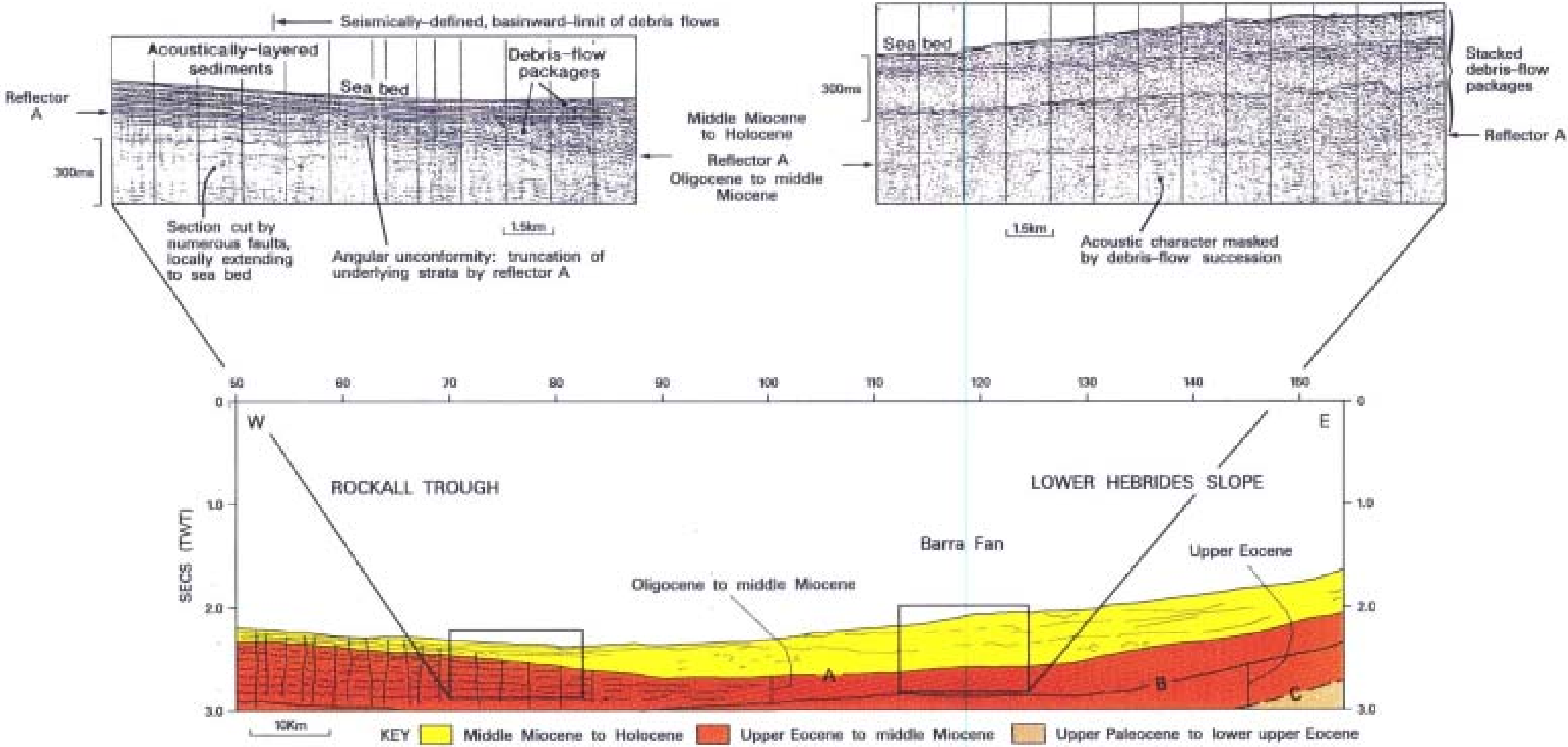


Fig. 3.25 Interpreted line drawing of, and seismic insets from, airgun profile BGS 92 /01-56 across the distal part of the Barra Fan showing the variable acoustic character and seismic-stratigraphical relations of the middle Miocene to Holocene sequence (seismic interval A-sea bed): section located in Figure 3.23. See text for details.

Table 3.1. Seismic reflectors and seismic sequences

Seismic reflector	Typical characteristics of reflectors and sequences	Common age range
A	Basinwide unconformity, commonly angular, between prograding/downlapping slope-apron (Hebrides Slope) to acoustically well-layered basinal strata (Rockall Trough) above, and parallel-to-undulatory (current-moulded) stratified sequence below	Mid-Miocene
B_0	Unconformity, commonly angular, between acoustically well-stratified, onlapping strata above, and prograding/downlapping beds below, on western margin of the Rockall Trough	Latest Eocene to earliest Oligocene
B	Basinwide strong reflector in Rockall Trough separating parallel-to-undulatory stratified and locally prograding/downlapping beds above, and parallel stratified sequence below; onlaps older sequence	Late Eocene (to earliest Oligocene?)
C	Marked angular unconformity at basin margins separating parallel-to-undulatory (current-moulded) stratified, onlapping and downlapping strata above, and variably acoustically layered to transparent sequence below: reflector appears more conformable within the basins	Late Eocene
C_1	Local angular unconformity on Rockall Bank separating prograding, stratified beds above, and prograding-to-chaotic stratified sequence below	Mid-Eocene
C_2	Local angular unconformity on Rockall Bank separating prograding-to-chaotic stratified sequence above, and parallel stratified to locally downlapping sequence below	Early Eocene
D*	Strong basinwide reflector, commonly irregular at base of imaged sedimentary succession: predominantly acoustic basement over most of the area, but some truncation of underlying strata on Rockall Bank	Late Paleocene to earliest Eocene
D_1	Strong reflector, commonly irregular, at base of acoustically transparent-to-layered sequence on axial seamounts of Anton Dohrn and Rosemary Bank	Late Cretaceous

* Locally marks top of metamorphic basement on Rockall Bank

Table 3.2. Regional seismic reflectors and common age range of seismic sequences

Seismic reflector	Common age range	Previous informal stratigraphical nomenclature of Hitchen and Stoker (1993a)
Sea bed	Mid-Miocene to Holocene	Rockall Trough sequence A Upper part of 'banks' and 'seamounts' cover sequences
A	Late Eocene to mid-Miocene	Rockall Trough sequences B and C
B		(REFLECTIVE ZONE)
	Late Eocene	Upper part of Transparent Zone (Rockall Trough)
C	MAJOR BASIN-MARGIN UNCONFORMITY	
	Late Paleocene to early late Eocene	Transparent Zone (Rockall Trough) Rockall and George Bligh bank sequences (including pre-wedge strata) Lower part of Anton Dohrn sequence
D/D_1	ACOUSTIC BASEMENT	
	Late Cretaceous to Paleocene/earliest Eocene	Sub-Transparent Zone (Rockall Trough) Rockall and George Bligh banks Rosemary Bank and Anton Dohrn seamounts
	Early Proterozoic	Rockall Bank

Table 3.3. Biostratigraphical ages from BGS shallow cores and boreholes: latest Cretaceous and Palaeogene

BGS no:	Original site no:	Seismic interval	Age*
TOP AND EASTERN FLANK OF ROCKALL BANK			
57-13/77	S56	D-C	Mid-Eocene (NP15-16) [3]
58-14/29	S13	D-C	Early to mid-Eocene (NP10/11-15) [1, 2]
94/2		D-C	Mid- to earliest late Eocene (NP16-18) on mid-Eocene (NP14) [1, 2, 3]
94/1		D-C	Mid-Eocene (NP16-18) [1, 2, 3]
94/3		D-C and acoustic basement	Late mid-Eocene (NP16-17) on late early to mid-Eocene (NP13-14) on late Paleocene to early Eocene (NP4-10/11) [1, 2, 3]
94/6		D-C	Mid-Eocene (NP14-15) [1]
TOP AND EASTERN FLANK OF GEORGE BLIGH BANK			
58-14/10	S9	D-C	Late Paleocene to early Eocene (NP7-13) [2, 3]
58-14/11	S10	D-C	Late Paleocene (NP6-9) [3]
58-14/42	S7	Acoustic basement	Paleocene [3]
58-14/43	S9	D-C	Late Paleocene (NP6-9) [3]
58-14/57	S41	Acoustic basement	Paleocene [??]
94/7		D-C and acoustic basement	Mid- to earliest late Eocene (NP15-18) [3] on Paleocene [2]
WESTERN MARGIN OF ROCKALL TROUGH			
58-14/34	S14	D-C	Mid-Eocene (NP14-17) [2, 3]
58-14/44	S49	D-C	Mid-Eocene (NP16) [3]
58-14/53	S11	D-C	Mid-Eocene (NP16) [2, 3]
58-14/54	S42	D-C	Mid- to late Eocene (NP17-19) [2, 3]
59-14/6	S5	D-C	Early to earliest mid-Eocene (NP12-14) [1, 2]
59-14/7	S4	D-C	Early to mid-Eocene (NP13-15) [1]
59-14/8	S3	D-C	Early Eocene (NP13) [1, 3]
59-14/9	S6	D-C	Mid-Eocene (NP15-16) [3]
94/4		$B-B_0$	Late Eocene to earliest Oligocene [1, 2]
TOP OF ROSEMARY BANK SEAMOUNT			
90/18		Acoustic basement	Senonian (Maastrichtian) [3]
TOP OF ANTON DOHRN SEAMOUNT			
57-12/18	S30	?D-C	Mid- to late Eocene (NP17-19) [2]
90/15, 15A		D-C	Paleocene to early Eocene [3]

* Ages from: [1] Dinoflagellate cysts (J.B. Riding); [2] Foraminifera with occasional bolboformids, ostracods and radiolaria (I.P. Wilkinson); [3] Calcareous nannofossils (N.M. Hine).

