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FINAL GEOLOGICAL REPORT

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VOLUME 5: APPENDIX 4
PETROGRAPHY AND GEOCHEMISTRY OF IGNEOUS AND METAMORPHIC ROCKS

A C Morton

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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.

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PETROGRAPHY AND GEOCHEMISTRY OF IGNEOUS AND METAMORPHIC ROCKS RECOVERED DURING THE 1994 DRILLING PROGRAMME WEST OF BRITAIN

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PETROGRAPHY AND GEOCHEMISTRY OF IGNEOUS AND METAMORPHIC ROCKS RECOVERED DURING THE 1994 DRILLING PROGRAMME WEST OF BRITAIN

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1. INTRODUCTION

This report describes igneous and metamorphic rocks recovered during the two 1994 drilling cruises undertaken by BGS in the Rockall Trough and Rockall Plateau areas. The first of these cruises used the BGS rock drill to recover short (6 m maximum) lengths of material outcropping at the sea bed. This technique has helped to establish a regional lithological database. The second cruise used conventional coring methods, in order to provide a better stratigraphic framework.

Igneous rocks were recovered at several of the sites, including some of those on George Bligh Bank, Rosemary Bank, Anton Dohrn Seamount and Rockall Bank: in addition, metamorphic basement was also cored at one site on Rockall Bank. All the igneous and metamorphic lithologies recovered during the cruises were characterised petrographically under the optical microscope. Most of the sequences were also investigated using the electron microprobe, to identify and analyse individual constituent phases, and geochemically, to characterise the rock in compositional terms. A smaller number of samples was selected for isotopic analysis on the basis of the petrographic and geochemical data, in order to ascertain the nature of the source material and any possible crustal contaminants in the rocks.

Assigning rock names to the samples has been problematic, because of the fine-grained nature and high degree of alteration of some of the rocks. Although the TAS (total alkalis vs. silica) method of Le Maitre et al. (1989) should ideally be applied only to fresh rocks with low H_2O and CO_2 contents, it was decided that this scheme was best suited for assigning rock names. The samples are shown on the TAS plot in Fig. 1. Because some trace elements are less susceptible to secondary alteration, the affinities of the rocks as indicated by the TAS method were tested using the trace element criteria suggested by Winchester & Floyd (1977), as shown in Fig. 2.

The report discusses the samples on a geographical basis. As most of the samples are from Rockall Bank, this area is described first. George Bligh Bank, Rosemary Bank and Anton Dohrn Seamount are discussed subsequently. Detailed descriptions of individual samples are provided in section 8.

2. ROCKALL BANK

Volcanic material was recovered from 9 sites on the eastern margin of Rockall Bank (57-14/52, 57-13/54, 57-14/53, 57-13/66, 58-14/51, 94/2, 94/3, 94/5 and 94/6). In addition, metamorphic basement was found at 56-15/12, towards the southwest of the Bank. The volcanic rocks include basalts and basaltic differentiates (57-14/52, 57-13/66, 94/2, 94/3, 94/5, 94/6), basaltic agglomerate (57-13/54), trachytes (57-14/53, 58-14/51) and vitric tuffs of andesitic composition (94/3).

2.1 Metamorphic basement

Metamorphic basement was recovered at 56-15/12, on the southwest part of Rockall Bank. The sample has a gneissose fabric, and consists of leucocratic and melanocratic bands. The leucocratic layers are dominated by K-feldspar, plagioclase and quartz, with minor apatite. Some of the feldspar is clouded and altered. The melanocratic layers contain orthopyroxene, pale green clinopyroxene, brown titaniferous biotite, magnetite and minor allanite, sometimes with green amphibole. Biotite locally altered to chlorite, and the orthopyroxene is locally replaced by fibrous ?tremolite and minor carbonate. The rock is clearly of high-grade metamorphic origin.

The lack of aluminous phases such as sillimanite or kyanite suggests the rock is of igneous origin: geochemical analysis indicates that it has an intermediate composition. Using the TAS nomenclature system for igneous rocks (Le Maitre et al., 1989), it has the composition of latite. The rock has relatively elevated rare earth element (REE) concentrations (Fig. 3), with distinct light REE enrichment. The gradient of the pattern is steep over the light REE but becomes more shallow over the heavy REE. The sample also has strongly elevated abundances of incompatible elements relative to N-type MORB (Fig. 3), but has MORB-like abundances of the more compatible elements (Dy-Lu). It is relatively depleted in Th, Nb and Ta, a feature that is typical of many high-grade metamorphic basement rocks.

The gneiss displays distinctive isotopic characteristics. It has a large positive εSr value and a large negative εNd value (Fig. 4), features that are typical of amphibolite-facies metamorphic basement (Carter et al., 1978). It has strongly unradiogenic $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios (Figs 5 & 6), but has higher $^{207}Pb/^{204}Pb$ ratios than typical Lewisian. This, together with the model age (T_{DM}) of 1914 Ma indicates that the gneiss is not from an Archaean terrane such as the Lewisian, but represents a younger crustal block of early Proterozoic age. This is consistent with isotopic data from samples previously recovered from Rockall Bank (Roberts et al., 1973), which have T_{DM} ages of 1911-2170 Ma (recalculated from Morton & Taylor, 1991).

2.2 Basalts and associated rocks

Basalts and associated intermediate rocks were recovered at several sites on Rockall Bank (94/2, 94/3, 94/5, 94/6, 57-14/52 and 57-13/66). In addition, basaltic agglomerate was found at 57-13/54. These are described in geographical order, from south to north.

Borehole 94/2 terminated in a basalt flow. The sample, from 21.74-21.76 m, consists of very fine grained, sparsely vesicular, sparsely plagioclase-phyric basalt. Although it falls in the picrobasalt field on the TAS diagram (Fig. 1), it is considered likely that the low SiO_2 values result from alteration, and are not an indication that the magma was relatively primitive. The loss on ignition (LOI), a good index of alteration, is high (6.36%), and the high Fe/Mg ratio coupled with moderate Cr and Ni contents indicate that the magma was not primitive. It is considered to be subalkaline on the basis of its Nb/Y ratio (Fig. 2), although it is nepheline-normative. This latter feature is also considered to be a result of alteration, which can lead to significant uptake of alkalis causing an originally hypersthene-normative rock to appear nepheline-normative. It contains rare plagioclase phenocrysts with bytownitic cores and labradoritic rims in a groundmass of plagioclase laths of labradorite-bytownite composition, with finely-divided opaques, mafic phases (clinopyroxene and ?olivine, pseudomorphed by carbonate and iron oxides) and extensive areas of green-brown smectite (probably replacing interstitial glass). Fresh clinopyroxene is rare, but what remains has a titaniferous augite composition. The groundmass is highly altered throughout, with darker areas representing more oxidised zones. Vesicles are filled with a green-blue smectite clay phase. Alteration is particularly intense around vesicles. The sample does not have a trachytic texture.

In borehole 94/3, basalt flows were found at two levels. A single flow occurs high in the sequence, sampled at 47.75-47.80 m, and the borehole terminates in another basalt unit, sampled between 208.12 m and 209.57 m. The upper sample falls into the basalt field on the TAS diagram (Fig. 1), and although the lower sample falls into the basanite/tephrite field, it is close to the basalt field. In view of the relatively high degree of alteration (LOI=3.41%), it is considered that both rocks are basaltic. This is supported by their position on the Zr/TiO_2-Nb/Y diagram (Fig. 2). Both are hypersthene-normative and have low Nb/Y ratios, indicating that they are subalkaline in composition.

The upper thin flow comprises aphyric, sparsely vesicular basalt, comprising plagioclase laths, titanomagnetite and interstitial pale brown clinopyroxene set in a matrix of brown smectite (replacing glass). Clinopyroxene is partially altered to clays and finely divided opaques. Fresh clinopyroxene is salitic and rich in TiO_2. Plagioclase laths are andesine-labradorite. Some vesicles are open, but rest most are filled with brown smectite. Fractures filled with brown smectite are common, and areas adjacent to fractures are more highly altered than the rest of the basalt. The rock lacks an obvious trachytic texture. The basalts at the base of the borehole are closely comparable to the upper flow, the main differences being that they have a strong trachytic texture, and are slightly coarser-grained, non-vesicular and sparsely plagioclase phyric. They contain rare plagioclase phenocrysts with bytownite cores and labradorite rims in a matrix of plagioclase (labradorite) laths, titanomagnetite, granular to subophitic clinopyroxene and smectite, both as pseudomorphs of ?olivine and as a replacement of interstitial glass. The clinopyroxene is relatively Ti-rich augite. The smectite contains common finely divided secondary opaques, especially in the more highly altered samples (208.70-208.71 m and 209.57-209.58 m).

In addition to the flow units, basalt pebbles occur in the interbedded coarse-grained sediments, and one of these (sampled at 171.14-171.20 m) was examined for comparison. It shows some clear differences from the flow units, both petrographically and mineralogically. It consists of fine grained, sparsely vesicular aphyric basalt, containing plagioclase (andesine-labradorite) laths, granular colourless clinopyroxene (low-Ti augite), red-brown pseudomorphs of ?olivine and interstitial titanomagnetite in a green smectite groundmass. Vesicles are filled with green vermiform smectite. The sample lacks a trachytic texture. Because the pebble is different both in terms of texture and clinopyroxene composition compared with the overlying and underlying in-situ flows, it was evidently not derived from from the immediate vicinity of the borehole site.

The basalt from site 57-13/66 is holocrystalline and sparsely glomerophyric. It falls in the basalt field on the TAS diagram (Fig. 1) and in the subalkaline basalt field on the Zr/TiO_2-Nb/Y diagram (Fig. 2). Its subalkaline nature is confirmed by the presence of hypersthene in the norm. The lack of any flow alignment, together with the absence of glassy material (which suggests slow cooling) indicates that it may either be intrusive or from the middle of a thick flow. It comprises granular grey clinopyroxene (relatively low-Ti augite), plagioclase (labradorite) laths, titanomagnetite and pseudomorphs after olivine, with sparse glomerophyric aggregates consisting mainly of plagioclase in conjuction with altered olivine and/or clinopyroxene. Plagioclase phenocrysts are zoned, with bytownite cores and labradorite margins. The similarity in clinopyroxene composition between 57-13/66 and the pebble in 94/3 may indicate a link between the two, although this cannot be proven on the basis of the meagre evidence available at present.

Borehole 94/5 terminated in a flow unit with basaltic petrography. The sample, from 29.21-29.25 m, is extremely fine grained, aphyric, and consists of plagioclase (andesine) laths, interstitial anorthoclase, equant colourless clinopyroxene, minor titanomagnetite and scarce altered ?olivine in a highly altered oxidised groundmass. The rock contains common large partially resorbed slightly coarser basalt clasts, distinguished by their darker colour caused by their greater degree of alteration. Some of the resorbed clasts are sparsely vesicular, the vesicles being infilled by carbonate and/or smectite. On the TAS diagram (Fig. 1), it falls slightly outside the basalt field in the trachybasalt area, and corresponds to hawaiite using TAS nomenclature. Its relatively evolved nature is confirmed by its position in the andesite/basalt field on the Zr/TiO_2-Nb/Y diagram (Fig. 2), its very high Fe/Mg ratio, and its very low abundances of trace elements such as Cr and

Ni. Nevertheless, it is clearly genetically linked with the basaltic rocks found at adjacent sites, representing a later stage of magmatic evolution through fractional crystallisation processes.

Agglomerate was recovered at 57-13/54, on the east margin of Rockall Bank. Because of the fragmentary nature and high degree of alteration, whole-rock geochemical data were not obtained from this sample: however, in petrographic terms it clearly comprises basaltic material. It contains two clast types: small, angular, non-vesicular vitric clasts with small partially altered plagioclase phenocrysts, together with larger, subangular, sparsely vesicular fine-grained basaltic clasts with common plagioclase phenocrysts and rare pseudomorphs of ?olivine phenocrysts in a very fine grained, highly altered matrix, some very dark due to oxidation. Microprobe analysis shows the vitric material to be strongly hydrated (analytical totals below 88%), but is probably basic in composition (SiO_2 34-40%, FeO 13-21%, MgO 9-13%). CaO is very low through alteration. TiO_2 contents are very variable within individual vitric particles indicating local remobilisation during alteration. Plagioclase laths have similar compositions in both vitric and lithic clasts, indicating that both types of clast were probably derived by fragmentation of one flow unit. Clasts are cemented by early clear isotropic potassium analcime and later green-brown smectite. It is interpreted as a volcaniclastic deposit, probably formed through submarine breakup of an extrusive basalt flow.

The sample from 57-14/52 is relatively highly altered, with an LOI of 5.67%. It falls into the basanite/tephrite field on the TAS diagram (Fig. 1), but because of the high degree of alteration it is more likely that the rock is basaltic. On the basis of its normative nepheline, it should be classed as an alkali basalt, but this could also be the result of alteration causing uptake of alkalis. Nevertheless, it has the highest Nb/Y of any of the basaltic rocks from Rockall Bank in this sample set, indicating that it has stronger alkalic tendencies than the other rocks. This is consistent with its more strongly LREE-enriched nature, as discussed below. In petrographic terms, it is composed of plagioclase laths in a fine-grained, high altered matrix, with large plagioclase phenocrysts and smaller pseudomorphed olivine phenocysts. Plagioclase laths show strong alignment imparting a trachytic texture. The plagioclase phenocrysts consist of labradoriteand show only limited evidence of zoning. The groundmass plagioclase is also mainly labradoritic, but there are some later-stage more sodic plagioclases. The rock is extensively fractured, the fractures being filled with brown smectite and later ferroan-magnesian calcite with a botryoidal texture.

Basaltic material was also recovered at the base of borehole 94/6. The position of the sample in the basanite/tephrite field on the TAS diagram (Fig. 1) is possibly spurious due to alteration (LOI being 2.3%), and it is considered that the rock should be termed a basalt. The sample has a high Fe/Mg ratio and low Cr and Ni abundances, and was clearly not produced by a primitive magma. It is hypersthene-normative and has low Nb/Y (Fig. 2), and is therefore considered to be a subalkali basalt. The uppermost sample, from the top of a flow unit, is fine-grained, highly altered, vesicular and aphyric, comprising partially altered plagioclase laths, abundant ilmenite, and scarce pinkish-brown clinopyroxene, with abundant green-brown smectite (probably replacing interstitial glass and possibly some mafic phases). There are common large round vesicles, infilled with smectite and minor rhombic carbonate. Towards the flow centre, the basalt becomes medium grained, non-vesicular, and shows a subtrachytic texture. It consists of plagioclase laths and ilmenite subophitically enclosed by pale brown Ti-rich augite. The plagioclase laths are andesine-labradorite in composition, but there is some minor late-stage interstitial anorthoclase feldspar. Interstitial green-brown smectite is widespread, probably replacing glass.

All of the basaltic rocks recovered from the Rockall Bank during the 1994 drilling activity have broadly comparable trace and rare earth element (REE) compositions, in that they all show light REE enrichment to some degree. This is measured as $(La/Yb)_N$, the chondrite-normalised La/Yb ratio. LREE enrichment is least well-developed in the basalts from 94/2 and 94/3 (Fig. 7), which have $(La/Yb)_N$ values of 1.4 to 1.9. The sample from 57-13/66 is slightly more LREE enriched, with $(La/Yb)_N$ of 2.8, and that from 94/6 has $(La/Yb)_N$ of 3.8, that from 57-14/52 has $(La/Yb)_N$ of 4.1. The sample from 94/5 has the steepest pattern, with $(La/Yb)_N$ of 4.7. These variations essentially reflect the degree of partial melting of the mantle source, the lowest degrees of melting generating the steepest REE patterns. The relative depletion of the heavy REE indicates that garnet is a stable component in the mantle source, and thus that melting took place in the garnet stability field. Several (notably 57-14/52 and 94/6) have slight positive Eu anomalies. This is usually ascribed to plagioclase accumulation, and the common plagioclase phenocrysts in 57-14/52 is in accord with this. However, this cannot be the case for 94/6, as the sample is aphyric. The explanation for this anomaly is therefore unclear at this stage.

The basalts have similar features on MORB-normalised spidergrams (Fig. 8), with the most notable features being the ubiquitous presence of a positive Ba anomaly, generally accompanied by Rb, and the presence of a small negative Nb-Ta anomaly, in some cases accompanied by a negative Th anomaly. The presence of Ba and Rb anomalies may be related to seawater alteration, but the ubiquitous occurrence of such anomalies even in the least altered rocks suggests they may have a different cause. An alternative origin of positive Ba and Rb anomalies is continental crustal contamination. Continental crustal contamination would also cause the negative Nb-Ta anomalies seen in most of the samples, and this is therefore considered to be the most likely explanation of these spidergram patterns. As an example, the basement sample S25 shows similar positive Rb-Ba and negative Nb-Ta (and Th) anomalies to those found in the igneous rocks. Therefore, the trace element data suggests that most, if not all, of the basaltic rocks have assimilated some crustal material during magma ascent through the basement of Rockall Bank.

This is given considerable support by the isotopic data. Of the samples from Rockall Bank, only 57-13/66 and 94/3, 209.57 m, have isotopic signatures that fall within or close to the range of North Atlantic MORB. All of the others show evidence for contamination by crustal material to some degree. On the εSr-εNd plot (Fig. 4), 57-13/66 falls close to the MORB field and within the mantle array, but although 94/3 (209.57 m) falls in the mantle array it has markedly lower εSr and εNd values than MORB. 94/2 is displaced from the mantle array towards low εNd values, a tendency that is displayed to increasing degrees by 94/3 (47.75 m) and 94/6. Similar trends in the British Tertiary Volcanic Province have been interpreted as the result of assimilation of granulite-facies basement (Carter et al., 1978). The sample from 94/5 shows a different trend, being displaced towards positive εSr and negative εNd values, consistent with contamination by amphibolite-facies crust, possibly similar to that cored at 56-15/12. The Pb-isotopic variations can also be modelled by mixing between mantle-derived MORB components and crustal rocks, with 94/3 and 94/6 having lower $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ values than typical North Atlantic MORB (Figs 5 and 6). The trend suggested by the data is not consistent with contamination by Archaean (Lewisian) crust, which would have generated a much steeper trend towards low $^{207}Pb/^{204}Pb$ values. However, the data can be readily modelled by contamination of MORB with basement that has characteristics similar, though not identical, to the sample from 56-15/12 and those analysed previously from Rockall Bank (Morton & Taylor, 1990). This suggests that Rockall-type crust extends at least as far north as borehole 94/6, and includes both amphibolite- and granulite-facies material. The sample from 94/5, which appears to have had a different type of contamination on the basis of εNd and εSr, also shows a different type of Pb-isotopic contamination. It lacks displacement towards low $^{206}Pb/^{204}Pb$ or $^{208}Pb/^{204}Pb$ values, but has slightly higher $^{207}Pb/^{204}Pb$. This suggests possible contamination by upper crustal material such as high-level granites.