NB. Sample type: 59-14/8 - BGS shallow core
90/18, 94/1 - BGS borehole

Table 3.4. Biostratigraphical ages from BGS shallow cores and boreholes: Neogene and Quaternary

BGS no:	Original site no:	Seismic interval	Age*
TOP AND EASTERN FLANK OF ROCKALL BANK			
56-14/13	S24	A-sea bed (veneer)#	Mid-Pleistocene to Holocene (NN21) [1, 2, 3]
57-13/57	S31	A-sea bed (veneer)#	Mid-Pleistocene to Holocene (NN21) [1, 2, 3]
57-14/54	S23	A-sea bed (veneer)#	Mid-Pleistocene to Holocene (NN20-21) [1, 2, 3]
58-14/32	S12	A-sea bed (veneer)#	Pliocene (NN12-15) [2, 3, 4]
94/1		A-sea bed	Mid-Miocene to late Pliocene (NN6-15) [1, 2, 3]
94/3		A-sea bed (veneer)#	Pleistocene to Holocene [1, 2, 3]
94/5		A-sea bed (veneer)	Pleistocene to Holocene (NN19-21) [1, 2, 3]
94/6		A-sea bed (veneer)	Pliocene to Holocene (NN14-21) [1, 2, 3]
TOP AND EASTERN FLANK OF GEORGE BLIGH BANK			
58-14/9	S8	A-sea bed (veneer)	Mid- to late Pleistocene (NN20-21) [1, 2, 3]
58-14/57	S41	A-sea bed (veneer)	Mid-Pleistocene (NN21) [1, 2, 3]
WESTERN MARGIN OF ROCKALL TROUGH			
57-13/53	S16	A-sea bed (veneer)#	Early/mid-Pleistocene to Holocene (NN19-21) [1, 2, 3]
57-13/75	S47	A-sea bed (veneer)#	Early/mid-Pleistocene to Holocene (NN19-21) [1, 3]
57-13/76	S48	A-sea bed (veneer)	Late Pliocene to Holocene (NN16-21) [1, 3]
57-14/48	S21	A-sea bed (veneer)#	Pleistocene (NN19-21) on Pliocene (NN13-15) [1, 2, 3]
58-14/34	S14	A-sea bed (veneer)#	Mid- to late Pleistocene (NN20-21) [1, 2, 3]
58-14/60	S51	A-sea bed (veneer)#	Early/mid-Pleistocene to Holocene (NN19-21) [1, 2, 3]
94/4		A-sea bed (veneer)	Pleistocene to Holocene (NN19-21) [1, 2, 3]
AXIS OF ROCKALL TROUGH			
57-12/33	S27	A-sea bed (veneer)#	Pleistocene to Holocene (NN19-21) on Pliocene (NN15) [1, 2, 3]
57-13/26	S26	A-sea bed	Late Pleistocene to Holocene (NN21) [1, 2, 3]
58-11/2	S45	A-sea bed	Late Pleistocene to Holocene (NN21) [1, 2, 3]
58-12/5	S46	A-sea bed	Late Pleistocene to Holocene (NN21) [1, 2, 3]
TOP AND SOUTHERN FLANK OF ROSEMARY BANK SEAMOUNT			
59-11/13	S2	A-sea bed	Mid-Pleistocene to Holocene (NN21) [1, 2, 3]
59-11/16	S43	A-sea bed	Mid-/late Pleistocene (NN21) [3]
59-11/17	S44	A-sea bed (veneer)#	Mid-/late Pleistocene to Holocene (NN21) [1, 2, 3]
90/18		A-sea bed	Late Pliocene (NN15-18) on mid- to late Miocene (NN7-9) [3]
TOP AND SOUTHERN FLANK OF ANTON DOHRN SEAMOUNT			
57-11/67	S29	A-sea bed	Mid-Pleistocene to Holocene (NN20-21) [1, 2, 3]
57-12/19	S28	A-sea bed (veneer)#	Late Pliocene to late Pleistocene (NN18-21) [1, 2, 3]
90/15, 15A		A-sea bed (veneer)	Mid- to late Miocene (NN8-9) [3]

* Ages from: [1] Dinoflagellate cysts (J.B. Riding); [2] Foraminifera with occasional bolboformids, ostracods and radiolaria (I.P. Wilkinson); [3] Calcareous nannofossils (N.M. Hine); [4] Macrofauna (M.A. Woods).

Beyond seismic resolution

NB. Sample type: 59-11/13 - BGS shallow core
90/18, 94/1 - BGS borehole

Table 3.5. Stratigraphical sequences and sample density

Original site no:	BGS no:	Original site no:	BGS no:	Original site no:	BGS no:
		MIDDLE MIOCENE TO HOLOCENE (Seismic interval A-sea bed)			
S2	59-11/13	S22	57-14/42	S49	58-14/44,45
S3	59-14/8	S23	57-14/37,44,45,54	S50	58-14/56
S4	59-14/7	S24	56-14/10,13	S51	58-14/60
S5	59-14/4	S25	56-15/11	S52	58-14/61
S6	59-14/2,3,9,10	S26	57-13/26	S53	58-14/62,63
S7	58-14/42	S27	57-12/33	S54	58-14/52,64
S8	58-14/9	S28	57-12/19	S55	58-14/50,51
S9	58-14/43	S29	57-11/67	S56	57-13/77
S10	58-14/11	S31	57-13/57		90/15,15A
S11	58-14/53	S40	58-14/55		90/18
S12	58-14/32	S41	58-14/57,58		94/1
S13	58-14/29	S42	58-14/54		94/2
S14	58-14/34	S43	59-11/16		94/3
S15	57-14/49,51,52	S44	59-11/17		94/4
S16	57-13/53	S45	58-11/2		94/5
S19	57-13/63,64,65	S46	58-12/5		94/6
S20	57-13/66,68	S47	57-13/75		94/7
S21	57-14/47,48	S48	57-13/76		
		UPPER EOCENE TO MIDDLE MIOCENE (Seismic interval C-A)			
	94/1		94/4		
		UPPER PALEOCENE TO LOWER UPPER EOCENE (Seismic interval D-C)			
S3	59-14/5,6	S14	58-14/34		90/15,15A
S4	59-14/7	S19	57-13/65		94/1
S5	59-14/5,6	S22	57-14/43		94/2
S6	59-14/9,10	S30	57-12/18		94/3
S9	58-14/10,43	S40	58-14/55		94/6
S10	58-14/11	S42	58-14/54		94/7
S11	58-14/53	S49	58-14/44,45		
S13	58-14/29,30	S56	57-13/77		
		UPPER CRETACEOUS TO PALEOCENE/LOWEST EOCENE (Volcanogenic acoustic basement)			
S1	59-11/12	S18	57-14/53		94/3
S7	58-14/8,42	S41	58-14/57,58		94/5
S12	58-14/31,32		90/18		94/6
S17	57-13/54		94/2		94/7
		LOWER PROTEROZOIC (Metamorphic acoustic basement)			
S25	56-15/11,12				

NB. Sample type: 58-14/11 - BGS shallow core
90/18, 94/1 - BGS borehole

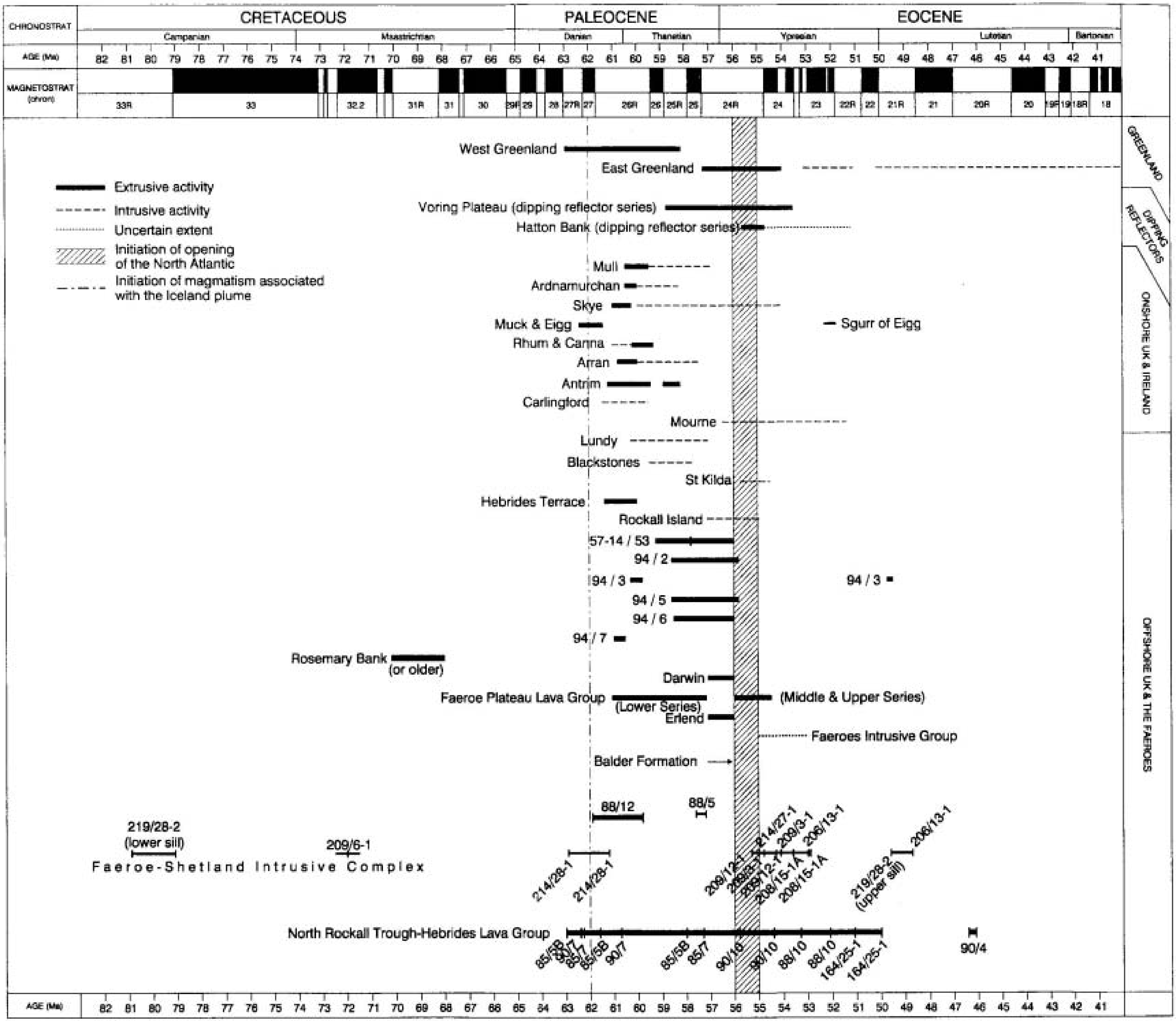


Fig. 4.2 Age correlation chart for the volcanics offshore NW Britain. Timescale after Harland et al. (1990).

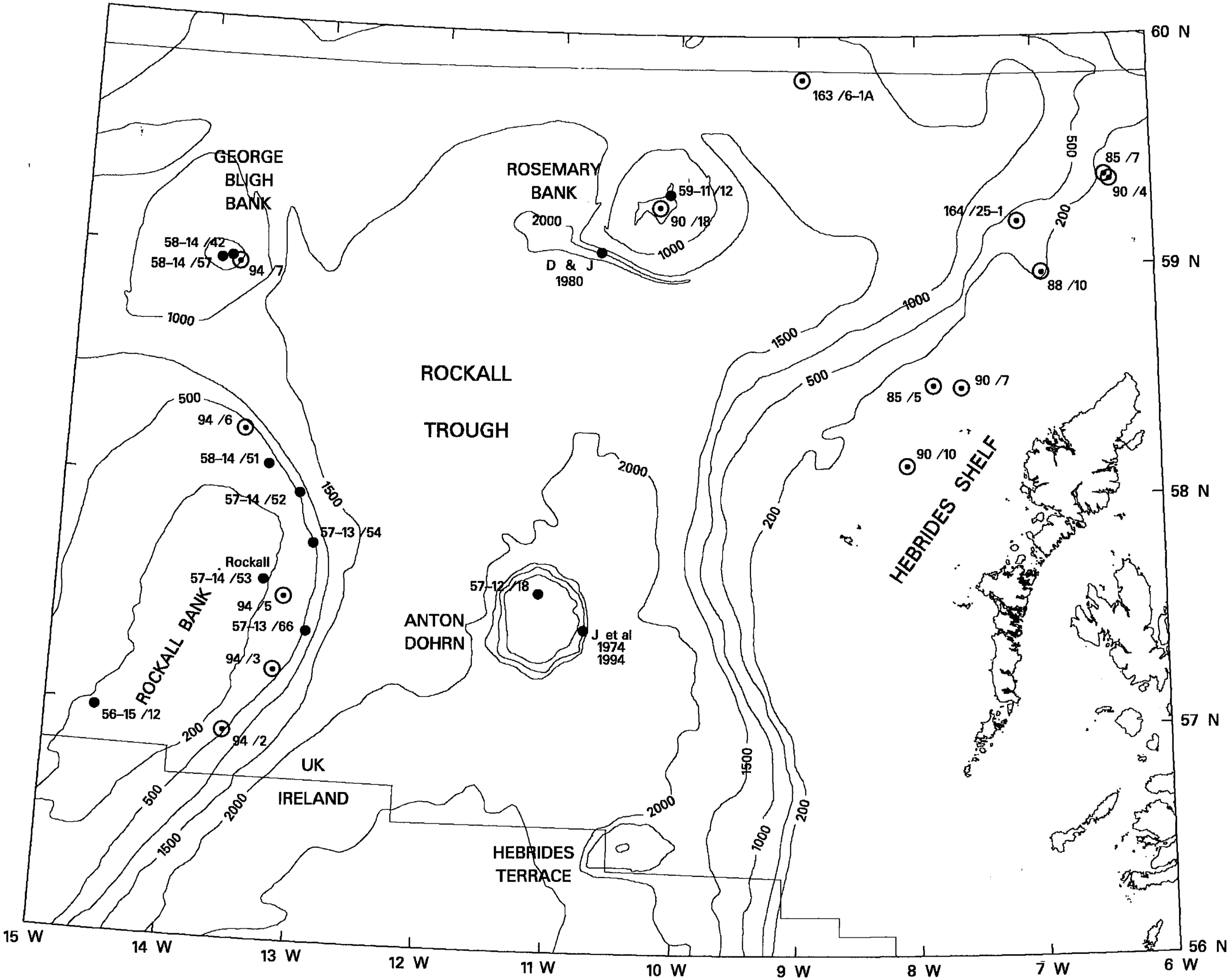


Fig. 4.3 Location of volcanic samples with geochemical analyses.
J et al 1974,1994: Jones et al. (1974; 1994)
D&J 1980: Dietrich and Jones (1980)

Table 4.1

SUMMARY OF IGNEOUS ROCKS

Abbreviations:

Alk	Alkaline
S-Alk	Subalkaline
UCS	Upper crustal sediments
SCLMM	Subcontinental lithospheric mantle material
NAAM	North Atlantic asthenospheric mantle
*	Tentative

Location	Depth (m)	Lithology	Source	Contaminant
Hebrides Shelf				
85/7	28.20	S-Alk basalt	NAAM	None
	30.85	S-Alk basalt	NAAM	UCS
90/4	15.30	S-Alk basalt	NAAM	None
164/25-1	1993.65	Basalt	NAAM	Lewisian
	1994.60	Basalt	NAAM	Lewisian
88/10	129.90	S-Alk basalt	NAAM	Lewisian
	132.70	S-Alk basalt	NAAM	Lewisian
85/5B	41.65	Basalt	NAAM	None
	42.65	Basalt	NAAM	None
90/7	10.45	Basalt	NAAM	Lewisian
90/10	9.80	Basalt	NAAM	Lewisian
Darwin				
163/6-1A				
Core 4	XX	S-Alk basalt	NAAM	None
	XX	S-Alk basalt	NAAM	None
	XX	S-Alk basalt	NAAM	None
	XX	S-Alk basalt	NAAM	None
Core 5	XX	S-Alk basalt	NAAM	None
	XX	S-Alk basalt	NAAM	None
Core 6	XX	S-Alk basalt	NAAM	None
	XX	S-Alk basalt	NAAM	SCLMM
Core 7	XX	Dacite	Anatexis of UCS	
	XX	Dacite	Anatexis of UCS	