2.3 Trachytes and intermediate/acidic tuffs

Trachytes have been cored at two sites, 57-14/53 and 58-14/51. 57-14/53 is holocrystalline, dominated by feldspar laths of anorthoclase to sanidine composition, with subordinate titanomagnetite and interstitial very fine grained brown pleochroic amphibole, pale green augite and green titaniferous aegirine. There are sparse feldspar phenocrysts with anorthoclase composition. A strong alignment of feldspar laths imparts a trachytic texture to the rock. Clusters of finely-divided opaques represent altered biotite phenocrysts or xenocrysts. The trachytic texture indicates that the rock is extrusive and is from a trachyte flow.

58-14/51 is has more abundant phenocrysts than 57-14/53, mainly of feldspar with less common pale green clinopyroxene and altered olivine. The phenocrysts are set in a groundmass of feldspar laths, granular clinopyroxene, titanomagnetite, minor fine grained brown pleochroic amphibole and interstitial brown slightly argillised glass. Both feldspar laths and phenocrysts consist of anorthoclase compositions, and the phenocrysts lack significant compositional zoning. Groundmass and phenocryst clinopyroxene consists of low-Ti augites. Minor partially resorbed finer-grained trachyte xenoliths are present. The sample is believed to be from a flow unit, the abundant phenocrysts indicating a history of fractionation in shallow level magma chambers.

The two samples have somewhat different trace and REE compositions. Chondrite-normalised REE plots (Fig. 9) indicate that 57-14/53 has stronger LREE enrichment, with an $(La/Yb)_N$ of 7.5 compared with 3.1. Although the absolute REE values are higher in the trachytes compared with the basalts, the ranges of LREE enrichment are reasonably similar. This may indicate that the trachytes and basalts had similar parental magmas, with the trachytes representing more evolved material. Both of the samples have negative Eu anomalies, indicating their magmas have undergone plagioclase fractionation. On MORB-normalised spidergrams (Fig. 10), the two samples have strong negative Sr, Ti and P anomalies. These elements have probably been depleted through fractionational crystallisation of plagioclase, ilmenite and apatite. The samples also have small negative Nb-Ta anomalies, in common with the basaltic rocks.

One of the two samples, 57-14/53, was analysed isotopically. As shown on Figs 4, 5 and 6, it falls close to the areas defined by Rockall Bank basalts, and appears to be allied with them. However, it differs in having slightly more negative εNd values and slightly lower $^{206}Pb/^{204}Pb$ ratios than any of the basalts. This indicates that 57-14/53 had a similar source to the basalts, but was contaminated by Rockall-type basement to a greater extent.

The trachytes could represent either late-stage evolved magmas of basaltic parentage, or crustal melts caused by ponding of basaltic magmas in the crust. The trace element evidence for fractional crystallisation (depletion in Sr, Ti, Eu and P) and the similarity in REE patterns between the trachytes and the basalts suggests that they most probably originated through fractionation. The isotopic data are in support of this, because 57-14/53 falls close to the basaltic field. The slightly more negative εNd and lower $^{206}Pb/^{204}Pb$ indicates greater crustal assimilation, as would be predicted during a longer history of fractional crystallisation. If the rocks were to represent pure crustal melts, their isotopic compositions would diverge more strongly from the basalts, and would tend to be more comparable to those of the basement sample 56-15/12 or the basement rocks previously described from Rockall Bank (Morton & Taylor, 1990). Assuming that the trachytes were generated by AFC (assimilation and fractional crystallisation) processes, it would seem that 57-14/53 was derived from a more alkaline magma than 58-14/51, to account for the steeper REE pattern.

Borehole 94/3 provides further evidence for early Tertiary intermediate/acidic volcanism on Rockall Bank. Petrographic examination of four samples, from 92.91-92.96 m, 109.97-110.00 m, 112.50-112.54 m and 115.76-115.80 m, indicates the presence of a number of vitric tuffs. They consist of large particles of colourless or pale yellow highly vesicular volcanic glass, best described as pumice. The pumice fragments consist essentially of interconnected bubble walls, the vesicles ranging from round to highly elongate. The highly vesicular nature of the glass imparts an unusually high porosity to the tuffs. The glass ranges from colourless and isotropic to pale yellow and weakly birefringent, with a speckly appearance under crossed polars. The latter appears to indicate a higher degree of alteration. The tuffs also contain minor mineral phases, probably phenocrysts. These include K-feldspar, anorthoclase, clinopyroxene (ferrohedenbergite), biotite and quartz. There are also some xenolithic particles of sedimentary origin, including siltstone and glauconitic material.

Electron microprobe analysis of one sample (115.76-115.80 m) shows the glass to be relatively silicic, consistent with its colourless appearance in thin section. The tuffs are considered to be andesitic on the basis of the position of the glass compositions on the TAS diagram (Fig. 1). Although this method must be treated with some caution because of the high degree of alteration and because it ignores the presence of phenocryst phases, the estimate is in accord with the composition of the phenocrysts, which are all commonly associated with intermediate-acidic rocks. Notably, ferrohedenbergite has been identified in the early Tertiary Western Redhills granite of Skye (Bell, 1966).

The tuffs probably resulted from the flow of andesitic magmas into water, causing rapid cooling, degassing and fragmentation. The fragmentation process also caused the incorporation of sedimentary particles from the underlying substrate. Although they are of similar age, the tuffs bear no resemblance to the air-fall basaltic tephras characteristic of the Balder Formation, both in terms of texture and composition, and are probably local in origin.

3. GEORGE BLIGH BANK

Igneous rocks were recovered in four cores on George Bligh Bank, 94/7, 58/14-8, 58/14-42 and 58-14/57. Two of these, 58/14-8 and 58/14-42, are from the same site. The material recovered in 94/7 falls into the trachybasalt field on the TAS diagram (Fig. 1), and using the additional criteria of Le Maitre et al. (1989) is termed hawaiite. Its alkalic nature is confirmed by its high Nb/Y ratio (Fig. 2). The top sample (21.07-21.10 m) is aphyric, non-vesicular and fine grained, comprising plagioclase laths and ilmenite, which are either ophitically enclosed by pale brown clinopyroxene or set in a groundmass of brown, oxidised smectite. The clinopyroxene (titaniferous augite) is fresh, and does not appear to be altered into smectite. Therefore, the smectitic zones probably represent more glassy (rapidly cooled) zones. The plagioclase laths (andesine) define a strong trachytic fabric. In addition to the plagioclase laths, there is some minor late-stage interstitial anorthoclase. Alteration decreases in the underlying part of the sequence, as at 22.25-22.57 m, where the smectite is green and largely unaltered. In the lowest sample (23.20-23.25 m), the grain size increases and the trachytic texture becomes less well defined, but the mineralogy remains essentially the same.

The fine-grained nature of the upper two samples suggests they are from near the tops of flow units, but the lowest sample is more slowly cooled and from the central part of a flow. The uppermost sample is more extensively altered due to its proximity to the unconformity with the overlying sedimentary sequence.

Drilling at 58-14/42 recovered very fine grained, sparsely vesicular, highly altered igneous rock with plagioclase (andesine) laths, later interstitial anorthoclase and titanomagnetite, in an argillised groundmass. Sparse vesicles are open, but have smectite rims. There are rare large plagioclase phenocrysts and smaller pseudomorphs after olivine. The rare fractures are carbonate-filled. On the TAS diagram (Fig. 1), this sample falls in the trachyandesite field, and is termed benmoreite using the additional criteria of Le Maitre et al. (1989). This is supported by its position on the Zr/TiO_2-Nb/Y diagram (Fig. 2), on which it also falls in the trachyandesite field.

At the same site, another core (58-14/8) recovered basaltic agglomerate, composed of subangular lithic basaltic fragments set in a highly vesicular glassy framework. The vitric material contains minor plagioclase laths, and is highly altered, much of it being virtually opaque. Vesicles are smectite-rimmed but centres remain empty. The lithic clasts are more well-crystallised, and are dominated by plagioclase laths with minor ?olivine pseudomorphs. Plagioclase compositions are consistent within individual clasts, and four of the five clasts analysed have comparable ranges (Table 1). However, one has markedly less calcic feldspars, suggesting that derivation may have been from more than one flow unit. Some laths consist of K-feldspar, probably through submarine alteration.

Basaltic agglomerate was also recovered at 58-14/57. This sample consists of basalt and limestone clasts. Basalt clasts contain plagioclase laths, with or without granular clinopyroxenes, in an argillised groundmass showing variable degrees of alteration. Some are partially glauconitised. Pyroxene and plagioclase compositions (Tables 2 & 3) vary from clast to clast, indicating that derivation was from more than one flow unit. Limestone clasts are rich in bioclastic material, especially forams. Glaucony grains are common, and have relatively high K_2O contents (7.7-8.6%) suggesting they formed during a fairly long period of non-deposition. The sample also has a ferroan alteration crust, evidently of polyphase origin because it is interlaminated with glauconitic layers. This sample clearly represents reworking of basaltic and limestone lithologies after cessation of basaltic volcanism, and had a different origin to the entirely basaltic agglomerate at 58-14/8, which probably represents autobrecciation of basalt flows during submarine extrusion.

Major, trace and REE data are available for the basalts from 94/7 and 58-14/42, and for a basaltic clast from 58-14/57. However, the data from the clast shows that it has been extensively altered and phosphatised, and therefore provides little reliable information on the original composition of the material. Geochemical data from the other two samples show that they are relatively evolved rocks sourced by an alkali basalt magma. Their alkalic nature is shown by their high Nb/Y ratios, and their relatively evolved nature is indicated by their high Fe/Mg ratios and very low Cr and Ni contents. The two samples have marked LREE enrichment, $(La/Yb)_N$ being 5.0 in 94/7 and 10.2 in 58-14/42 (Fig. 11). Both samples therefore show stronger LREE enrichment than all the Rockall Bank basalt samples. This implies that the George Bligh basalts were generated by lower degrees of partial melting than those further south. The REE pattern also indicates that melting took place in the garnet stability field, enabling the retention of HREE in the magma source.

The spidergram plots (Fig. 12) are noteworthy for the presence of positive Ba anomalies (together with positive Rb in 58-14/42) and negative Nb-Ta anomalies. As discussed in section 2.1, this provides good evidence for contamination of the magma by crustal rocks. The isotopic data support this inference. 58-14/42 has negative εNd and positive εSr, indicating contamination by granulite-facies basement (Fig. 4). The evidence is less strong in 94/7, but the sample is displaced from the mantle array in the direction of 58-14/42, suggesting that it may have been contaminated by similar material, but to a lesser degree. A similar pattern is shown by the Pb isotopes. 94/7 falls close to the North Atlantic MORB field, whereas 58-14/42 has distinctly lower $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ (Figs 5 and 6), implying involvement of ancient crustal rocks. It is worthy of note that the trend shown by 58-14/42 and 94/7, although ideally requiring substantiation with a larger sample base, is distinctly different to that shown by the Rockall Bank samples. The trend in the George Bligh area is considerably steeper, and is very similar to the trend caused by Archaean (Lewisian) contamination on Skye (Dickin, 1980). The inference is that George Bligh Bank is not underlain by Rockall-type basement, but by

Archaean rocks similar to those in the Outer Hebrides and East Greenland. This implies that there is a major deep-seated structural feature between the northern part of Rockall Bank and George Bligh Bank marking an ancient terrane boundary. This structure may have played an important role in the subsequent structural development of the northern Rockall Trough.

4. ROSEMARY BANK

At 59-11/12 on Rosemary Bank, a sparsely vesicular, glassy basic rock was recovered, interbedded with limestone. It is evidently extrusive in origin, its glassy nature indicating that it was rapidly cooled (quenched), probably in a submarine environment. In thin section, the glass is pale pinkish brown with little petrographic evidence for alteration. However, microprobe analysis suggests some hydration has occurred, because analytical totals are between 90 and 95%. Some areas are yellowish and are slightly more hydrated. The composition of the glass is highly alkalic, with $Na_2O + K_2O$ between 11.11-13.51% and SiO_2 between 49.12 and 52.16%. K_2O/Na_2O ratios exceed 1, indicating that the magma was ultrapotassic. Elongate to acicular clinopyroxene is abundant, and has chrome-diopside compositions. Pyroxene phenocrysts are scarce, but have similar compositions. Small equant forsteritic olivine crystals are common: olivine phenocrysts are rare, and tend to be more magnesian. Vesicles are lined with a potassium-rich isotropic zeolitic mineral, probably a potassium analogue of phillipsite. This also lines the fractures, which are filled with carbonate.

On the TAS diagram (Fig. 1), the sample falls in the phono-tephrite field, confirming the evidence from glass analyses for an extremely alkalic ultrapotassic composition. It has a very high Nb/Y ratio (5.62), confirming that it is a highly alkalic rock: on the Zr/TiO_2-Nb/Y diagram (Fig. 2), it falls in the basanite/ nephelinite field. It has an extraordinarily steep chondrite-normalised REE pattern (Fig. 13), with $(La/Yb)_N$=90.4. Its MORB-normalised spidergram pattern (Fig. 13) is similarly steep, with the most compatible elements being depleted relative to MORB. The patterns indicate an origin by very small degrees of partial melting in the garnet stability field of the mantle. The MORB-normalised spidergram indicates depletion of Th, Ta and Nb, which may be indicative of a continental crustal component. This is also a possible explanation of its Nd and Sr isotopic composition (Fig. 4). However, its Pb isotopic composition is difficult to explain by crustal contamination, because although it has lower $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ than MORB, it has a similar $^{207}Pb/^{204}Pb$ value (Fig. 5). This trend is not possible to model using known basement terrane compositions from the area: neither Lewisian nor Rockall-type basement would give such a pattern. It is widely considered that similar, very low degree partial melts from other parts of the world are derived from metasomatised subcontinental lithospheric mantle (eg. Thompson et al., 1989). Furthermore, the Pb isotopic composition of 59-11/12 is closely comparable to that of the Loch Roag dyke on the Outer Hebrides, a dyke that is believed to be derived from metasomatised sub-Hebridean mantle because it hosts a large variety of mantle xenoliths (Menzies et al., 1987). It is therefore considered that the most likely explanation for the unusual composition of 59-11/12 is that it was derived by very small degree partial melting of metasomatised mantle very similar in composition to that underlying the adjacent continental landmass of the Outer Hebrides.

5. ANTON DOHRN SEAMOUNT

Material was recovered from one site on Anton Dohrn Seamount (57-12/18). The sediment at the base of the core contains basalt pebbles. One of the pebbles has been analysed. It consists of abundant plagioclase laths, common altered olivine and minor titanomagnetite, ophitically enclosed by pale brown clinopyroxene. Plagioclase laths are labradoritic and show well-developed trachytic texture. The clinopyroxene is salitic and relatively titanium-rich. Olivines are all replaced by red-brown 'iddingsite'. Rare vesicles occur, filled with a radiating colourless zeolite phase, with a K-rich phillipsite composition. The sample is locally fractured: the fractures are filled by a red-brown ferroan phase, and the zones around fractures are also oxidised. The petrographic evidence indicates that the pebble was derived from an extrusive flow, reworked during the subsequent phase of sedimentation.

The sample falls in the basalt field on the TAS diagram (Fig. 1). Because it contains normative nepheline, it should be classed as an alkali basalt. However, the LOI value of 2.5% indicates a moderate degree of alteration, and it is therefore possible that the alkalic nature is a secondary feature caused by uptake of alkalis. This possibility is supported by the trace element geochemistry: on the Zr/TiO_2-Nb/Y diagram, the sample falls in the subalkali basalt field (Fig. 2). The high Fe/Mg ratio and moderate Ni and Cr values indicate a relatively high degree of evolution. The sample has slight LREE enrichment, with $(La/Yb)_N$ of 2.5 (Fig. 14). On the MORB-normalised spidergram (Fig. 14), the sample has clear positive Rb and Ba anomalies, but lacks an obvious Nb-Ta anomaly. The positive Rb-Ba anomaly could have resulted from continental crustal contamination (as discussed in section 2.1), but the lack of a negative Nb-Ta anomaly tends to rule this out. Therefore, other possibilities, such as seawater alteration or involvement of a subcontinental lithospheric mantle component, should be considered as more likely alternatives in this case. However, in view of the very limited data set no firm conclusions can be made at this stage.

The isotopic data confirm that crustal contamination is insignificant in 57-12/18. On the εNd-εSr plot (Fig. 4) the sample falls well within the mantle array, and on both the $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ diagrams (Figs 5 and 6) it falls in the North Atlantic MORB field. It therefore appears to have a pristine mantle source. It has relatively radiogenic $^{207}Pb/^{204}Pb$, akin to that found in the basalts of Rosemary Bank (Morton et al., 1995), and may have been derived from a source with similar characteristics.

6. CONCLUSIONS

The igneous material recovered during the 1994 drilling programme on the western margin of Britain is diverse in terms of both its mode of formation and its magmatic source. Most of the samples described are considered to come from lava flows, although a shallow intrusive origin cannot be categorically ruled out in all cases. However, some samples are fragmentary, and clearly have different origins. The basaltic agglomerates at 58/14-8 and 57-13/54 probably formed through autobrecciation of lava flows in a submarine environment, whereas the basaltic agglomerates at 57-12/18 and 58-14/57 represent reworked basalt flow material formed during a subsequent phase of sedimentation. The basalt clast in 94/3 (171.14-171.20 m) is also reworked, and appears to be exotic, in that it represents material different to that extruded at the borehole site. Finally, the sequence in borehole 94/3 also includes some vitric tuffs (92.91-92.96 m, 109.97-110.00 m, 112.50-112.54 m, 115.76-115.80 m), which were probably formed through rapid cooling and fragmentation of acidic lavas in a submarine setting.

Most of the igneous material recovered is basaltic in composition. In addition, a number of sites encountered intermediate rocks evidently representing basaltic differentiates. None of the basalts are primitive, all having relatively high Fe/Mg ratios and low abundances of Cr and Ni. There are differences in silica saturation, with basalts ranging from alkaline to subalkaline, and in degrees of LREE enrichment. These features indicate variable degrees of partial melting. The relative depletion in HREE indicates that melting took place mainly in the garnet stability field of the mantle.

The only two samples that appear to represent uncontaminated asthenospheric mantle-derived material are the basalt from 57-13/66 (Rockall Bank) and the reworked basalt pebble from 57-12/18 (Anton Dohrn Seamount). Neither of these samples have negative Nb-Ta anomalies and their isotopic compositions place them firmly within the range of North Atlantic MORB. Apart from these two, all the basalts and basalt differentiates display evidence of crustal contamination to some degree. For the most part, contamination was by lower crustal, granulite and amphibolite facies material, but one sample (from borehole 94/5) was contaminated by upper crustal material (possibly a high-level granite).