Depths not officially released

Table 4.1 (continued)

Location	Depth (m)	Lithology	Source	Contaminant
Rosemary Bank				
90/18	29.43	S-Alk basalt	NAAM	None
	30.65	S-Alk basalt	NAAM	None
	35.10	S-Alk basalt	NAAM	None
	38.10	S-Alk basalt	NAAM	None
	39.90	S-Alk basalt	NAAM	None
Dredge[1]		S-Alk basalt	NAAM	UCS*
Dredge[2]		Lapilli tuffs	SCLMM	
59-11/12		Phono-tephrite	SCLMM	

[1] Dietrich and Jones *et al.* (1980)
[2] Waagstein *et al.* (1989)

Location	Depth (m)	Lithology	Source	Contaminant
Anton Dohrn				
Dredge[3]		Basalt	NAAM	None
57-12/18		Alk basalt	NAAM	None

[3] Jones *et al.* (1974; 1994)

Location	Depth (m)	Lithology	Source	Contaminant
Hebrides Terrace				
Dredge[4]		S-Alk basalt	NAAM	Islay terrane*

[4] Omran (1990)

Location	Depth (m)	Lithology	Source	Contaminant
George Bligh Bank				
Dredge[5]		Alk basalt	NAAM	Lewisian
58-14/42		Alk basalt	NAAM	Lewisian
94/7	23.20	Alk basalt	NAAM	Lewisian
58-14/8		Basaltic agglomerate		
58-14/57		Basaltic agglomerate		

[5] DGU expedition (1988, unpublished)

Location	Depth (m)	Lithology	Source	Contaminant
Hatton-Rockall Basin				
DSDP 117		Alk basalt	NAAM	None

Table 4.1 (continued)

Location	Depth (m)	Lithology	Source	Contaminant
Rockall Bank				
Helen's Reef		Microgabbro	NAAM	None
94/2	21.74	S-Alk basalt	NAAM	Rockall basement
94/3 (upper)	47.75	S-Alk basalt	NAAM	Rockall basement
94/3 (lower)	209.57	S-Alk basalt	NAAM	None
94/5	29.21	Hawaiite	NAAM	Granite[6]
94/6	20.12	S-Alk basalt	NAAM	Rockall basement
57-14/52		Alk basalt	NAAM	Rockall basement
57-13/54		Basaltic agglomerate		
57-13/66		Basalt	NAAM	None
Pisces EH5795		Basalt	NAAM	None
Pisces EH5796		S-Alk basalt	NAAM	Pre-Camb Granite
Rockall Island		Aegirine granite	SCLMM	Mantle source
94/3		Andesitic tuffs		
58-14/51		Trachyte	NAAM	Islay terrane
57-14/53		Trachyte	NAAM	Islay terrane

[6] or other upper crustal rock

Table 4.2

ORIGINAL SOURCE MATERIAL

<u>NAAM</u>	
Hebrides Shelf:	85/5B, 85/7, 88/10, 90/4, 90/7, 90/10.
Darwin:	163/6-1A (basalts, cores 4,5 and 6)
Rosemary Bank:	Dredge (Dietrich and Jones, 1980)
Anton Dohrn:	Dredge (Jones *et al.* 1974; 1994)
	57-12/18
Hebrides Terrace:	Dredge (Omran, 1990)
George Bligh Bank:	Dredge (DGU expedition 1988)
	58-14/42
	94/7
Rockall Bank:	Helen's Reef
(basic)	94/2, 94/5, 94/6.
	94/3 (upper and lower lavas)
	Pisces samples EH5795, EH5796
Rockall Bank:	58-14/51
(acidic)	57-14/53
Malin Shelf:	Irish well 13/3-1
Hatton-Rockall:	DSDP 117*
<u>Subcontinental lithospheric material</u>	
Rosemary Bank:	Dredge (Waagstein *et al.* 1989)
	59-11/12
Rockall Bank: contamination	Rockall Island (aegirine granite). Possibly SCLMM or NAAM with
<u>Anatexis of sediments</u>	
Darwin:	163/6-1A (dacites, core 7)
Erlend:	209/4-1A, 209/9-1
Voring Plateau:	DSDP 642

* Tentative

Table 4.3

CONTAMINANTION OF NAAM-SOURCED ROCKS

No contamination	
Hebrides Shelf:	85/5B, 85/7, 90/4.
Darwin:	163/6-1A Cores 4,5, and 6.
Rosemary Bank:	90/18
Anton Dohrn:	Dredge (Jones *et al.* 1974, 1994)
	57-12/18
Rockall Bank:	Helen's Reef
	94/3 (lower lava)
	57-13/66
	Pisces sample EH5795
Hatton-Rockall:	DSDP 117
Subcontinental lithospheric material	
Darwin:	163/6-1A (Core 6)
Lewisian	
Hebrides Shelf:	88/10, 90/7, 90/10, 164/25-1
George Bligh Bank:	Dredge (DGU expedition 1988)
	94/7
	58-14/42
Rockall basement	
Rockall Bank:	94/2, 94/6
	94/5 (high level granite)
	94/3 (upper lava)
	57-14/52
	Pisces sample EH5796
Islay terrane	
Hebrides Terrace:	Dredge (Omran, 1990)*
Sediments	
Hebrides Shelf:	85/7 (slight contamination only)
Rosemary Bank:	Dredge (Dietrich and Jones, 1980)*
Malin Shelf:	Irish well 13/3-1