Pb isotopes distinguish two types of lower crustal contamination. Samples from Rockall Bank have been contaminated by Proterozoic crust with characteristics similar to the gneiss recovered at 56-15/12 and to metamorphic basement rocks previously described from the area (Morton & Taylor, 1990). By contrast, samples from George Bligh Bank appear to have been contaminated by Archaean crust similar to the onshore Lewisian. This implies that there is a major structural feature between the two banks which may represent an important terrane boundary.

The only sample that does not appear to have been derived from typical North Atlantic mantle with or without crustal contamination is the ultrapotassic phono-tephrite from Rosemary Bank (59-11/12). Trace element and isotopic data indicate that the magma responsible for this flow was derived by partial melting of subcontinental lithospheric mantle. This is mantle that has been isolated from circulating asthenospheric mantle and metasomatically enriched over a long period. The characteristics of the phono-tephrite from 59-11/12 are similar to those of the Loch Roag dyke on the Outer Hebrides (Menzies et al., 1987), which was derived from the subcontinental lithosphere underplating the Archaean block of NW Scotland. The results from 59-11/12 suggests this subcontinental lithospheric domain may extend from the Outer Hebrides at least as far west as Rosemary Bank.

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8. PETROGRAPHIC DATA

Sample site: 56-15/12 (S25) **Location**: south-west Rockall Bank
Lithology: Gneiss
Description: banded leucrocratic and melanocratic layers. Leucocratic layers dominated by K-feldspar, plagioclase and quartz, with minor apatite. Feldspar locally clouded and altered. Melanocratic layers contain orthopyroxene (Mg_{46}), pale green clinopyroxene ($Ca_{44-45}Mg_{34-35}Fe_{20-22}$), brown titaniferous biotite (TiO_2 4.1-4.7%), magnetite and minor allanite, sometimes with green amphibole (composition?). Biotite locally altered to chlorite. Orthopyroxene is locally replaced by fibrous ?tremolite and minor carbonate.
Origin: high-grade metamorphic.

Sample site: 57-12/18 (S30) **Location**: Anton Dohrn Seamount
Lithology: Basalt (pebble)
Description: consists of abundant plagioclase laths, common altered olivine and minor opaques ophitically enclosed by pale brown clinopyroxene. The clinopyroxene is salitic, $Ca_{44-46}Mg_{35-38}Fe_{16-20}$, and is relatively titanium-rich (TiO_2 2.2-3.4%). Plagioclase laths are labradoritic (An_{58-64}) and show well-developed trachytic texture. Olivines are all replaced by red-brown 'iddingsite'. Rare vesicles occur, filled with a radiating colourless zeolite phase with a K-rich phillipsite composition. The rock is locally fractured, the fractures being filled by a red-brown ferroan phase. Zones around fractures are also oxidised..
Origin: extrusive, flow: reworked during subsequent phase of sedimentation.

Sample site: 57-13/54 (S17) **Location**: east margin of Rockall Bank
Lithology: Basaltic agglomerate
Description: consists of two clast types - (i) small, angular, non-vesicular vitric clasts with small plagioclase phenocrysts, partially altered, and (ii) larger, subangular, sparsely vesicular fine-grained basaltic clasts with common plagioclase phenocrysts and rare pseudomorphs of ?olivine phenocrysts in a very fine grained, highly altered matrix, some very dark due to oxidation. Microprobe analysis shows the vitric glass to be strongly hydrated (analytical totals below 88%), but is probably basic in composition (SiO_2 34-40%, FeO 13-21%, MgO 9-13%). CaO is very low through alteration. TiO_2 contents are very variable within individual vitric particles indicating local remobilisation during alteration. Plagioclase laths have similar compositions in both vitric (An_{68-71}) and lithic (An_{67-73}) clasts, indicating that both types of clast were probably derived by fragmentation of one flow unit. Clasts cemented by early clear isotropic potassium analcime and later green-brown smectite.
Origin: Extrusive: volcaniclastic.

Sample site: 57-13/66 (S20A) **Location**: east margin of Rockall Bank
Lithology: Basalt
Description: holocrystalline, sparsely glomerophyric. Comprises granular grey clinopyroxene, plagioclase laths, titanomagnetite and pseudomorphs after olivine. Sparse glomerophyric aggregates, mainly of plagioclase, in conjuction with olivine (pseudomorphed) and/or clinopyroxene. The pyroxene is augite, $Ca_{36-40}Mg_{39-45}Fe_{17-26}$, and is relatively low in titanium (TiO_2 0.9-1.2%). Plagioclase phenocrysts are zoned, with cores of An_{77} and margins of An_{53}. The plagioclase laths are similar in composition to phenocryst margins (An_{48-63}).

Origin: No evidence of flow alignment: together with the lack of glassy material (suggesting slow cooling) suggests it is either intrusive or from the middle of a thick flow.

Sample site: 57-14/52 (S15) **Location**: north-east margin of Rockall Bank
Lithology: Plagioclase-phyric basalt
Description: composed of plagioclase laths in a fine-grained, high altered matrix, with large plagioclase phenocrysts and smaller pseudomorphed olivine phenocysts. Plagioclase laths show strong alignment imparting a trachytic texture. The plagioclase phenocrysts consist of labradorite, An_{64-69}, with only limited evidence of zoning. The groundmass plagioclase is also mainly labradoritic, An_{64-68}, but there are some later more sodic plagioclases as low as An_{51}. Extensively fractured, fractures filled with ? brown smectite and later calcite with a botryoidal texture. The calcite contains both Fe and Mg, with FeO up to 1.9% and MgO up to 1.5%.
Origin: Extrusive; basalt flow.

Sample site: 57-14/53 (S18) **Location**: north-east Rockall Bank
Lithology: Trachyte
Description: holocrystalline, dominated by feldspar laths, anorthoclase to sanidine (Or_{29-48}) in composition, with subordinate titanomagnetite and interstitial very fine grained brown pleochroic amphibole, pale green augite ($Ca_{38-41}Mg_{33-37}Fe_{24-28}$) and green titaniferous aegirine. Sparse feldspar phenocrysts with anorthoclase composition (Or_{30}). Strong alignment of feldspar laths imparts trachytic texture. Clusters of finely-divided opaques represent altered biotite phenocrysts or xenocrysts.
Origin: Extrusive: trachyte flow.

Sample site: 58-14/8 (S7) **Location**: George Bligh Bank
Lithology: Basaltic agglomerate
Description: composed of subangular lithic basaltic fragments set in highly vesicular glassy framework. Vitric material contains minor plagioclase laths, and is highly altered, much of it being virtually opaque. Vesicles are smectite-rimmed but centres are not filled. Lithic clasts are more well-crystallised, dominated by plagioclase laths with minor ?olivine pseudomorphs. Plagioclase compositions are consistent within individual clasts (Table 1), and four of the five clasts analysed have comparable ranges. However, one clast has markedly more sodic plagioclases, suggesting that derivation was from more than one flow unit. Some laths consist of K-feldspar, probably through submarine alteration.
Origin: Extrusive: volcaniclastic.

Table 1. Plagioclase compositions in five basaltic clasts in basaltic agglomerate, 58-14/8.

Clast 1			Clast 2			Clast 3			Clast 4			Clast 5		
An	Ab	Or	An	Ab	Or	An	Ab	Or	An	Ab	Or	An	Ab	Or
49.7	48.5	1.8	11.3	71.8	16.9	48.3	49.4	2.3	50.8	47.6	2.6	46.3	51.4	2.3
56.6	42.1	1.3	8.4	72.0	19.6	50.7	46.5	2.8	53.4	44.1	2.5	49.0	49.0	2.0
50.4	47.6	2.0	11.2	71.3	17.5	51.2	46.6	2.2	-	-	100	8.5	9.3	82.2
50.3	46.9	2.8												
49.4	49.0	1.6												

Sample site: 58-14/31 (S12) **Location**: north margin of Rockall Bank
Lithology: Iron-manganese crust on glauconitic limestone
Description: deep red iron-rich zone containing layers and blebs of opaque, manganese-rich material, overlying limestone, containing composed mainly of fine-grained (micritic) material together with glaucony grains, forams, and terrigenous clastic particles. Limestone appears to be fragmented, possibly through submarine alteration processes. Iron-manganese zone retains texture of original sediment, with ghosts of glaucony grains particularly clear. Manganese-rich areas also have high Ba contents. Dendritic manganese development occurs at the interface between the alteration zone and the limestone. Glaucony grains are oxidised with high Fe/Mg ratios: K_2O contents are 6.3-6.5%.
Origin: In-situ sea-floor alteration of limestone substrate.

Sample site: 58-14/42 (S7) **Location**: George Bligh Bank
Lithology: Benmoreite
Description: Very fine grained, sparsely vesicular, highly altered basalt with plagioclase (An_{35-45}) laths, later interstitial anorthoclase ($An_{5-10}Ab_{62-66}Or_{24-33}$) and titanomagnetite, in an argillised groundmass. Sparse vesicles are open with smectite rims. Rare large plagioclase phenocrysts and smaller pseudomorphs after olivine. Fractures rare, carbonate-filled.
Origin: Extrusive: basalt flow.

Sample site: 58-14/51 (S55) **Location**: north-east margin of Rockall Bank
Lithology: Feldspar-phyric trachyte
Description: comprising abundant feldspar and less common pale green clinopyroxene and altered olivine phenocrysts in a groundmass of feldspar laths, granular clinopyroxene, titanomagnetite, minor fine grained brown pleochroic amphibole and interstitial brown slightly argillised glass. Feldspar laths and phenocrysts have similar anorthoclase compositions, with laths of $An_{3-10}Ab_{60-71}Or_{20-37}$ and phenocrysts of $An_{1-8}Ab_{56-68}Or_{24-43}$: phenocrysts lack significant compositional zoning. Clinopyroxene compositions of phenocrysts and groundmass are similar, consisting of low-Ti augites, $Ca_{39-43}Mg_{22-34}Fe_{29-35}$ with TiO_2 between 0.5 and 0.8%. Minor partially resorbed finer-grained basalt xenoliths are present.
Origin: Extrusive: trachyte flow. Abundant phenocrysts indicates history of fractionation in shallow level magma chambers.

Sample site: 58-14/57 (S41) **Location**: George Bligh Bank
Lithology: Conglomerate
Description: consists of basalt and limestone clasts. Basalt clasts contain plagioclase laths ± granular clinopyroxenes in argillised groundmass, with variable degrees of alteration. Some are partially glauconitised. Pyroxene and plagioclase compositions (Tables x & x) vary from clast to clast, indicating derivation from more than one flow unit. Limestone clasts are rich in bioclastic material especially forams. Glaucony grains are common, and high relatively high K_2O contents (7.7-8.6%) suggesting they formed during a relatively long period of non-deposition. Marginal development of ferroan alteration crust, evidently of polyphase origin, as shown by interlamination with glauconitic layers.
Origin: Submarine reworking of basalt and limestone lithologies. Development of ferroan crust indicates later in situ submarine alteration.

Table 2. Pyroxene compositions within four basaltic clasts in sample 58-14/57.

Clast 1				Clast 2				Clast 3				Clast 4			
Ca	Mg	Fe	TiO_2	Ca	Mg	Fe	TiO_2	Ca	Mg	Fe	TiO_2	Ca	Mg	Fe	TiO_2
45.6	40.0	14.4	2.0	40.3	46.1	13.5	1.0	44.3	42.5	13.2	1.3	38.6	49.2	12.2	0.9
44.4	39.0	16.6	2.0	43.5	45.7	10.8	0.9	44.0	44.5	11.5	0.9	44.7	42.1	13.2	1.5
46.3	40.6	13.1	1.8	39.9	43.9	16.2	1.2	44.1	43.6	12.3	1.3	44.6	41.0	14.4	1.30
44.3	35.5	19.3	2.1	45.0	42.8	12.2	1.2								

Table 3. Plagioclase compositions within four basaltic clasts in sample 58-14/57.

Clast 1			Clast 2			Clast 3			Clast 4		
An	Ab	Or	An	Ab	Or	An	Ab	Or	An	Ab	Or
53.5	45.0	1.5	39.3	58.3	2.4	49.0	49.0	2.0	67.8	32.2	-
47.8	49.7	2.5	67.0	33.0	-	50.1	48.1	1.8	67.3	32.7	-
			62.6	37.4	-	32.4	63.2	4.4	63.2	35.9	0.9
			38.2	59.2	2.6						

Sample site: 59-11/12 (S1) **Location**: Rosemary Bank
Lithology: Ultrapotassic phono-tephrite.
Description: sparsely vesicular, glassy basic rock. Glass is pale pinkish brown with little petrographic evidence for alteration. Microprobe analysis suggests some hydration has occurred, with analytical totals between 90 and 95%. Some areas are yellowish and may be more hydrated. The composition of the glass is highly alkalic, with Na_2O + K_2O between 11.11-13.51% and SiO_2 between 49.12 and 52.16%. K_2O/Na_2O ratios exceed 1, indicating that the rocks are ultrapotassic. Elongate to acicular clinopyroxene is abundant, and has chrome-diopside compositions ($Ca_{45-48}Mg_{45-47}Fe_{8-9}$, with Cr_2O_3 between 0.6 and 1.1% and TiO_2 between 1.1 and 1.3%). Pyroxene phenocrysts are scarce, but have similar compositions ($Ca_{45-46}Mg_{45-48}Fe_{7-9}$, with Cr_2O_3 between 0.7 and 0.8% and TiO_2 between 0.9 and 1.3%). Small equant olivine crystals (Fo_{84-85}) are common: olivine phenocrysts are rare, and tend to be more magnesian (up to Fo_{91}). Vesicles are lined with a potassium-rich isotropic zeolitic mineral. This also lines the fractures, which are filled with carbonate.
Origin: Extrusive: quenched, indicating very rapid cooling, probably submarine.

Sample site: 94/2 **Location**: eastern flank of Rockall Bank
Depth: 21.74-21.76 m
Lithology: Basalt
Description: very fine grained, sparsely vesicular, sparsely plagioclase-phyric basalt, consisting of rare plagioclase phenocrysts in a groundmass of plagioclase laths, finely-divided opaques and mafic phases (?clinopyroxene and olivine, pseudomorphed by carbonate and iron oxides), with extensive areas of green-brown ?smectite (probably replacing interstitial glass). Vesicles are filled with a green-blue clay phase, either smectite or celadonite. Alteration is intense around vesicles. The sample lacks any evidence of trachytic textures.
Origin: Extrusive, flow.

Sample site: 94/3 **Location:** eastern flank of Rockall Bank
Depth: 47.75-47.80 m
Lithology: Basalt
Description: aphyric, sparsely vesicular basalt, comprising plagioclase laths, titanomagnetite and interstitial pale brown clinopyroxene set in a matrix of brown smectite (replacing glass). Clinopyroxene is altered to clays and finely divided opaques. Fresh clinopyroxene is salitic ($Ca_{44-46}Mg_{25-27}Fe_{28-31}$) and rich in TiO_2 (3.1-5.2%). Plagioclase laths are andesine-labradorite, An_{47-61}. Some vesicles are open, the rest being filled with brown smectite. Fractures are common: they are filled with brown smectite and the areas adjacent to the fractures are more highly altered than the rest of the basalt. The basalt lacks an obvious trachytic texture.
Origin: Extrusive, flow.

Depths: 92.91-92.96 m, 109.97-110.00 m, 112.50-112.54 m, 115.76-115.80 m
Lithology: Vitric andesitic tuff
Description: Consists of large particles of colourless or pale yellow highly vesicular volcanic glass, best described as pumice. The pumice fragments consist essentially of interconnected bubble walls, the vesicles ranging from round to highly elongate. The glass ranges from colourless and isotropic to pale yellow and weakly birefringent, with a speckly appearance under crossed polars. The latter probably indicates a higher degree of alteration. The tuffs also contain minor phenocryst/xenocryst phases, including K-feldspar (Or_{39-40}), anorthoclase ($An_{12-13}Ab_{63-65}Or_{23-24}$), quartz, biotite and clinopyroxene (ferrohedenbergite). Some sedimentary clasts occur, including siltstone and glauconitic particles. The tuffs have very high porosity owing to the high vesicle/glass ratio.
Origin: These rocks probably resulted from the flow of intermediate/acidic magmas into water, causing rapid cooling, degassing and fragmetation. The fragmentation process also caused the incorporation of sedimentary particles from the underlying substrate.

Depth: 171.14-171.20 m
Lithology: Basalt (pebble)
Description: Fine grained, sparsely vesicular aphyric basalt, containing plagioclase laths, granular colourless clinopyroxene, red-brown pseudomorphs of ?olivine and interstitial titanomagnetite in a green smectite groundmass. Clinopyroxene is low-Ti augite, with $Ca_{37-43}Mg_{39-45}Fe_{13-22}$ and TiO_2 0.9-1.3%. The plagioclase is mainly andesine-labradorite (An_{45-54}), but some is less calcic (minimum value An_{28}). Vesicles are filled with green vermiform smectite. The sample lacks trachytic texture.
Origin: Reworked extrusive flow. The pebble is different both in terms of texture and clinopyroxene composition (as deduced from its optical appearance) compared with the overlying and underlying in-situ flows, and therefore does not appear to be locally reworked.

Depth: 208.12-208.15m, 208.70-208.71 m, 208.72-208.73 m, 209.57-209.58 m
Lithology: Basalt
Description: medium-grained, non-vesicular, sparsely plagioclase phyric basalt. Contains rare plagioclase phenocrysts in a matrix of plagioclase laths, titanomagnetite, granular to subophitic clinopyroxene and smectite, both as pseudomorphs of ?olivine and as a replacement of interstital glass. The clinopyroxene is relatively Ti-rich augite, with

$Ca_{41-43}Mg_{28-40}Fe_{17-28}$ and TiO_2 1.7-3.6%. Plagioclase laths are labradoritic (An_{55-65}): phenocryst cores are more calcic than rims (An_{75}, compared with An_{63}). The smectite contains common finely divided secondary opaques, especially in the more highly altered samples (208.70-208.71 m and 209.57-209.58 m). All samples have a well-defined trachytic texture.
Origin: Extrusive, flow.

Sample site: 94/5 **Location**: eastern flank of Rockall Bank
Depth: 29.21-29.25 m
Lithology: Hawaiite
Description: extremely fine grained aphyric basalt, consisting of plagioclase laths, interstitial K-feldspar, equant colourless clinopyroxene, minor titanomagnetite and scarce altered ?olivine in a highly altered oxidised groundmass. Centres of plagioclase laths (probably originally more calcic zones) are altered to a colourless ?zeolite phase. Remnant plagioclase laths consist of andesine (An_{33-44}) and the K-feldspar is anorthoclase (An_{4-9} $Ab_{58-62}Or_{29-39}$). The rock contains common large partially resorbed slightly coarser basalt clasts, distinguished by the darker colour due to greater degree of alteration. Some of the resorbed clasts are sparsely vesicular, the vesicles being infilled by carbonate and/or smectite.
Origin: Extrusive, flow.