* Tentative

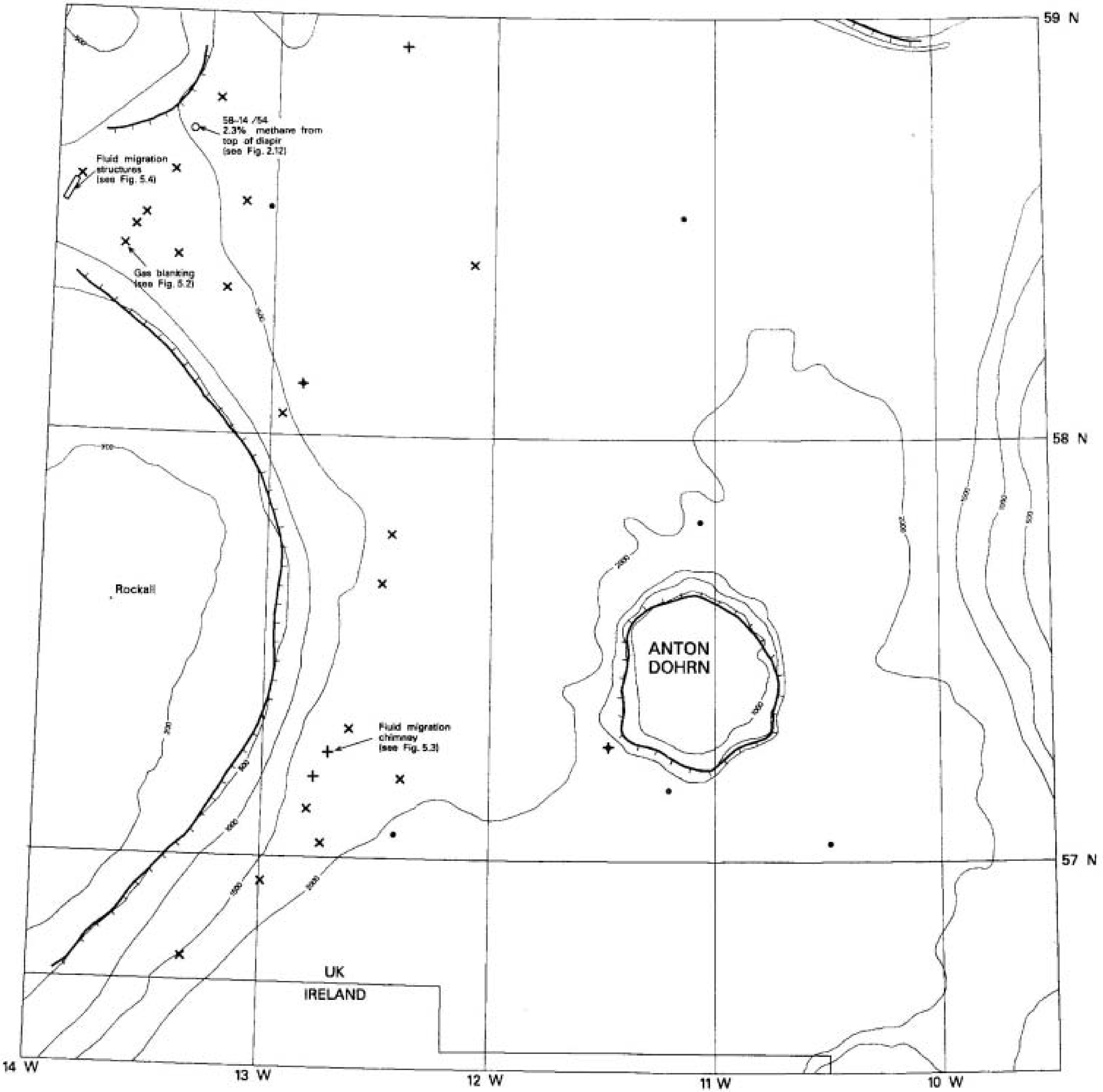


Figure 5.1
Synoptic prospectivity map

KEY

For fuller explanation see
Appendix 3 of this report

Bathymetry in metres

Bathymetric scarp

• Sample selected for GCMS

× Methane values >30ng /g

+ Significant fluorescence maxima on TSF data

0 20km

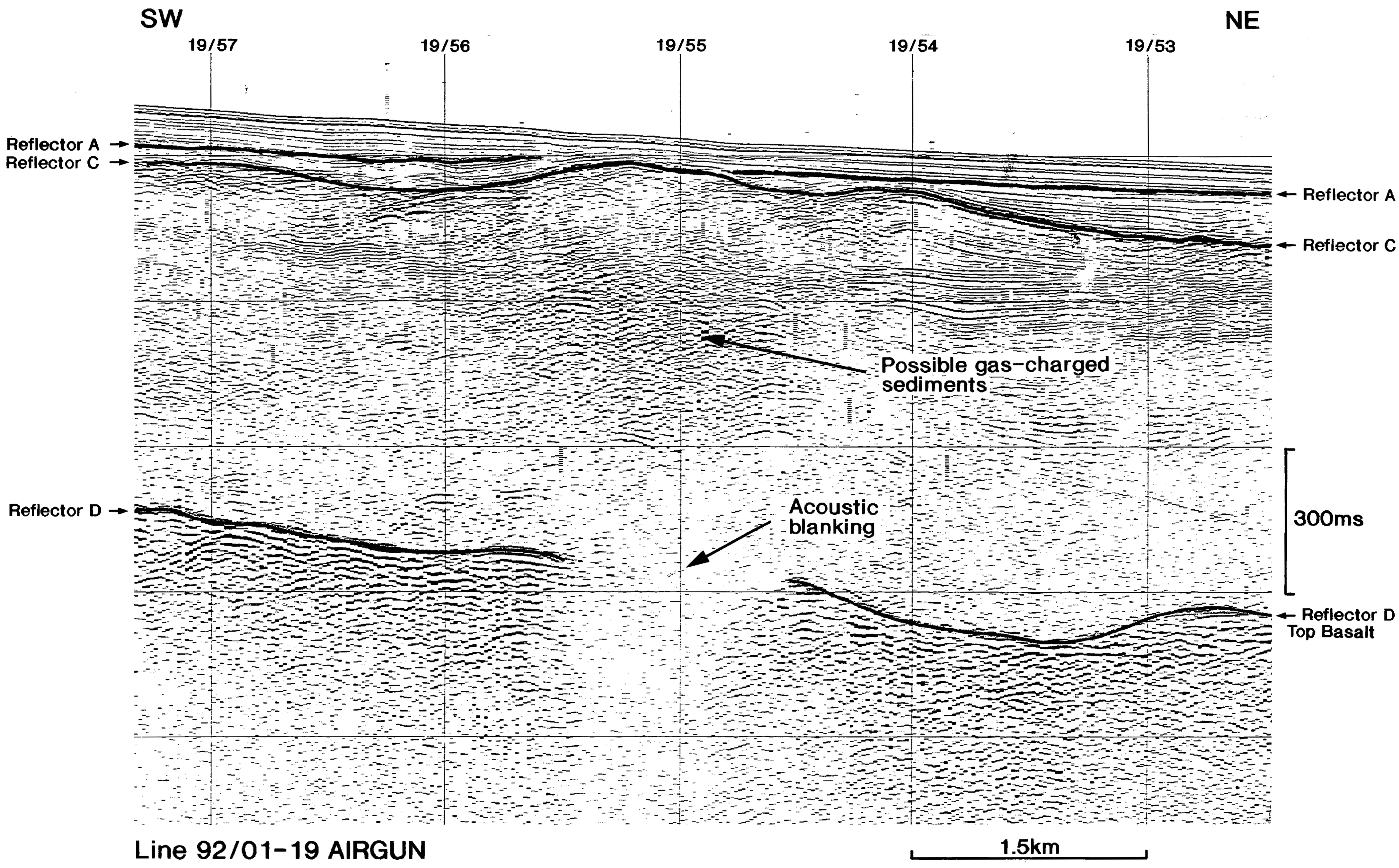


Fig. 5.2 Gas blanking between George Bligh and Rockall Banks

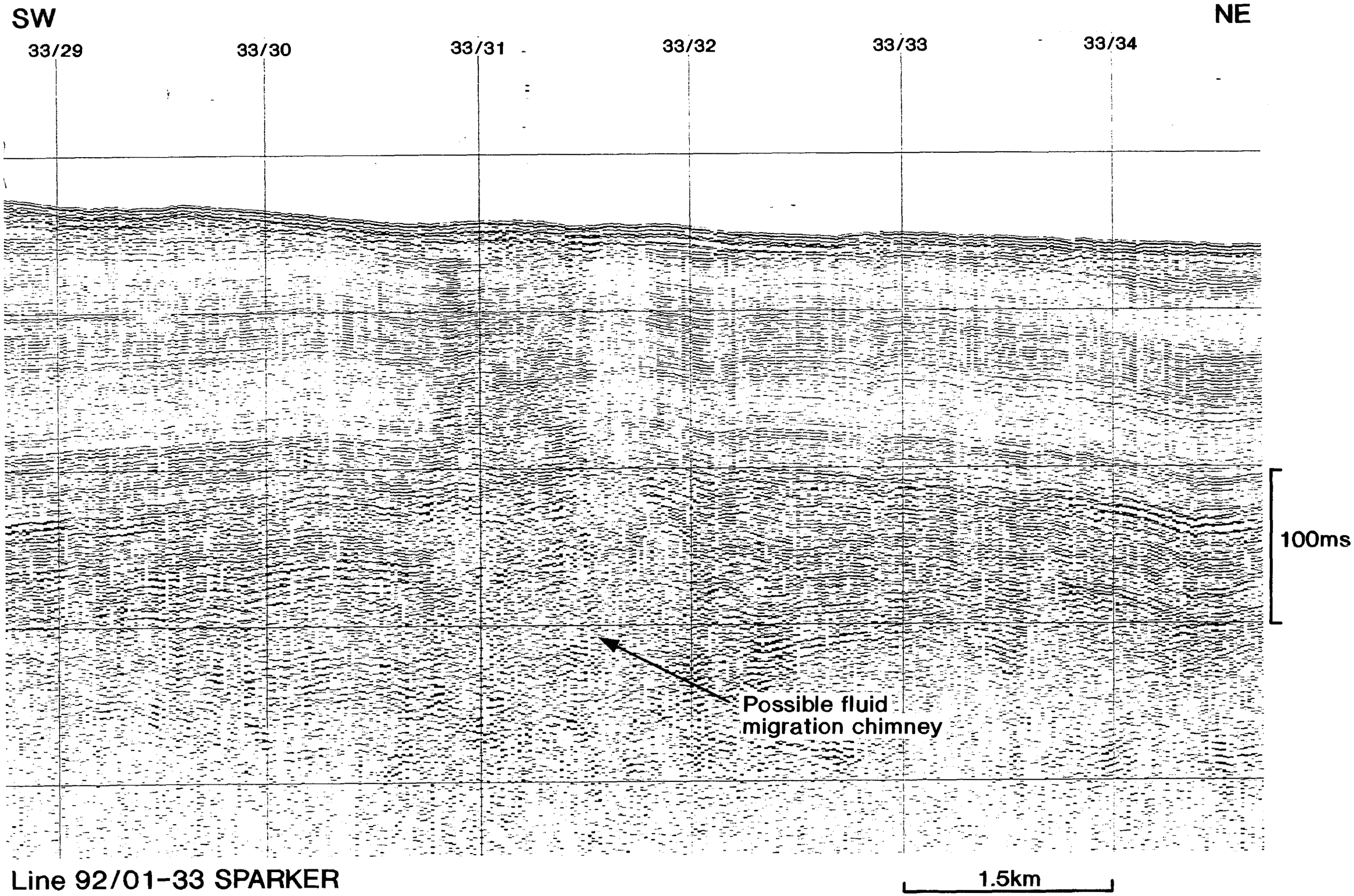


Fig 5.3 Fluid migration structure, east of Rockall Bank

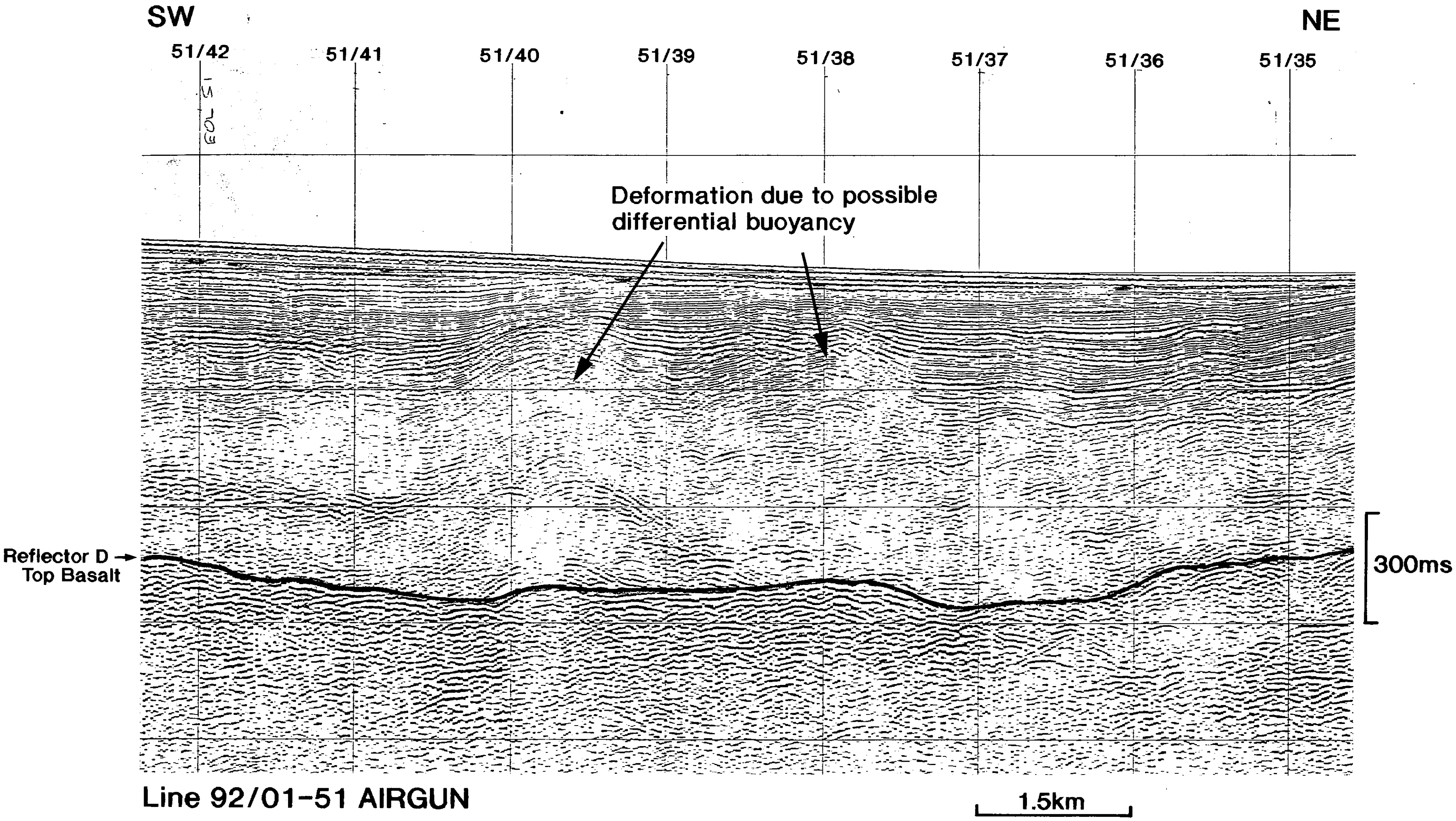


Fig. 5.4 Possible fluid migration structures between George Bligh and Rockall Banks

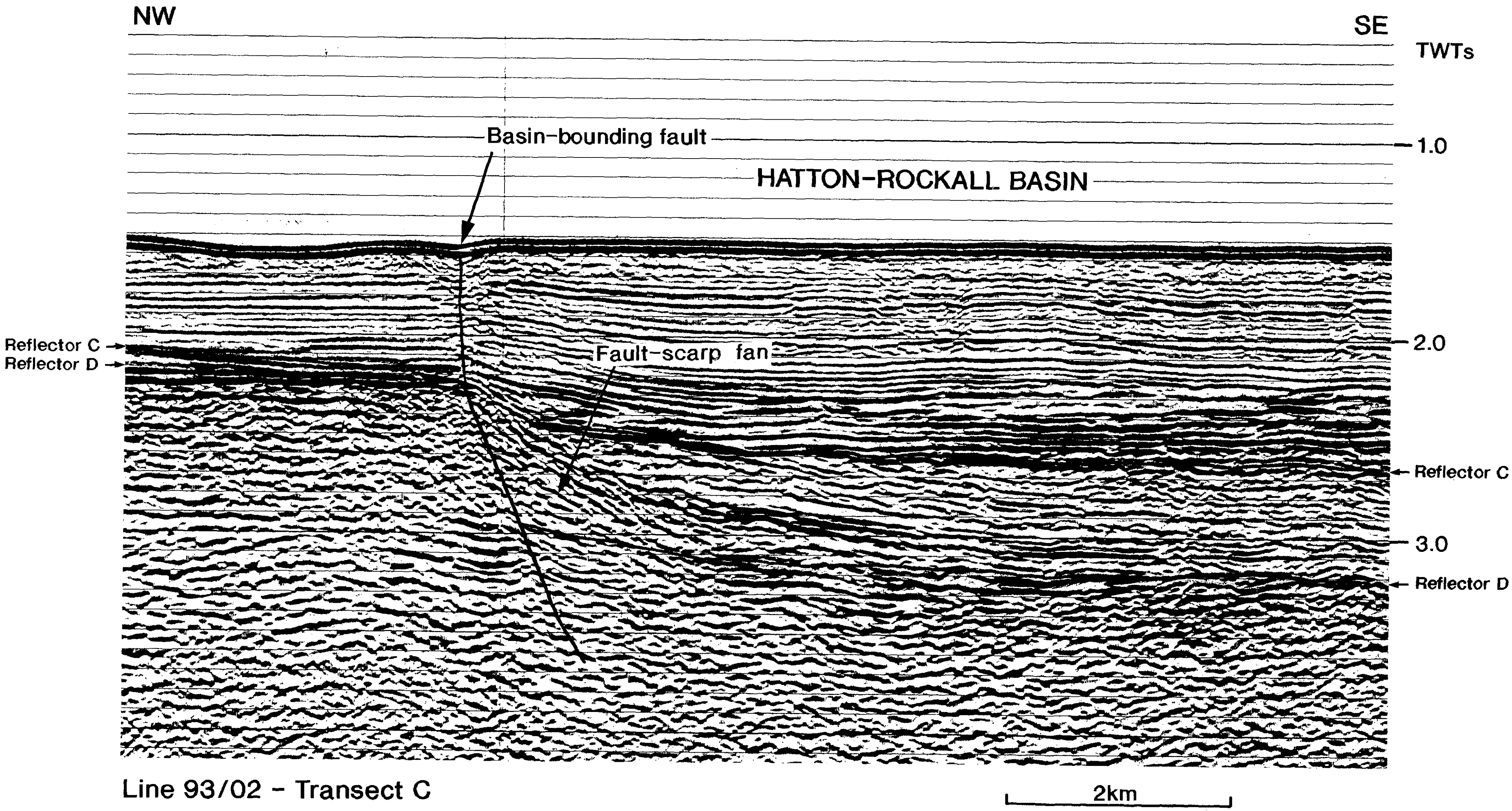


Fig. 5.5 Fault scarp fan adjacent to NW basin-bounding fault, Hatton-Rockall Basin