Sample site: 94/6 **Location**: eastern flank of Rockall Bank
Depth: 20.12-20.19 m
Lithology: Basalt
Description: fine-grained, highly altered, vesicular aphyric basalt, comprising partially altered plagioclase laths, abundant ilmenite and scarce pinkish-brown clinopyroxene, with abundant green-brown smectite (probably replacing interstitial glass and possibly some mafic phases). Common large round vesicles, infilled with smectite and minor rhombic carbonate.

Depth: 21.83-21.84 m
Lithology: Basalt
Description: medium grained aphyric basalt, comprising andesine-labradorite (An_{40-53}) laths and ilmenite subophitically enclosed by pale brown Ti-rich augite ($Ca_{42-45}Mg_{35-37}$ Fe_{19-23}: TiO_2 2.3%-3.1%). There is some minor late-stage interstitial anorthoclase feldspar ($An_{4-16}Ab_{63-68}Or_{15-33}$). Interstitial green-brown smectite is widespread, probably replacing glass. The rock is non-vesicular and the plagioclase laths show a subtrachytic texture.
Origin: Extrusive, flow. The upper samples is probably from the fine-grained vesicular zone near the flow top, whereas the lower sample is from the more slowly cooled central part of the flow unit.

Sample site: 94/7 **Location**: George Bligh Bank
Depth: 21.07-21.10 m
Lithology: Hawaiite
Description: aphyric, non-vesicular fine grained basalt comprising plagioclase laths and ilmenite, either ophitically enclosed by pale brown clinopyroxene or set in a groundmass of brown, oxidised smectite. The clinopyroxene (titaniferous augite, $Ca_{43-45}Mg_{39-42}Fe_{15-17}$, TiO_2 1.6-2.4%) is fresh and does not appear to be altered into smectite, and thus the

smectitic zones probably represent more glassy (rapidly cooled) zones. The plagioclase laths (andesine, An_{45-48}) define a strong trachytic fabric. In addition to the plagioclase laths, there is some minor late-stage interstitial anorthoclase ($An_{13}Ab_{71}Or_{15}$)

Depth: 22.25-22.57 m
Lithology: Hawaiite
Description: similar to the sample from 21.07-21.10 m, except that the smectite is green and largely unaltered.

Depth: 23.20-23.25 m
Lithology: Hawaiite
Description: similar to the sample from 22.25-22.57 m, except that the sample is coarser grained and the trachytic texture is less well defined.
Origin: extrusive, flow: the upper two samples are finer grained and are probably from near the top of the flow unit, whereas the lowest sample is more slowly cooled and from the central part of the flow. The uppermost sample is more extensively altered due to its proximity to the unconformity with the overlying sedimentary sequence.

Table 4. Geochemistry of igneous and metamorphic rocks recovered during the 1994 drilling programme

	56-15/12	57-12/18	57-13/66	57-14/52	57-14/53	58-14/8	58-14/51	58-14/57	59-11/12
SiO2	59.45	43.89	48.32	42.96	62.79	52.72	61.49	15.43	44.57
Al2O3	16.29	17.12	12.73	15.71	16.99	16.70	15.20	4.18	13.49
TiO2	1.19	2.61	2.63	2.14	0.66	2.07	0.79	0.55	1.97
Fe2O3	7.45	15.40	15.36	10.52	4.10	10.13	6.69	13.11	8.19
MgO	1.28	3.84	6.23	3.64	0.61	2.34	1.53	2.58	5.47
CaO	3.56	9.41	10.90	13.92	0.85	4.14	3.08	32.02	9.10
Na2O	4.01	3.32	2.58	3.25	6.53	5.14	5.47	1.23	4.53
K2O	5.13	0.84	0.32	0.87	5.90	3.03	4.42	1.03	4.83
MnO	0.13	0.20	0.23	0.19	0.09	0.07	0.17	0.37	0.11
P2O5	0.44	0.30	0.22	0.39	0.21	0.81	0.14	13.91	1.65
LOI	0.39	2.50	-0.23	5.67	0.34	1.97	0.42	13.35	5.27
Total	99.32	99.43	99.29	99.26	99.07	99.12	99.40	97.76	99.18
Ba	2120	217	145	334	91	764	219	82	2073
Cr	7	39	84	12	<1	<1	5	103	77
Ga	23	19	22	17	22	25	27	6	20
Nb	18	16	12	13	14	41	23	6	118
Ni	5	77	69	66	2	10	18	181	109
Pb	22	1	1	<1	13	5	9	13	17
Rb	107	13	4	25	47	59	49	24	107
Sc	14	29	34	28	11	16	9	12	9
Sr	352	295	194	817	11	439	77	963	1649
V	36	244	308	208	3	97	51	174	67
Y (XRF)	35	33	30	22	28	34	59	35	19
Y (ICP)	39	36	33	24	26	34	61	40	23
Zr	355	189	156	101	279	339	378	75	436
La	47.1	12.8	11.7	13.0	32.4	44.3	27.7	19.5	164
Ce	114	34	33	31	91	105	75	16	296
Pr	14.4	4.90	4.64	4.21	11.3	13.8	9.78	3.41	31.7
Nd	60.4	24.3	22.6	19.2	39.5	56.5	42.3	15.8	114
Sm	12.3	6.3	6.5	4.7	7.4	12.0	10.1	3.7	16.4
Eu	3.16	2.13	2.12	2.03	1.21	3.30	1.99	1.03	4.31
Gd	10.8	7.3	6.8	5.2	6.6	9.8	10.7	4.1	11.2
Tb	1.48	1.24	1.09	0.81	1.06	1.56	1.84	0.67	1.47
Dy	8.1	7.1	6.7	5.1	5.8	8.0	11.9	4.3	6.6
Ho	1.47	1.35	1.27	0.93	1.02	1.43	2.34	0.88	0.88
Er	4.02	4.05	3.45	2.34	3.27	3.69	6.58	2.63	2.06
Tm	0.56	0.51	0.47	0.37	0.43	0.50	0.97	0.41	0.20
Yb	3.58	3.68	3.05	2.30	3.09	3.10	6.38	2.27	1.30
Lu	0.55	0.53	0.44	0.34	0.47	0.43	0.96	0.38	0.16
Ta	1.3	1.5	1.1	1.1	1.8	3.0	1.7	0.1	1.8
Hf	9.5	5.6	5.1	3.1	7.5	9.2	10.8	1.5	7.5
Th	2.3	1.0	0.9	1.2	1.6	3.7	3.3	0.3	1.6

Table 4. Geochemistry of igneous and metamorphic rocks recovered during the 1994 drilling programme

	94/2, 21.74	94/3, 47.75	94/3, 209.5	94/5, 29.21	94/6, 20.12	94/7, 23.20
SiO2	41.68	46.63	44.44	50.41	43.21	48.22
Al2O3	14.48	14.84	13.28	14.02	12.28	15.21
TiO2	1.30	3.48	2.73	2.77	4.02	3.38
Fe2O3	12.51	15.37	14.87	14.42	16.85	14.05
MgO	6.60	4.47	6.95	3.87	7.11	4.31
CaO	13.07	8.93	9.58	5.94	6.44	7.12
Na2O	2.51	3.48	2.85	3.83	3.32	4.45
K2O	0.30	0.62	0.32	1.72	1.19	0.96
MnO	0.20	0.19	0.33	0.26	0.22	0.19
P2O5	0.14	0.39	0.33	0.43	2.15	0.63
LOI	6.36	0.68	3.41	1.56	2.30	0.94
Total	99.15	99.08	99.09	99.23	99.09	99.46
Ba	145	525	207	450	1723	331
Cr	63	39	37	<1	9	<1
Ga	17	24	22	24	21	21
Nb	3	8	6	12	9	30
Ni	99	60	47	3	27	3
Pb	1	3	1	5	3	4
Rb	9	3	3	20	6	13
Sc	30	47	42	39	51	19
Sr	266	406	240	269	298	559
V	211	449	382	261	244	132
Y (XRF)	20	34	35	47	56	40
Y (ICP)	22.0	31.7	34.7	51.3	56.2	41.8
Zr	64	91	116	263	132	309
La	4.58	9.33	8.11	25.0	26.7	30.3
Ce	12.6	22.9	22.8	62.6	68.5	76.3
Pr	1.93	3.59	3.29	8.72	10.1	10.5
Nd	10.4	19.1	18.6	40.6	54.4	49.1
Sm	3.32	5.68	5.89	10.8	13.9	11.6
Eu	1.27	2.40	2.50	3.42	5.92	3.93
Gd	3.60	5.87	6.47	9.82	13.1	9.91
Tb	0.63	1.11	1.25	1.79	2.27	1.76
Dy	4.38	6.85	7.50	10.9	12.6	9.69
Ho	0.91	1.34	1.53	2.12	2.30	1.82
Er	2.41	3.84	4.04	6.14	6.35	4.96
Tm	0.37	0.49	0.58	0.76	0.83	0.61
Yb	2.29	3.53	3.66	5.27	5.01	4.32
Lu	0.37	0.52	0.52	0.76	0.76	0.58
Ta	0.94	0.53	0.55	1.17	0.57	2.25
Hf	3.95	4.06	5.18	10.7	5.64	12.64
Th	0.35	0.53	0.62	2.65	0.94	2.40

Table 5. Isotopic data from igneous and metamorphic rocks recovered during the 1994 drilling programme

	56-15/12	57-12/18	57-13/66	57-14/53	58-14/42	59-11/12	94/2, 21.74	94/3, 47.75	94/3, 209.5	94/5, 29.21	94/6, 20.12	94/7, 23.20
87Rb/87Sr	0.806	0.108	0.044	15.726	0.347	0.19	0.013	0.023	0.034	0.165	0.059	0.057
87Sr/86Sr	0.722447	0.703275	0.703211	0.717533	0.704851	0.704664	0.703358	0.703827	0.703943	0.707197	0.704258	0.703402
eSr(60Ma)		-21.57	-21.71	-8.09	-1.99	-2.84	-19.20	-12.67	-11.15	33.43	-6.98	-19.11
eSr(70Ma)		-21.75	-21.75	-39.82	-2.75	-3.19	-19.23	-12.71	-11.22	33.11	-7.09	-19.23
147Sm/144Nd	0.10609	0.17285	0.17531	0.11151	0.11922	0.09038	0.19484	0.17627	0.19512	0.1529	0.15505	0.1476
143Nd/144Nd	0.511701	0.513069	0.512983	0.512182	0.512296	0.51238	0.512771	0.512589	0.51288	0.512558	0.512462	0.512892
eNd(60Ma)		7.04	5.34	-9.79	-7.63	-5.75	1.07	-2.34	3.71	-2.77	-4.66	3.78
eNd(70Ma)		6.83	5.13	-9.93	-7.78	-5.87	0.82	-2.57	2.95	-2.97	-4.86	3.59
206/204Pb	16.288	18.519	18.316	16.601	16.532	16.906	17.077	17.287	17.748	18.248	17.074	17.899
207/204Pb	15.377	15.494	15.422	15.319	15.074	15.467	15.408	15.385	15.449	15.49	15.379	15.373
208/204Pb	35.605	38.089	38.126	36.020	36.582	36.640	36.504	36.607	37.143	37.252	36.419	37.578

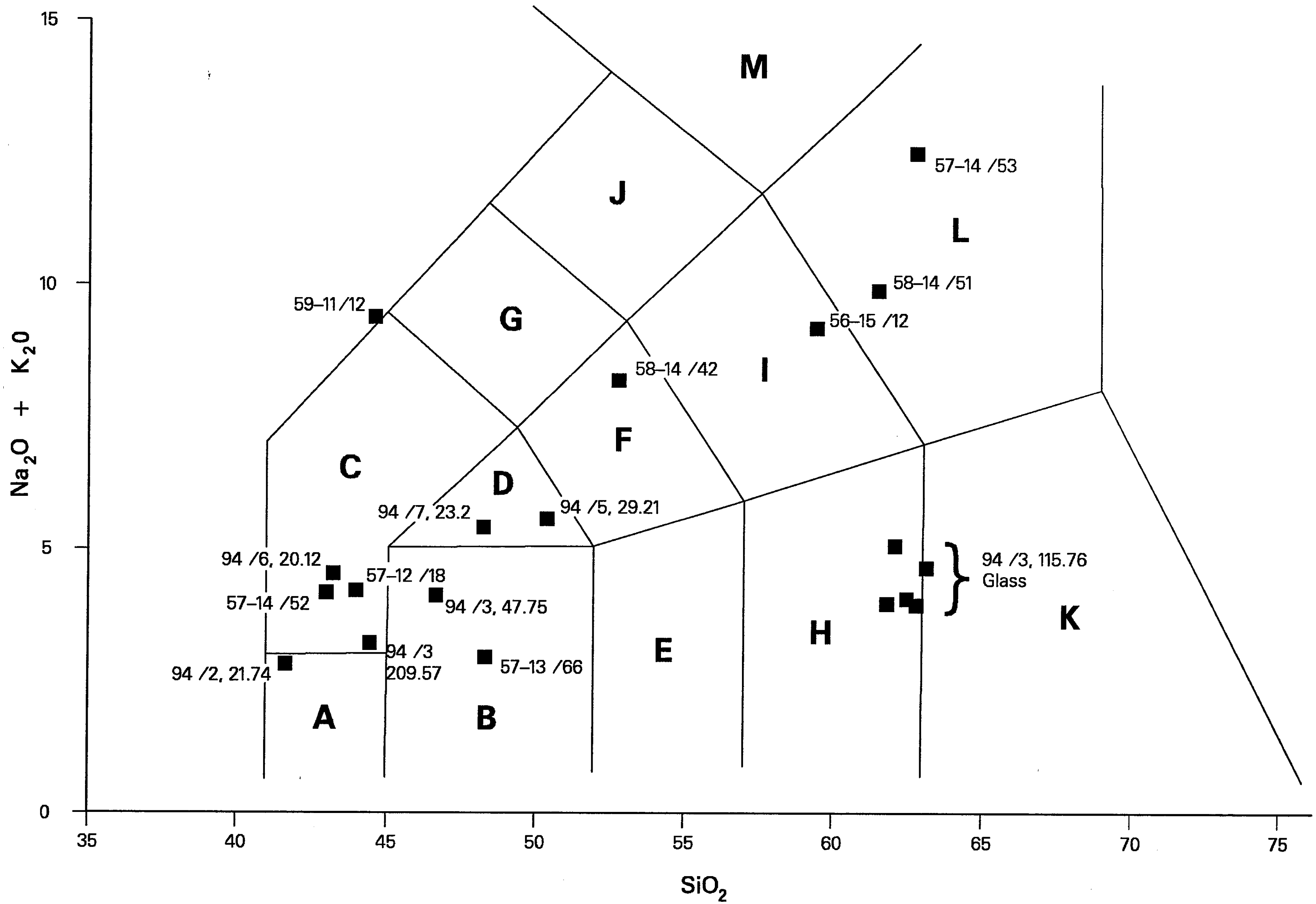


Fig. 1. Igneous and metamorphic basement samples from the 1994 drilling programme west of Britain plotted on the total alkalis-silica (TAS) diagram (Le Maitre et al., 1989). A=picrobasalt, B=basalt, C=basanite/tephrite, D=trachybasalt, E=basaltic andesite F=basaltic trachyandesite, G=phono-tephrite, H=andesite, I=trachyandesite, J=tephriphonolite, K=dacite, L=trachyte/trachydacite, M=phonolite.

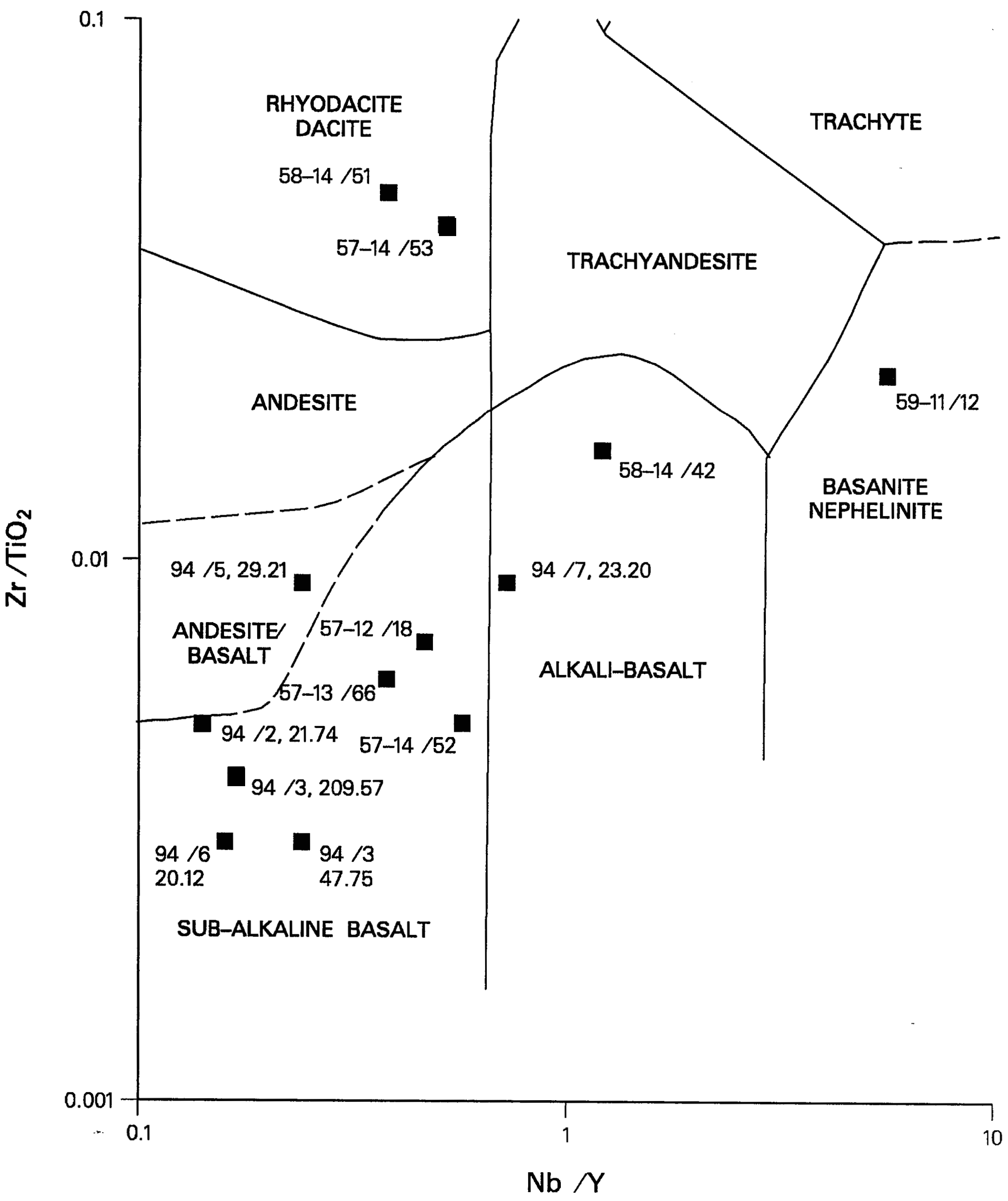
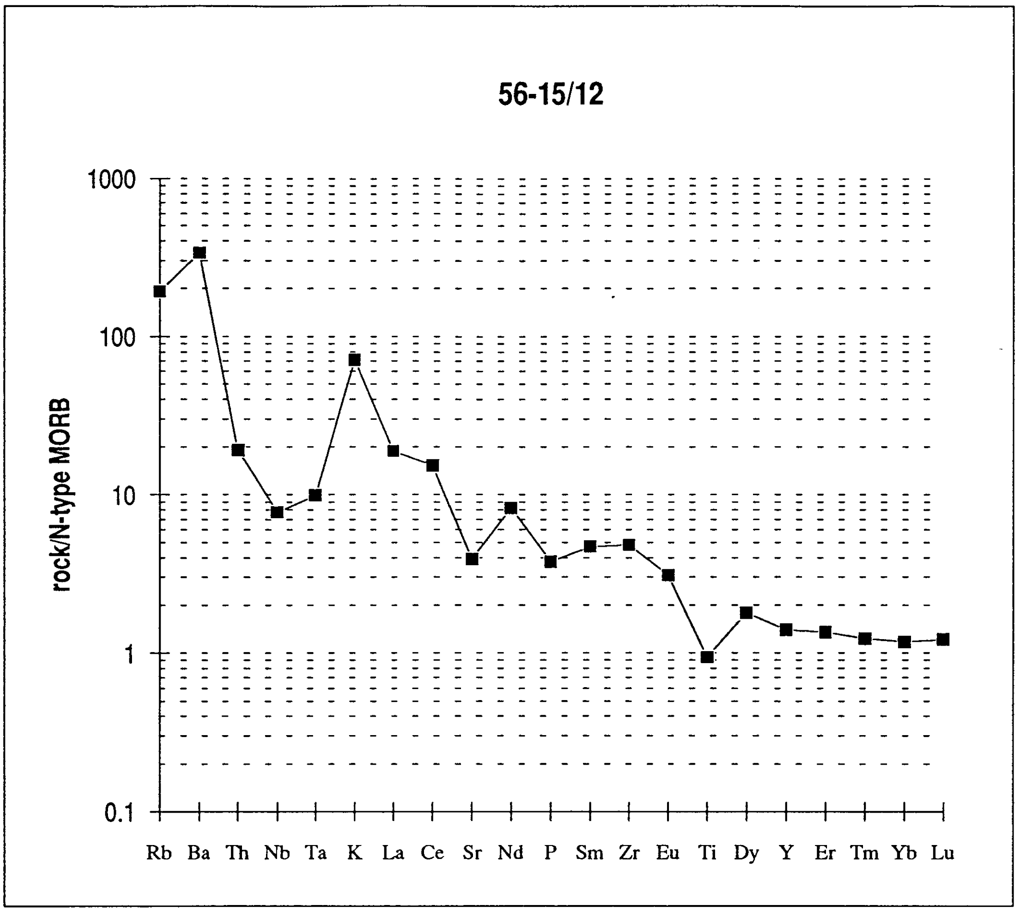


Fig. 2. Igneous rock samples recovered during the 1994 drilling programme west of Britain plotted on the Zr/TiO_2-Nb/Y diagram of Winchester & Floyd (1977).



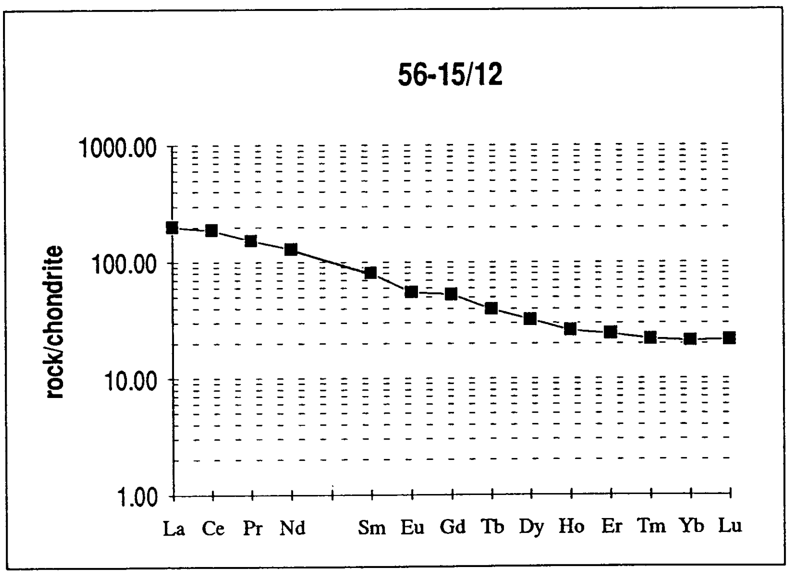


Fig. 3. MORB-normalised spidergram and chondrite-normalised REE plot of the metamorphic basement sample, 56-15/12.

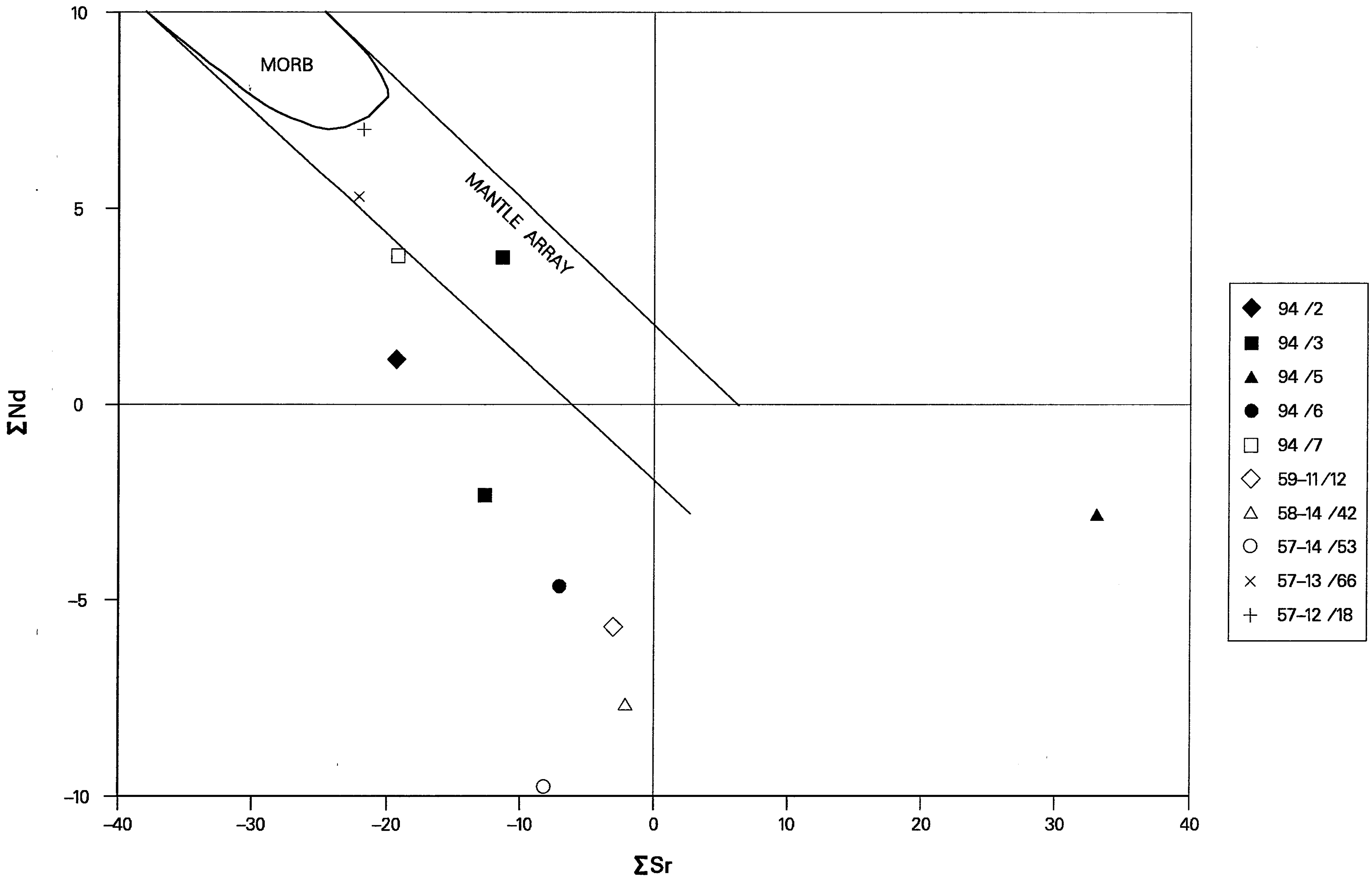


Fig. 4. ΣSr-ΣNd diagram showing position of igneous rock samples recovered during the 1994 drilling programme west of Britain. All values calculated assuming extrusion at 60Ma except 59-11/12, which was calculated at 70Ma.

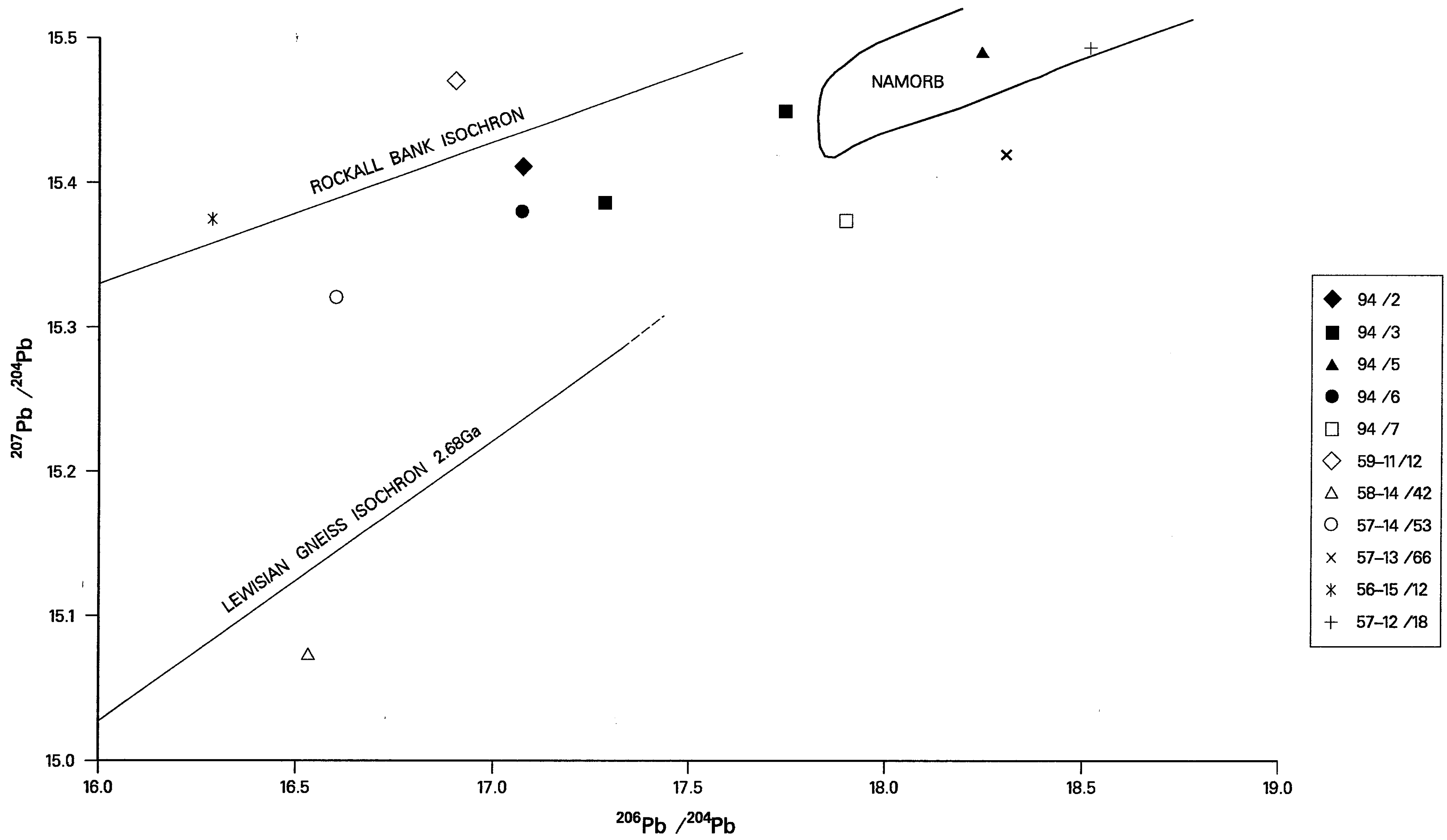


Fig. 5. Igneous rock samples recovered during the 1994 drilling programme west of Britain plotted on the $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ diagram. Area of typical North Atlantic MORB, the Lewisian Gneiss isochron and the Rockall Bank isochron are shown for comparison.

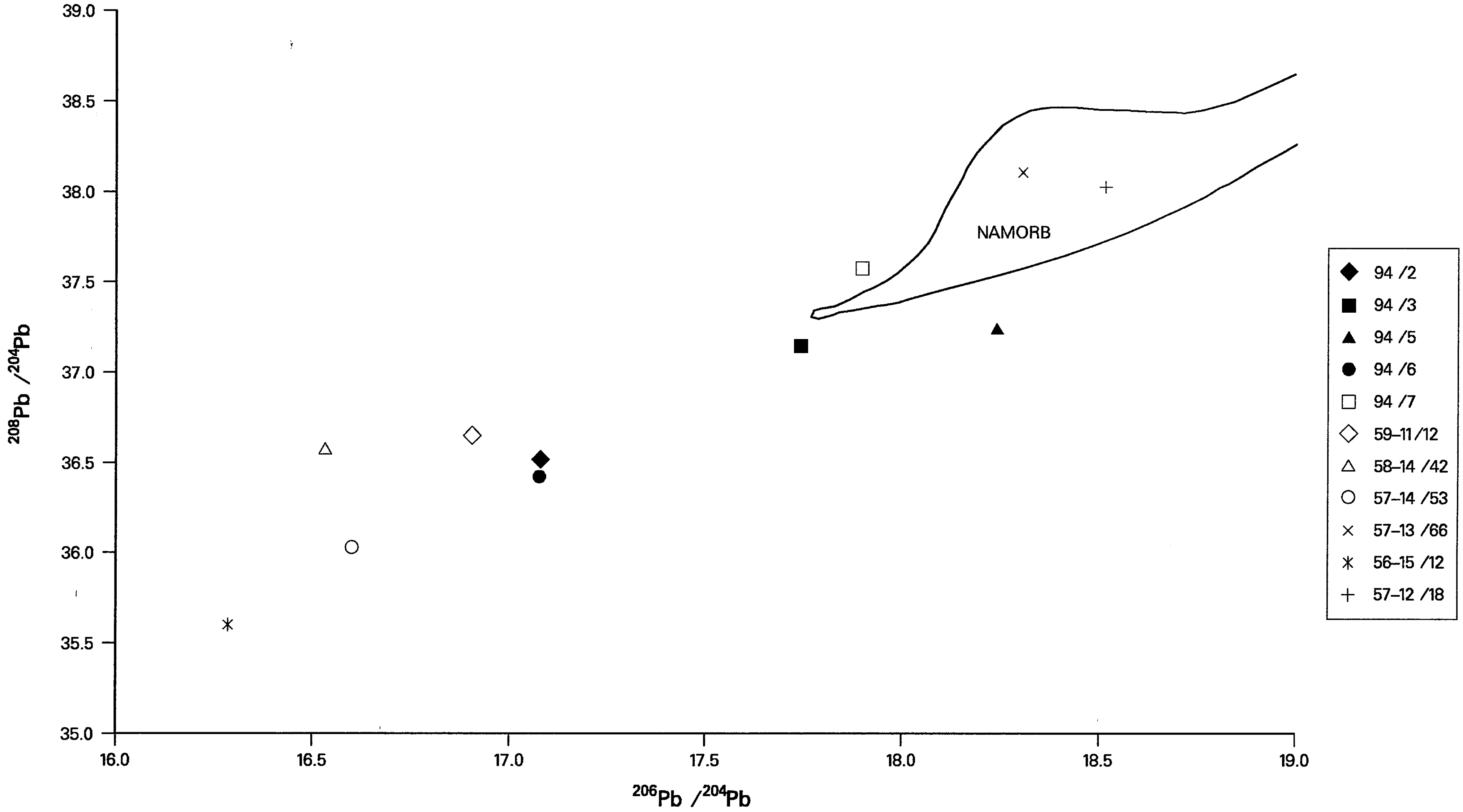


Fig. 6. Igneous rock samples recovered during the 1994 drilling programme west of Britain plotted on the $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ diagram. Area of typical North Atlantic MORB is shown for comparison.