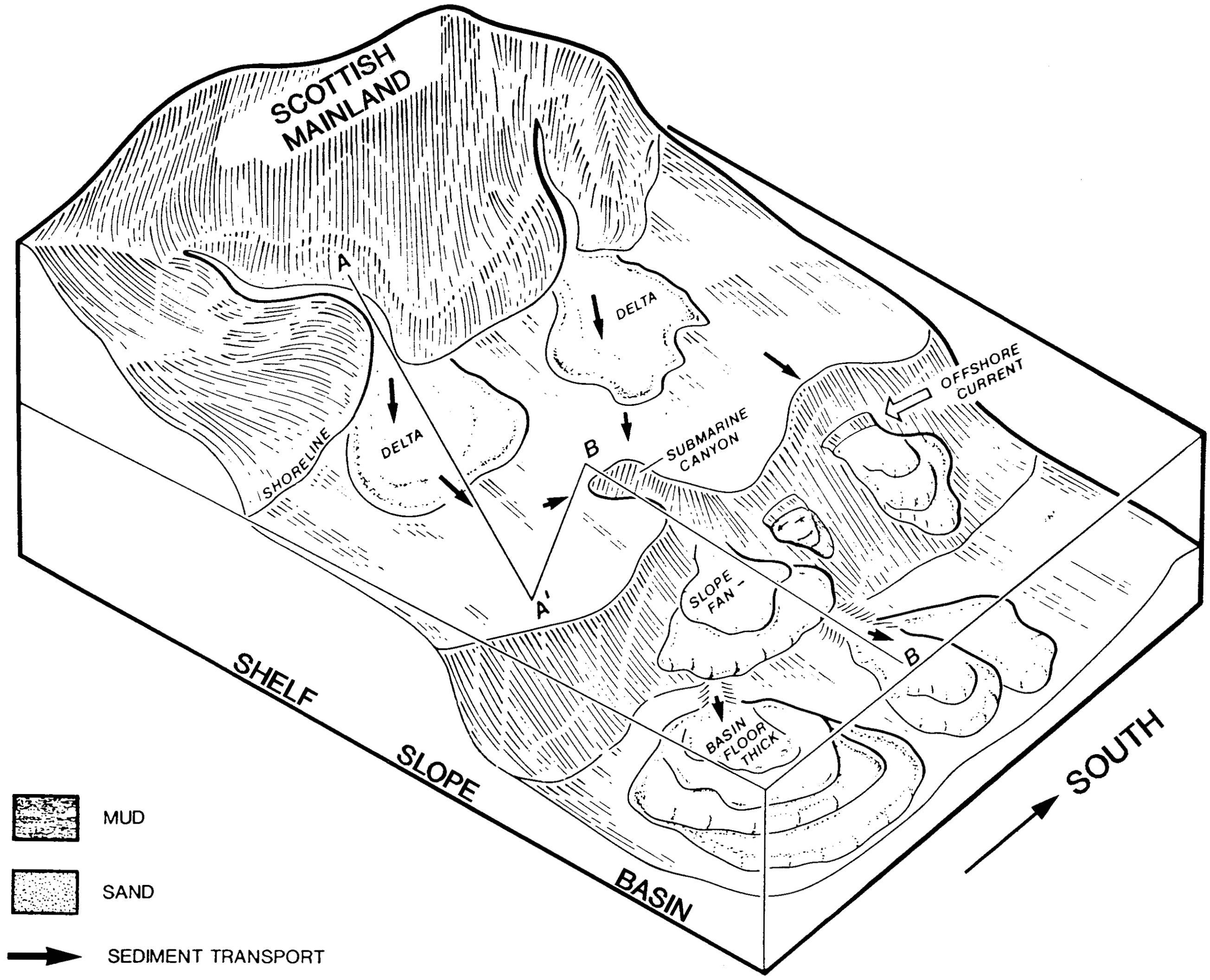


Fig. 5.6 Model for development of low-stand slope and basin floor fans

LARGE FIGURES

Figs. 1.2, 1.3, 1.4, 3.2, 3.3, 3.4, and 4.1

Fig. 1.2 Geophysical grid: 56.5° - 59.5° N, 9.0° - 17.0° W

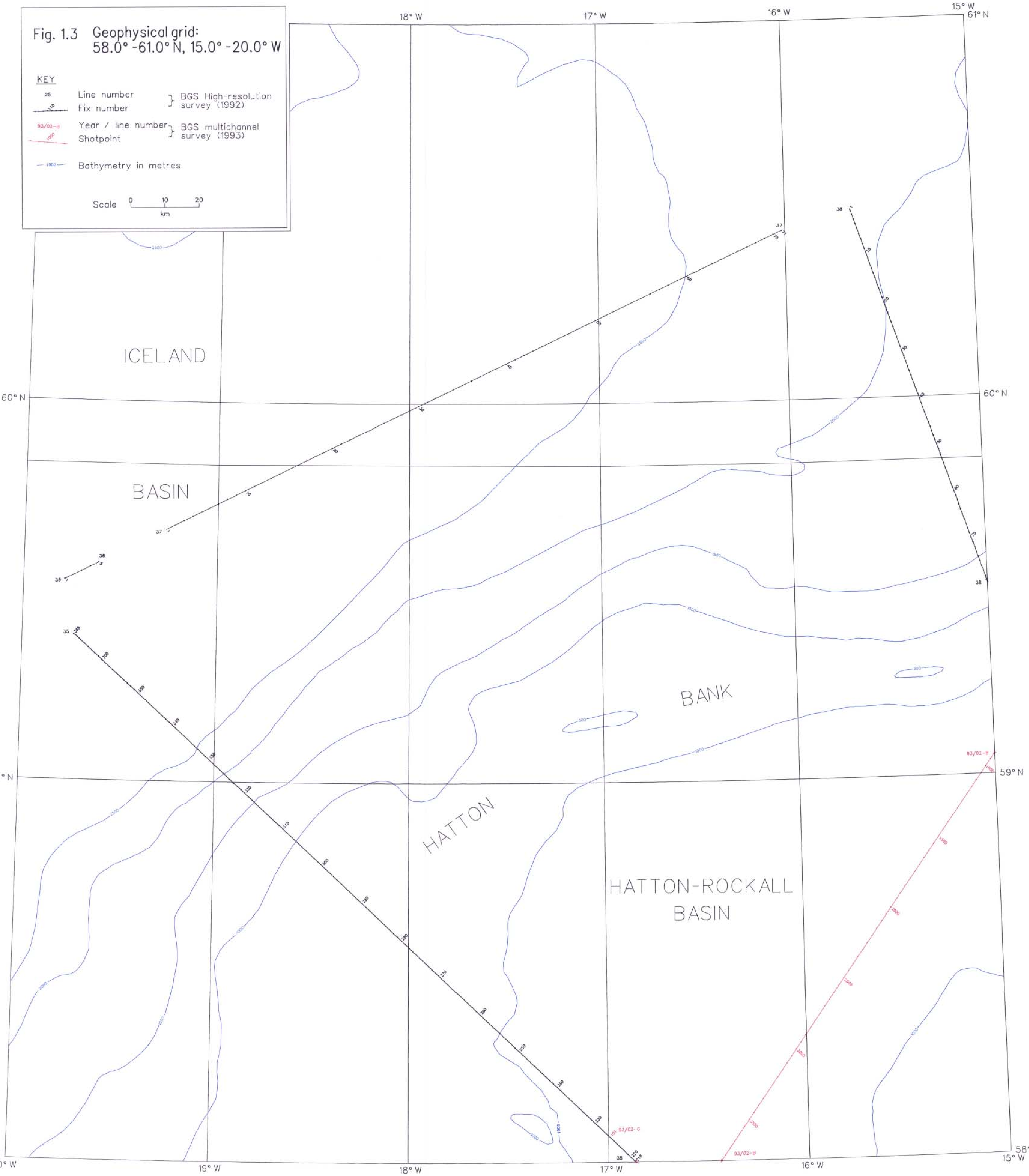


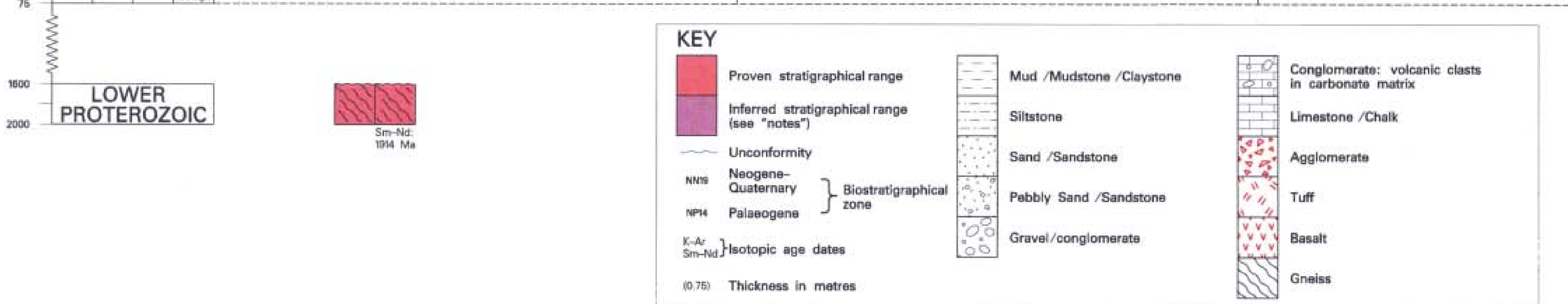
Fig. 1.3 Geophysical grid: 58.0°-61.0° N, 15.0°-20.0° W