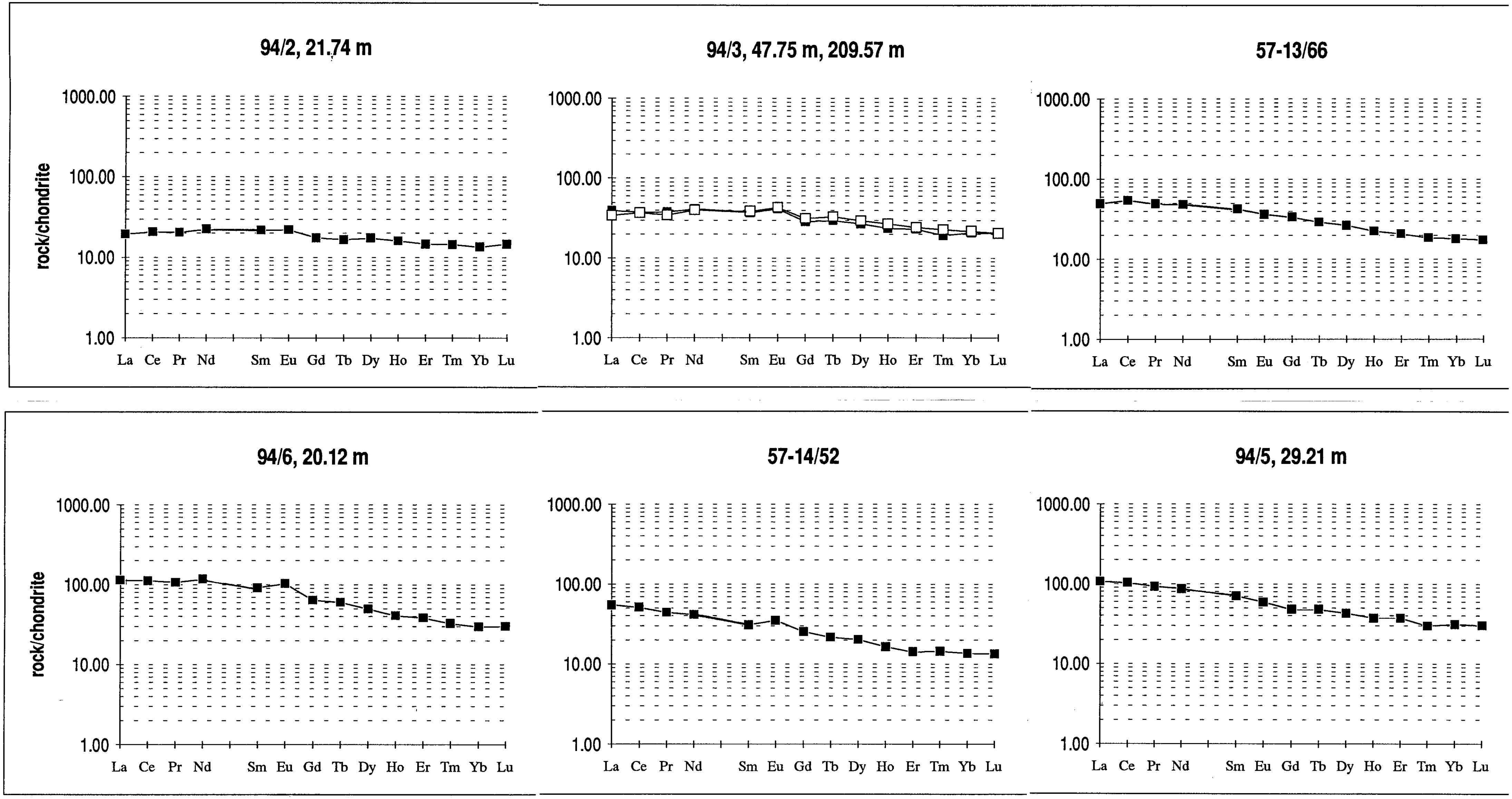


Fig. 7. Chondrite-normalised REE plots for basaltic rocks recovered from Rockall Bank.

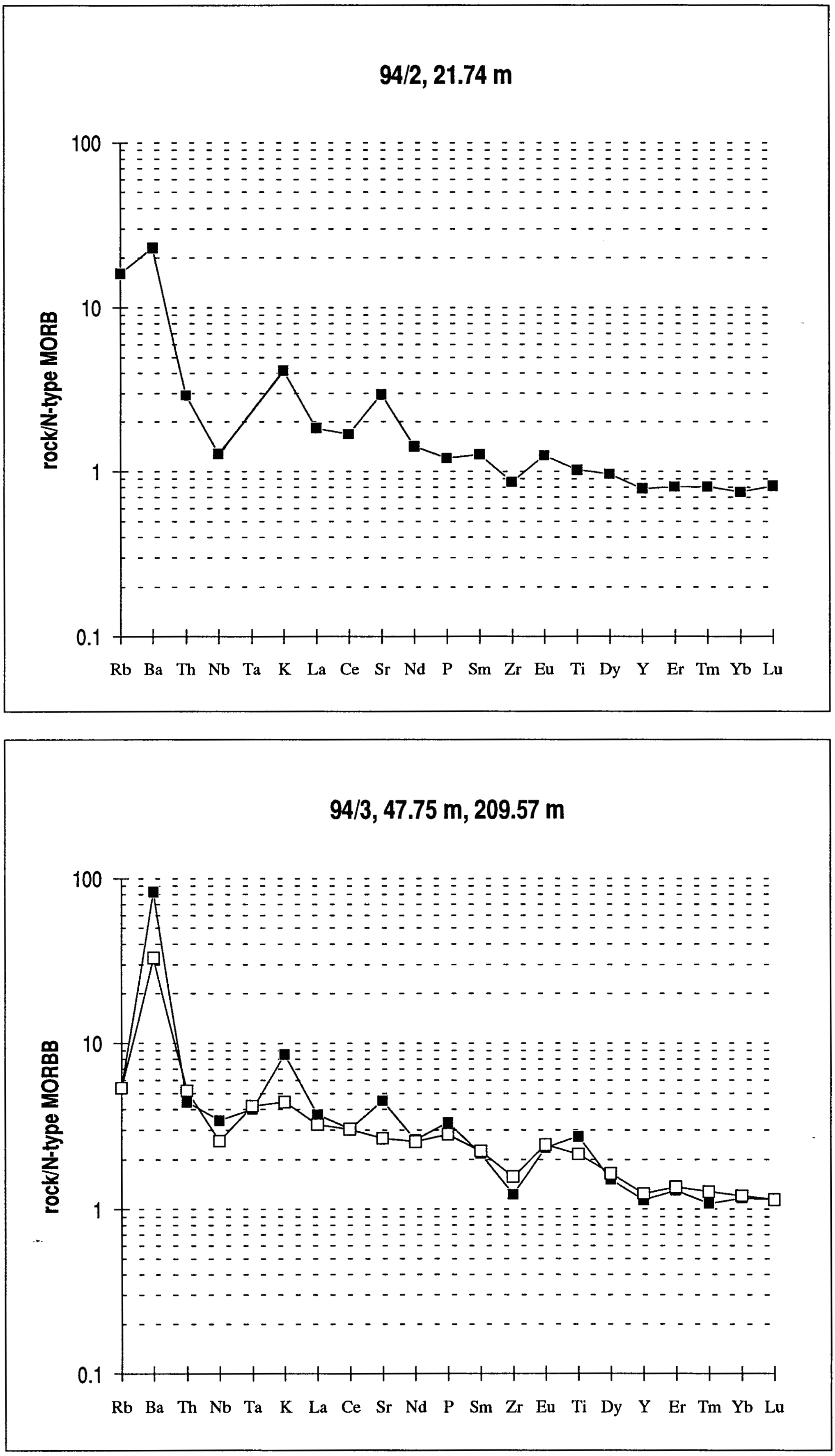
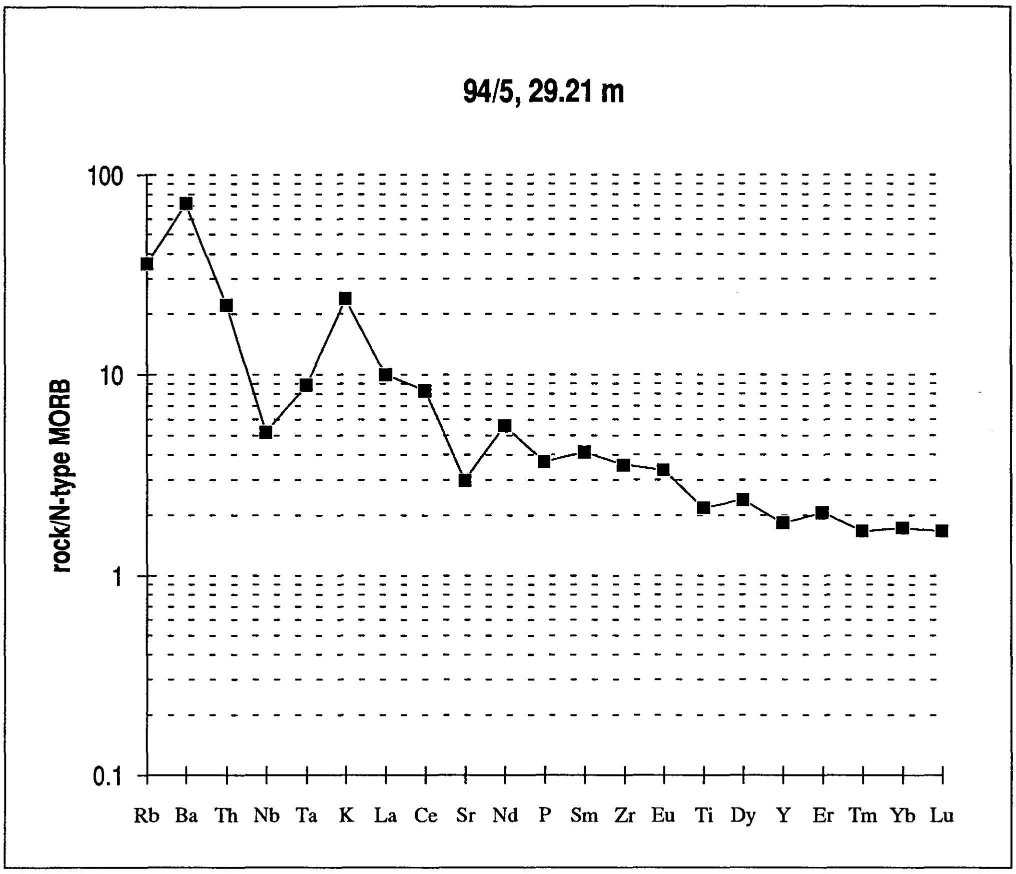


Fig. 8. MORB-normalised spidergrams for basaltic rocks recovered from Rockall Bank.



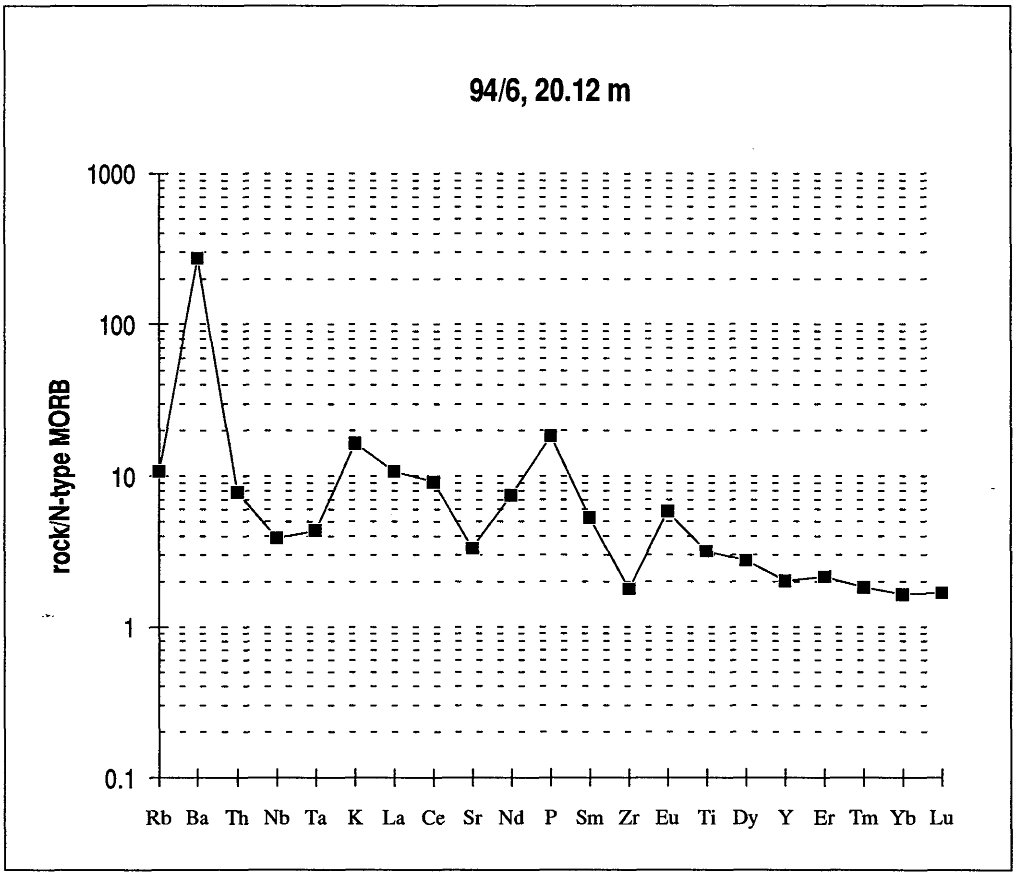
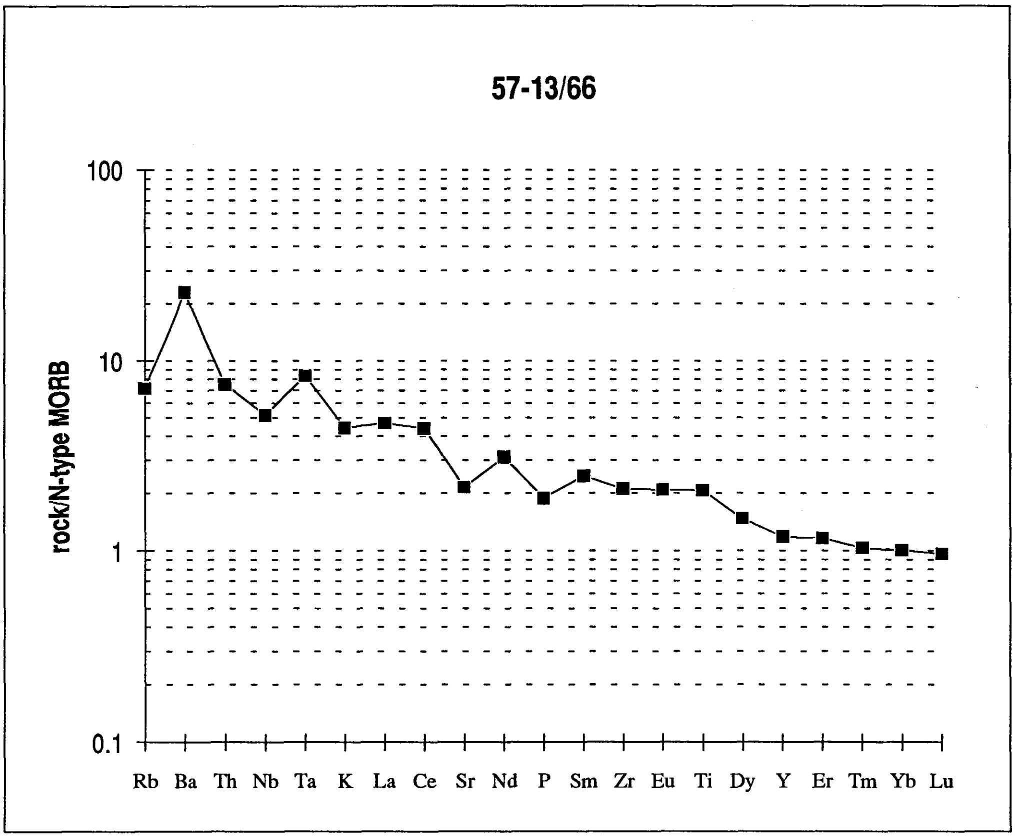


Fig. 8. Continued



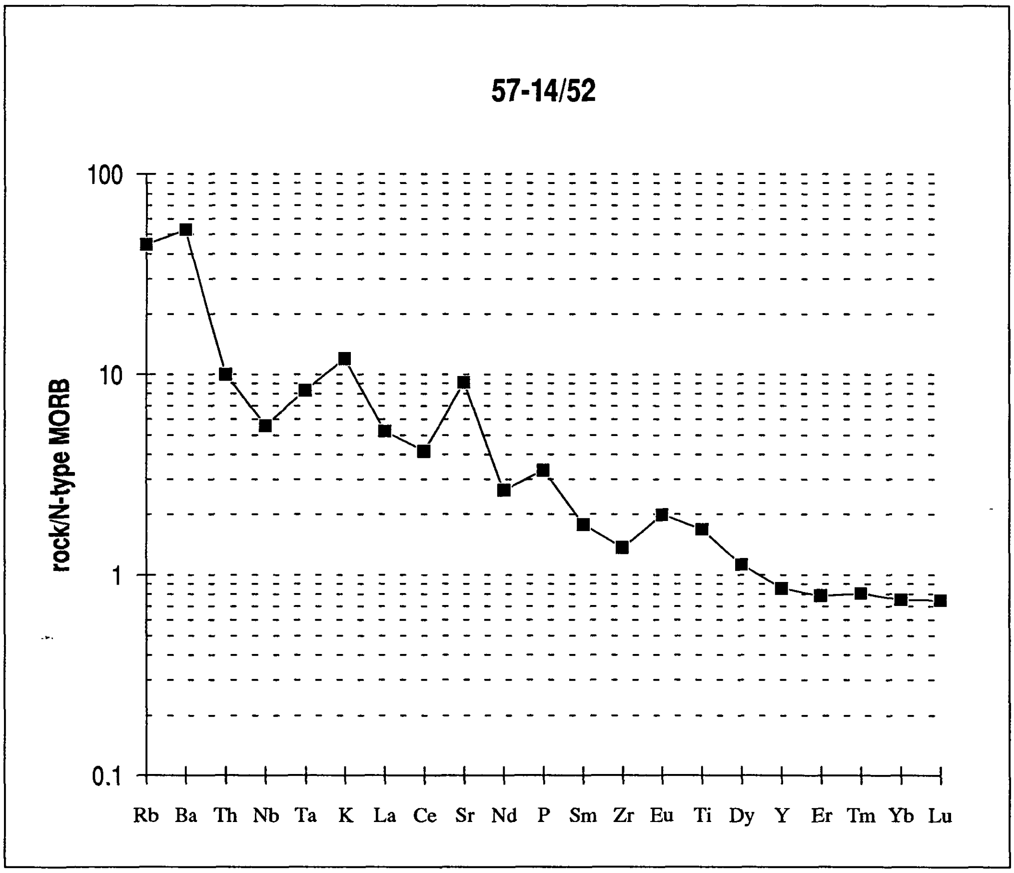


Fig. 8. Continued

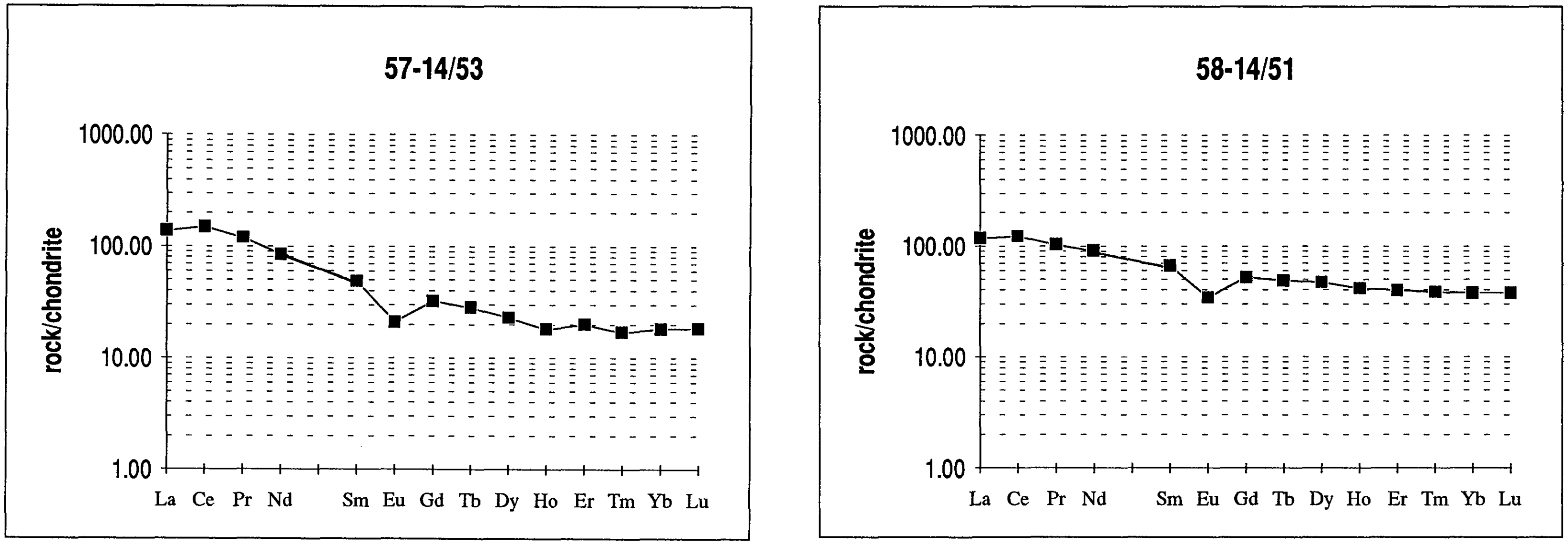
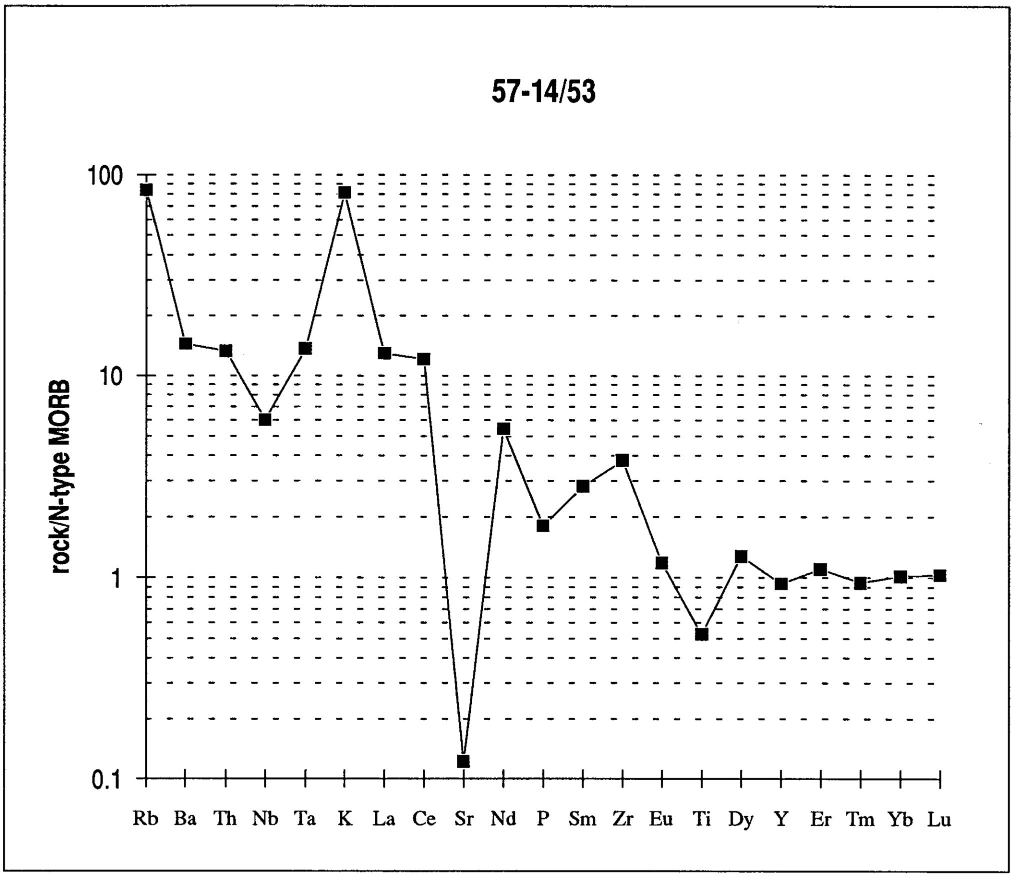


Fig. 9. Chondrite-normalised REE plots for trachytes recovered from Rockall Bank .



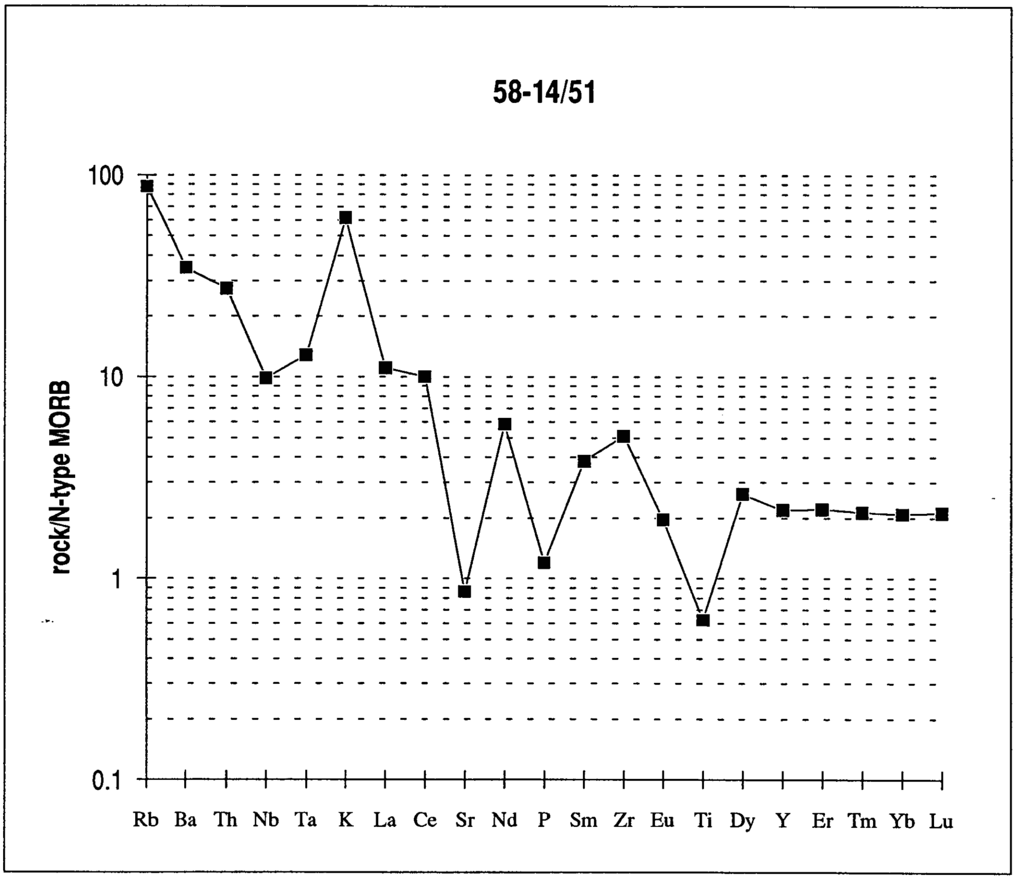
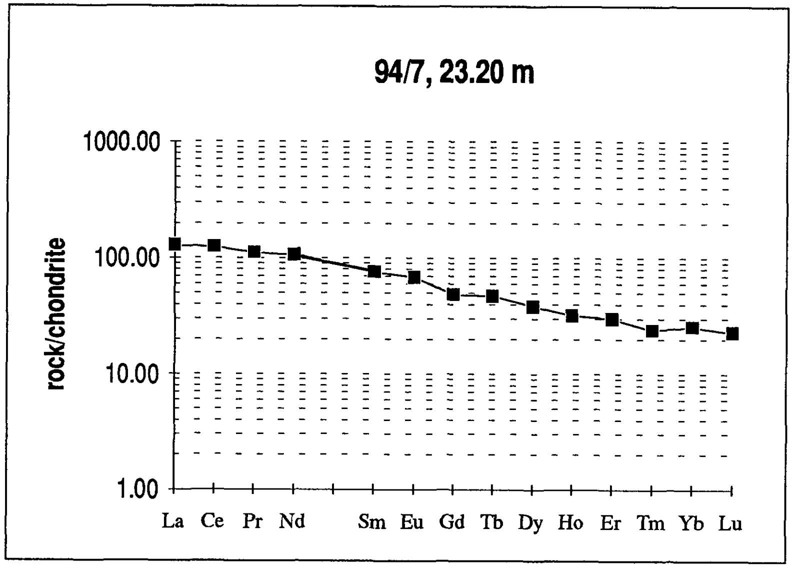


Fig. 10. MORB-normalised spidergrams for trachytes recovered from Rockall Bank.



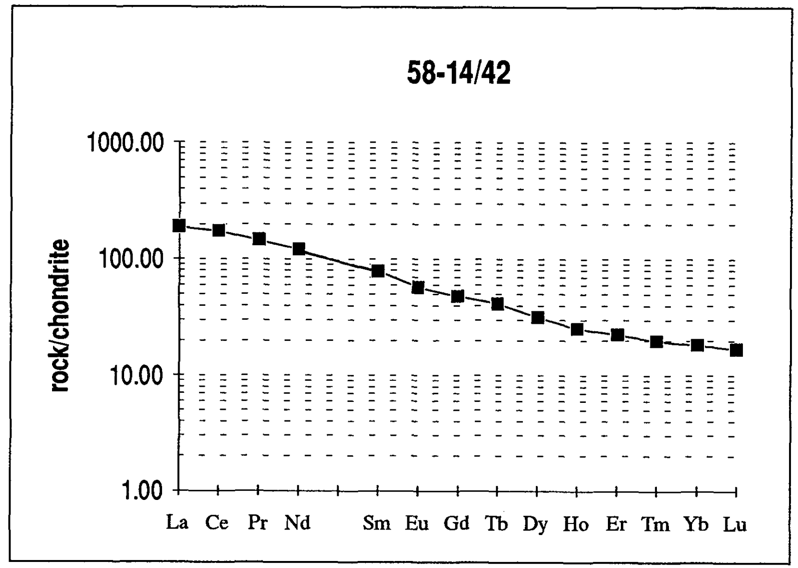
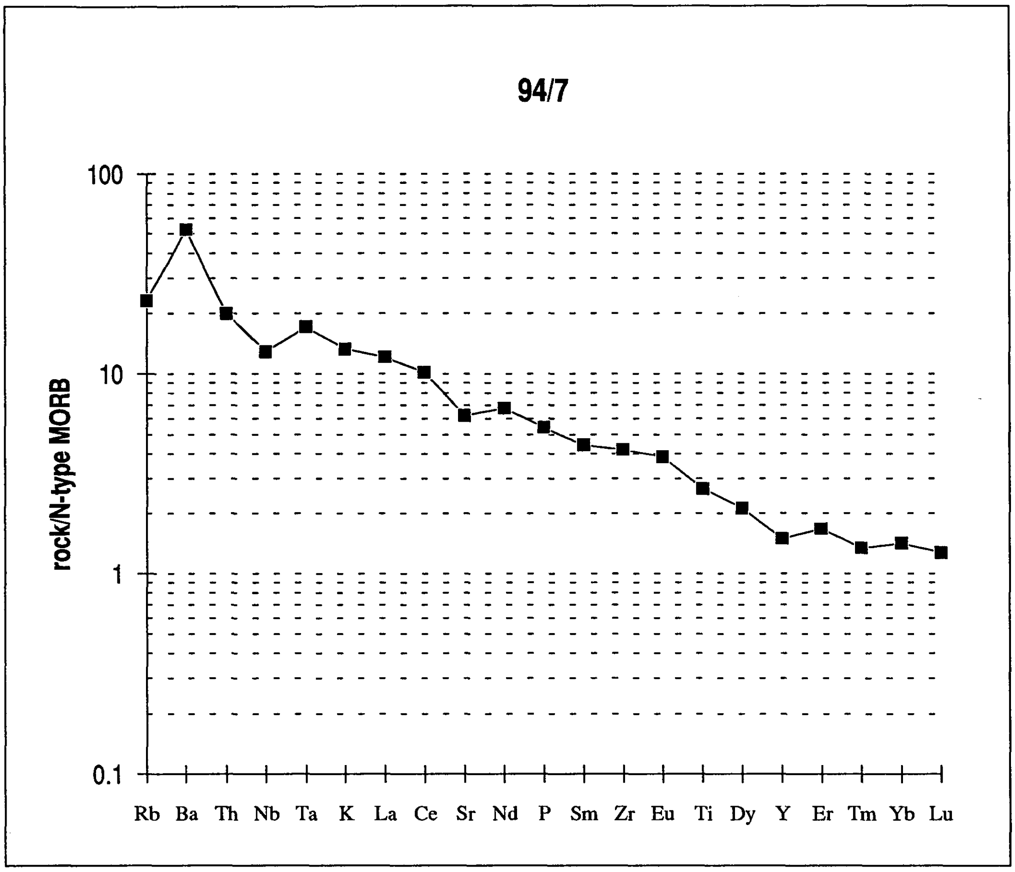


Fig. 11. Chondrite-normalised REE plots for basaltic rocks recovered from George Bligh Bank.



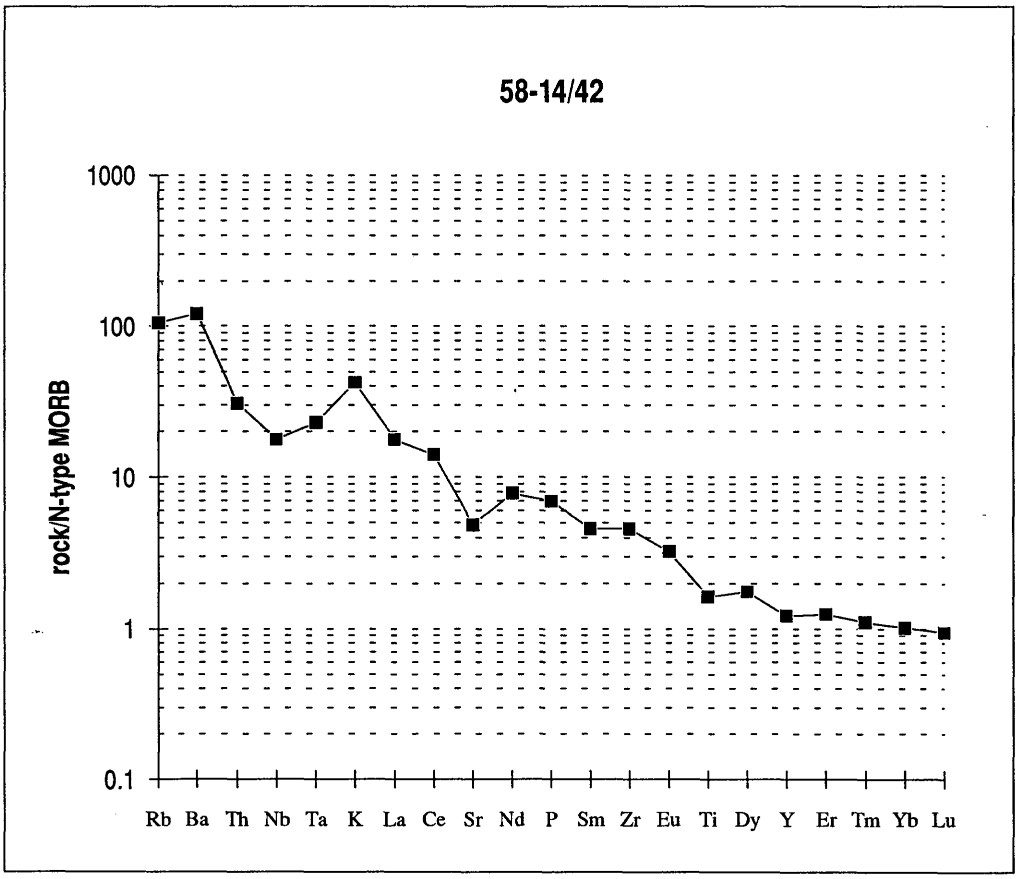
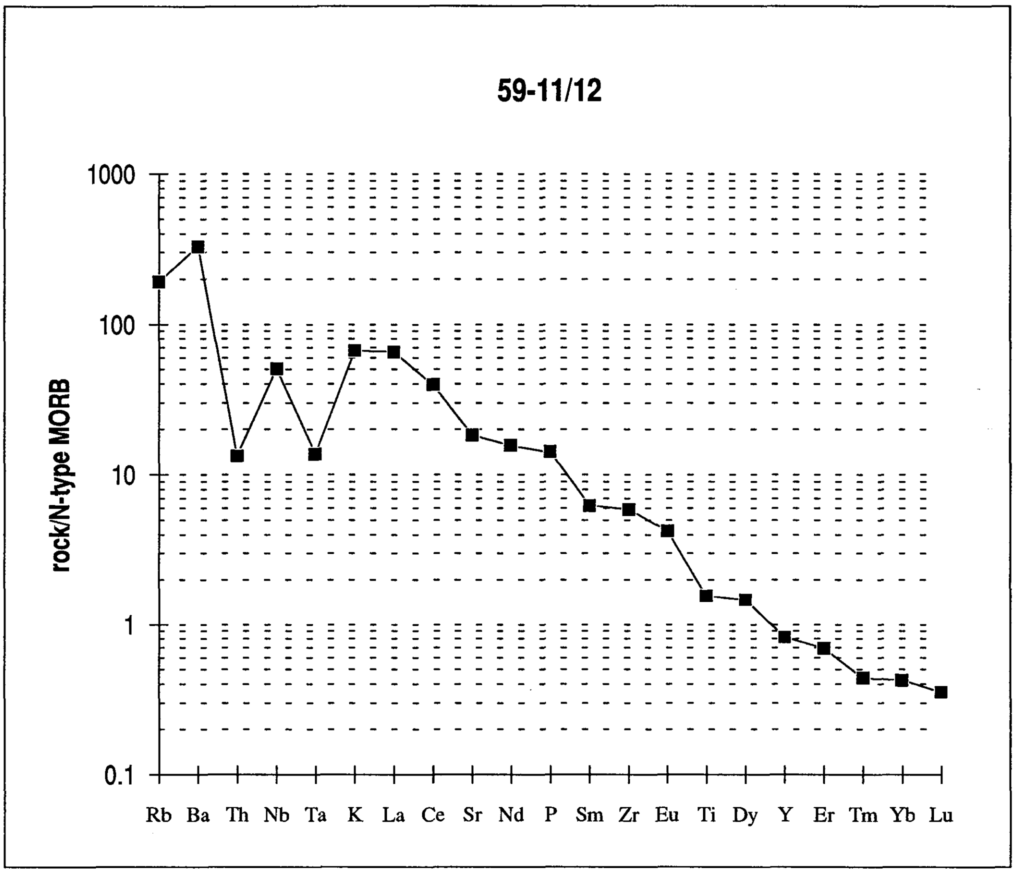


Fig. 12. MORB-normalised spidergrams for basaltic rocks recovered from George Bligh Bank.