Fig. 1.4 Location of boreholes and shallow cores
KEY
Stratigraphical site*
Organic geochemistry site
BGS shallow cores
BGS borehole
DSDP site
Bathymetry in metres
* (See Appendix 2 for BGS-listed number)
Scale
0
10
20
km
HATTON BANK
GEORGE BLIGH BANK
ROSEMARY BANK SEAMOUNT
HATTON-ROCKALL BASIN
ROCKALL TROUGH
ROCKALL BANK
Rockall
ANTON DOHRN SEAMOUNT
HEBRIDES SHELF
UK
IRELAND
17° W
16° W
15° W
14° W
13° W
12° W
11° W
10° W
9° W
59° N
58° N
57° N
DSDP 116
DSDP 117

Fig. 3.2 Regional Geology of the Rockall Continental Margin

Fig. 3.3 Line drawings of seismic sections across western Rockall Trough, adjacent banks, and axial seamounts, based on BGS Survey 92 /01 and incorporating line–related cores and boreholes and interpreted composite stratigraphical columns.

Fig. 3.4. Stratigraphical–range chart of Proterozoic, Mesozoic and Cenozoic strata cored from the Rockall Trough, adjacent banks and axial seamounts. Timescale after Harland et al. (1990).



NOTES

[a] Based on regional stratigraphical setting:– acoustic basement. Age range inferred relative to cores 57–14 /53 (S18) and 94 /3.

[b] Based on regional stratigraphical setting:– seismic interval C_1–C. Age range inferred relative to borehole 94 /3.

[c] Based on regional stratigraphical setting:– acoustic basement. Age range inferred relative to core 57–14 /53 (S18) and borehole 94 /3. Possibly affected by cataclasis.

[d] Based on regional stratigraphical setting:– ? acoustic basement. Age range inferred from nearby sub–reflector D age data.

[e] Proven undifferentiated Paleocene age. Regional stratigraphical evidence suggests a pre–NP6 age, relative to cores 58–14 /10, 43 and 11 (S9 & S10).

[f] Based on regional stratigraphical setting:– ? seismic interval A–sea bed. Age range inferred relative to core 58–14 /32 (S12): comparable lithology and occurrence.

[g] Nannofossil data give an age range of late Paleocene (NP4) to late Pliocene (NN16). From regional stratigraphical evidence – seismic interval D–C – a late Paleocene age is preferred on the basis of adjacent cores 58–14 /10, 43 (S9) and 58–14 /11 (S10).

[h] Whilst foraminiferal evidence suggest an NP18–lower NP23 age range for interval B–B_0, a late Eocene–earliest Oligocene age is favoured. An age range of NP19–21 is inferred relative to core 58–14 /54 (S42), which sampled NP17–19 age sediments from the underlying seismic interval D–C, and well 164 /25–2 which proved sediments of NP22 age which onlap interval B–B_0.

[i] Taken from Ferragne et al. (1984).

[j] Taken from Jones et al. (1974)

[k] Taken from Stevenson (1990)

[l] Taken from Stevenson (1990) and Morton et al. (In Press)

[m] Based on regional stratigraphical setting:– acoustic basement. Age range inferred relative to borehole 90 /18.

[n] No recovery in uppermost part of borehole section.

Nb: Other inferred age ranges – mainly Plio–Pleistocene – based on regional setting: mostly relate to sea bed veneer.

FIGURE 4.1

ROCKALL CONTINENTAL MARGIN PROJECT

DEPTH TO TOP BASALT

KEY

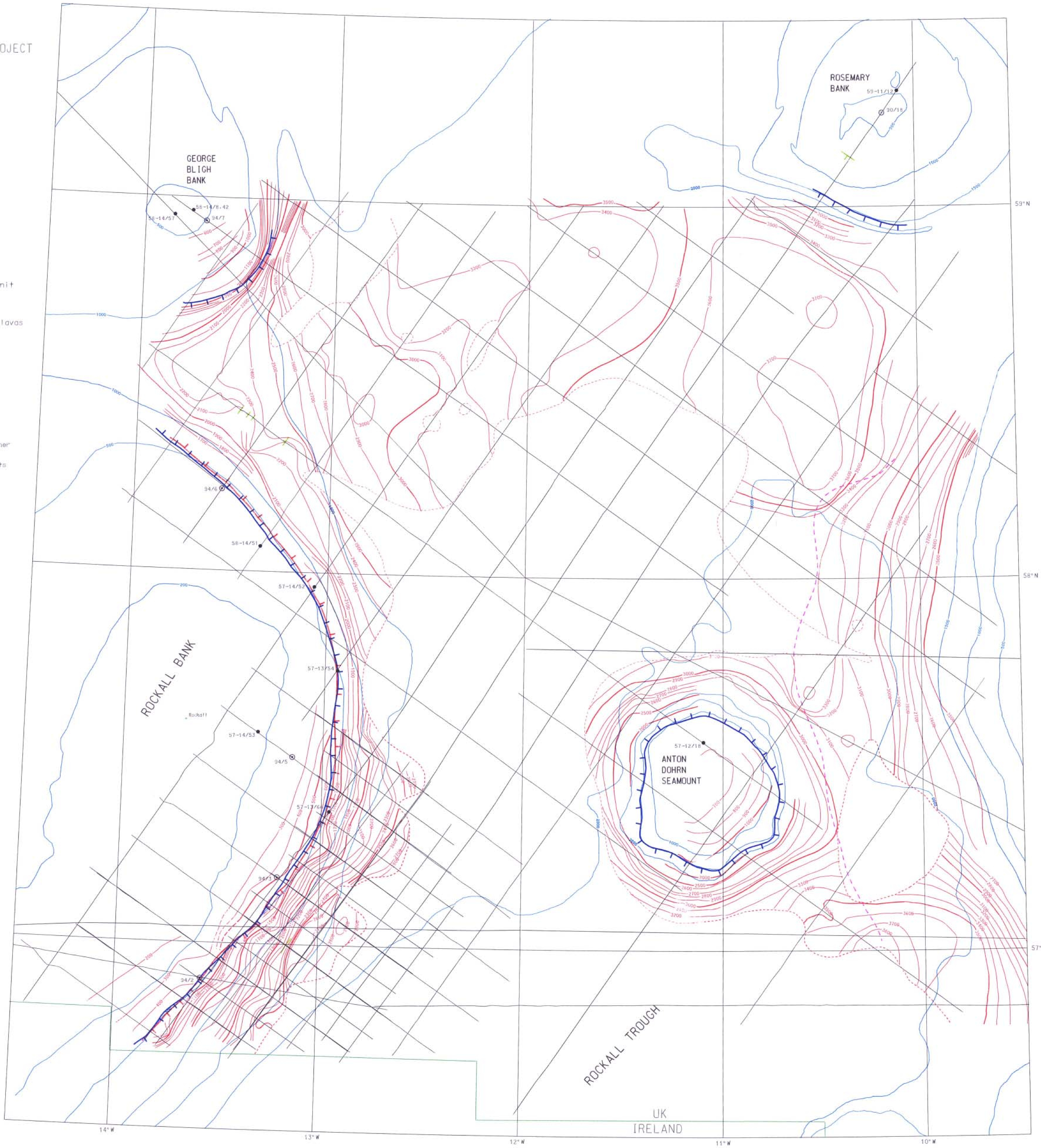
- 2500 — Depth to Top Basalt (metres below sea level)
- Limit of basalt subcrop
- 500 — Bathymetry (metres)
- Top of bathymetric scarp
- Top of basalt scarp
- Survey line
- Western limit of multi-layered unit immediately overlying basalts
- 94/3 BGS borehole which proved lavas
- 57-14/53 BGS rockdrill site which proved lavas

0 — 20km

Notes:

1. All boreholes, and rockdrill site 59-11/12 (Rosemary Bank), proved in situ igneous rocks. Other rockdrill sites sampled igneous rocks either as boulders or as clasts in conglomerates.

2. Not all igneous rocks in the area are basalts (see Appendix 4).



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