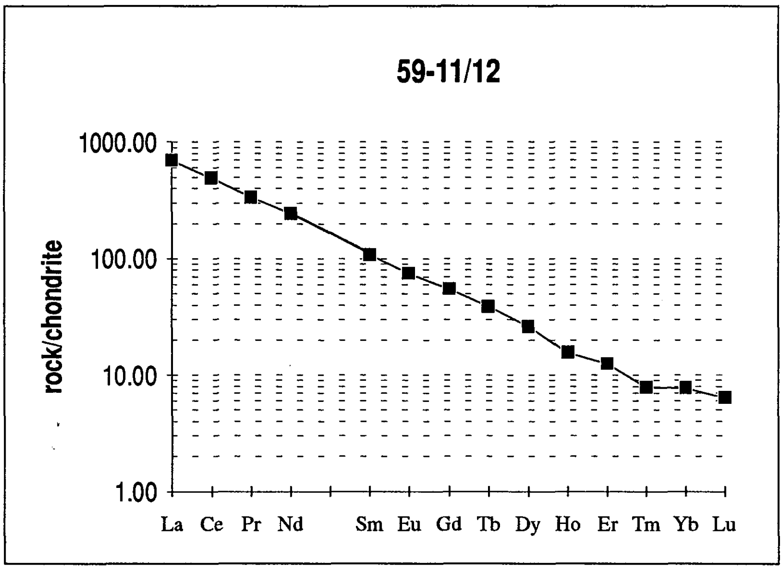
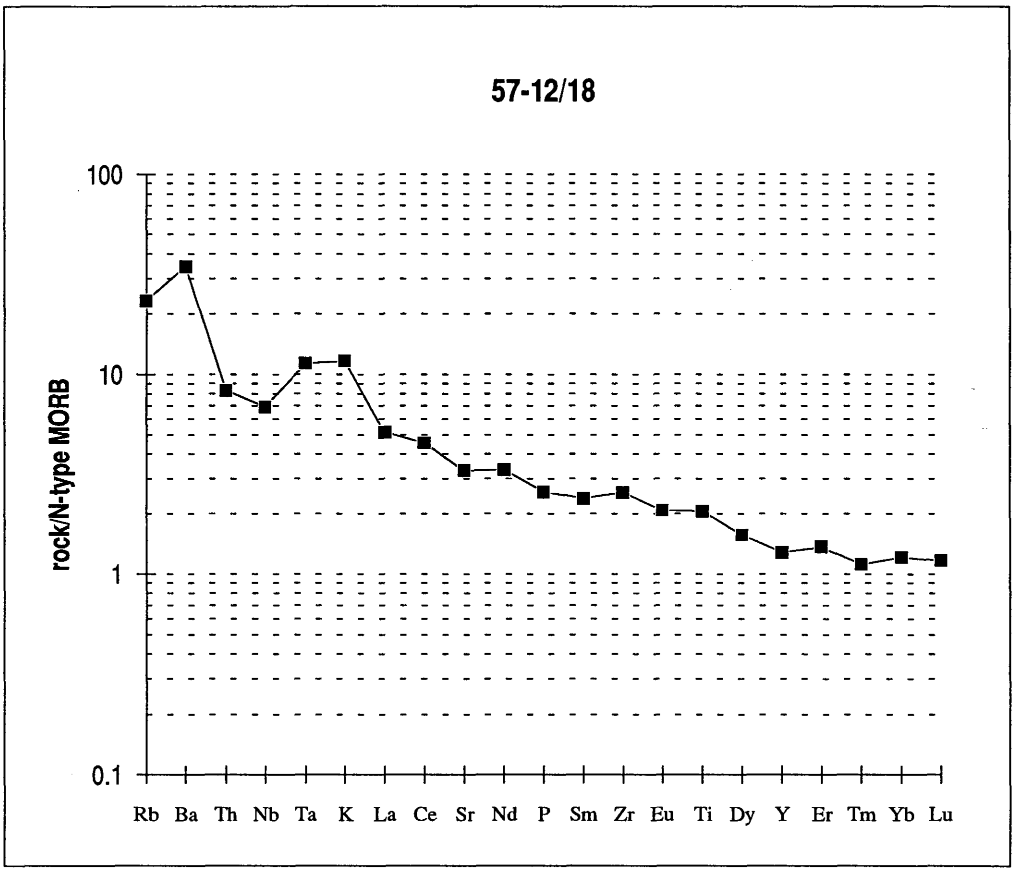


Fig. 13. MORB-normalised spidergram and chondrite-normalised REE plot of the phonotephrite from Rosemary Bank, 59-11/12.



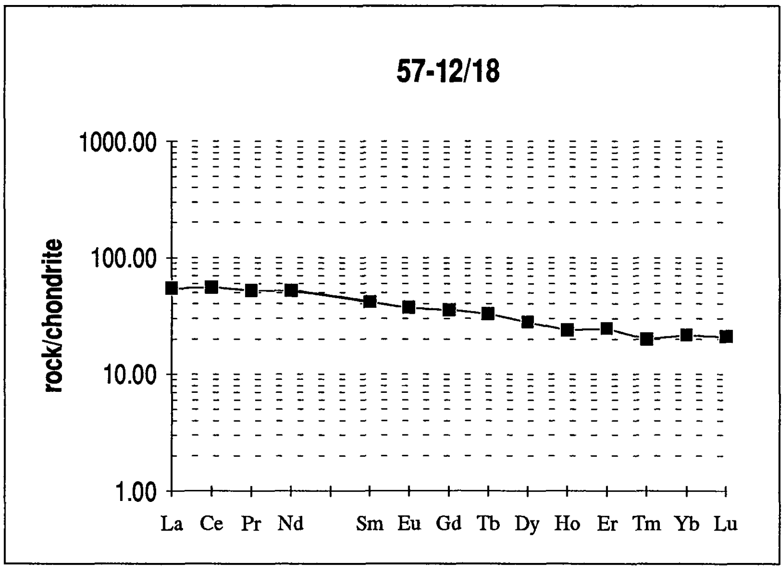


Fig. 14. MORB-normalised spidergram and chondrite-normalised REE plot of the basalt from Anton Dohrn Seamount, 57-12/18.

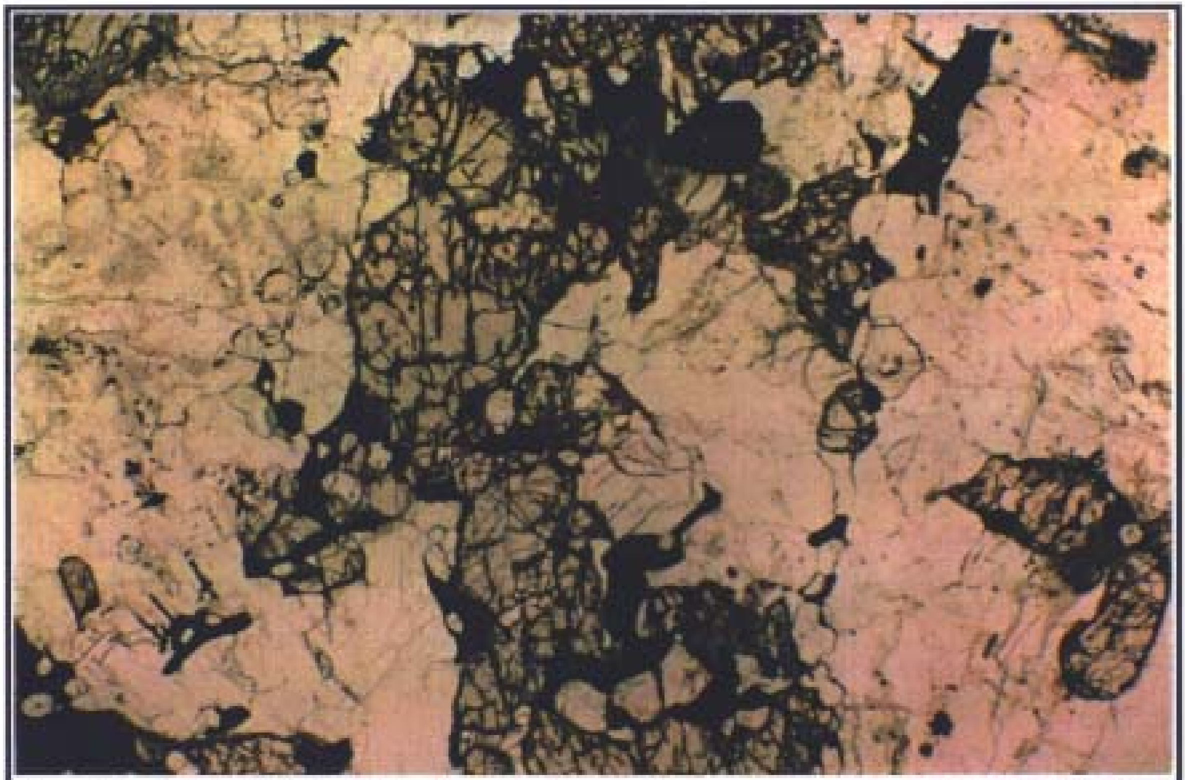


Plate 1. Gneiss, 56-15/12. Band of pale greenish-brown clinopyroxene, opaques and minor biotite set within leucocratic zone dominantly consisting of K-feldspar. Plane polars, x63.

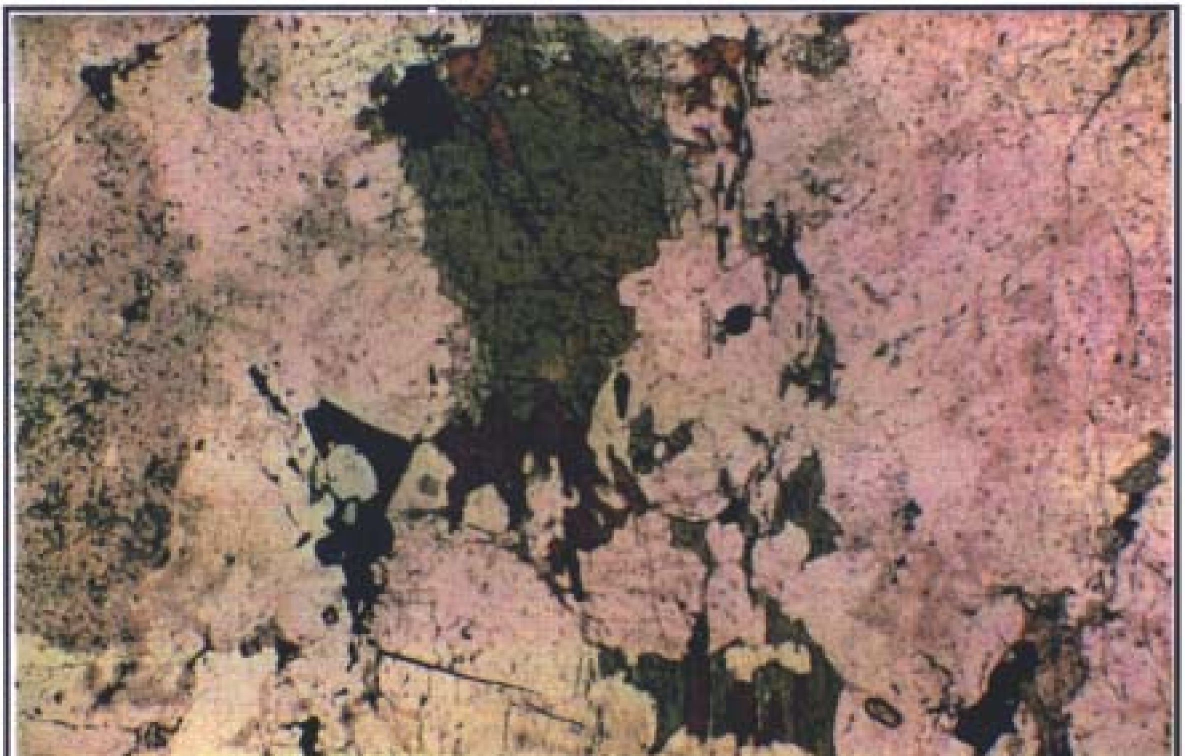


Plate 2. Gneiss, 56-15/12. View showing minor occurrence of green amphibole, intergrown with red-brown biotite. K-feldspar to right of frame is cloudy through alteration. Plane polars, x63.

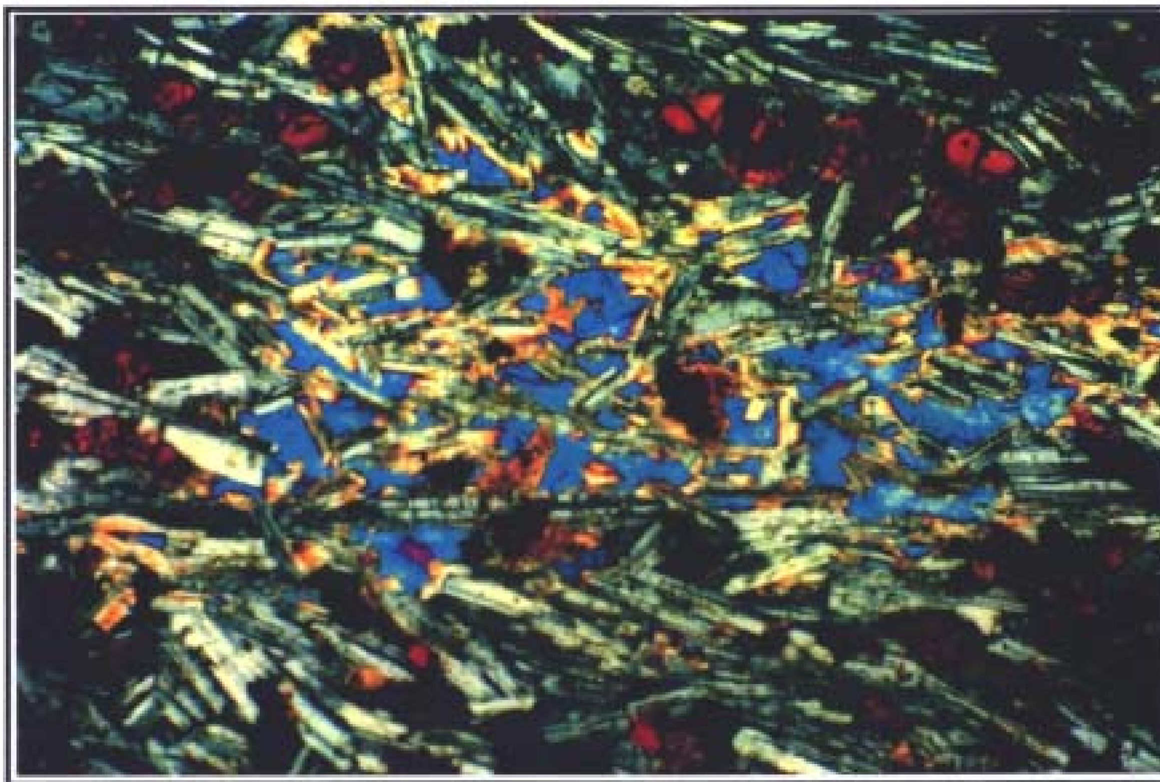


Plate 3. Basalt, 57-12/18. Ophitic clinopyroxene encasing trachytic plagioclase laths, opaques and altered ?olivine. Crossed polars, x160.

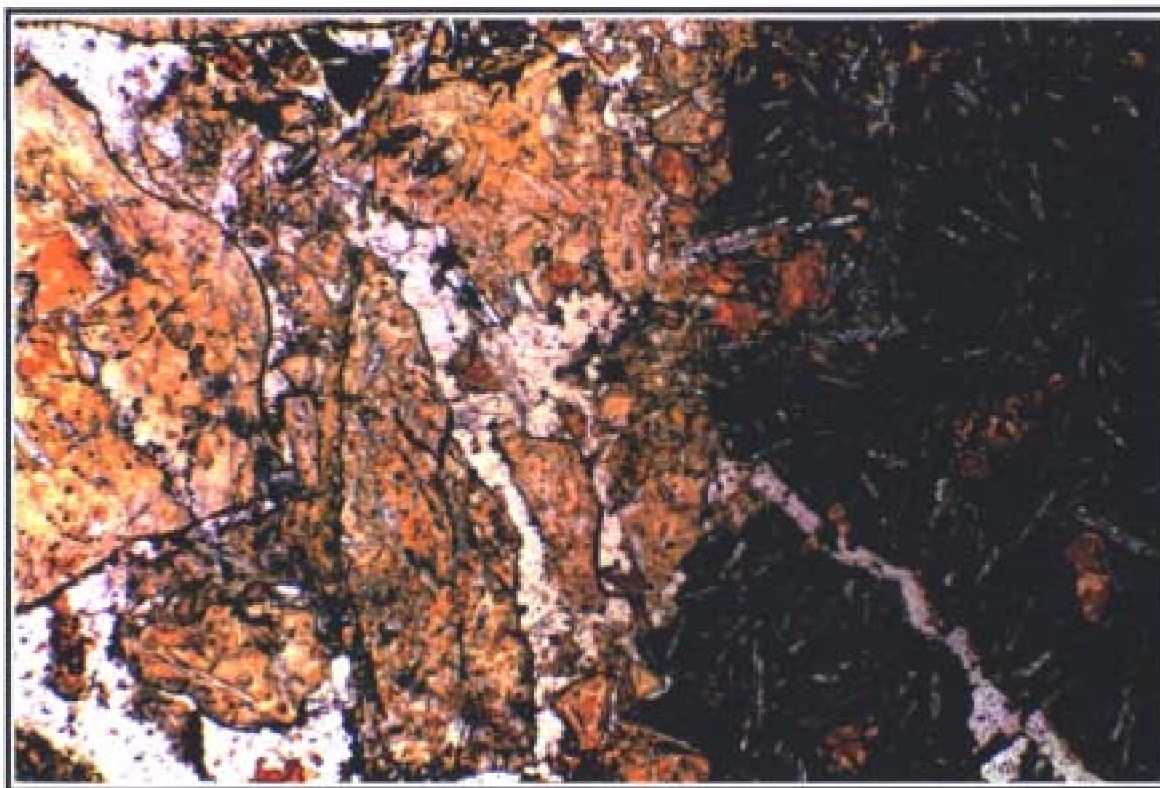


Plate 4. Basaltic agglomerate, 57-13/54. Pale brown, angular vitric clasts and larger, very dark lithic fragment set in clear secondary ?analcime. Plane polars, x63.

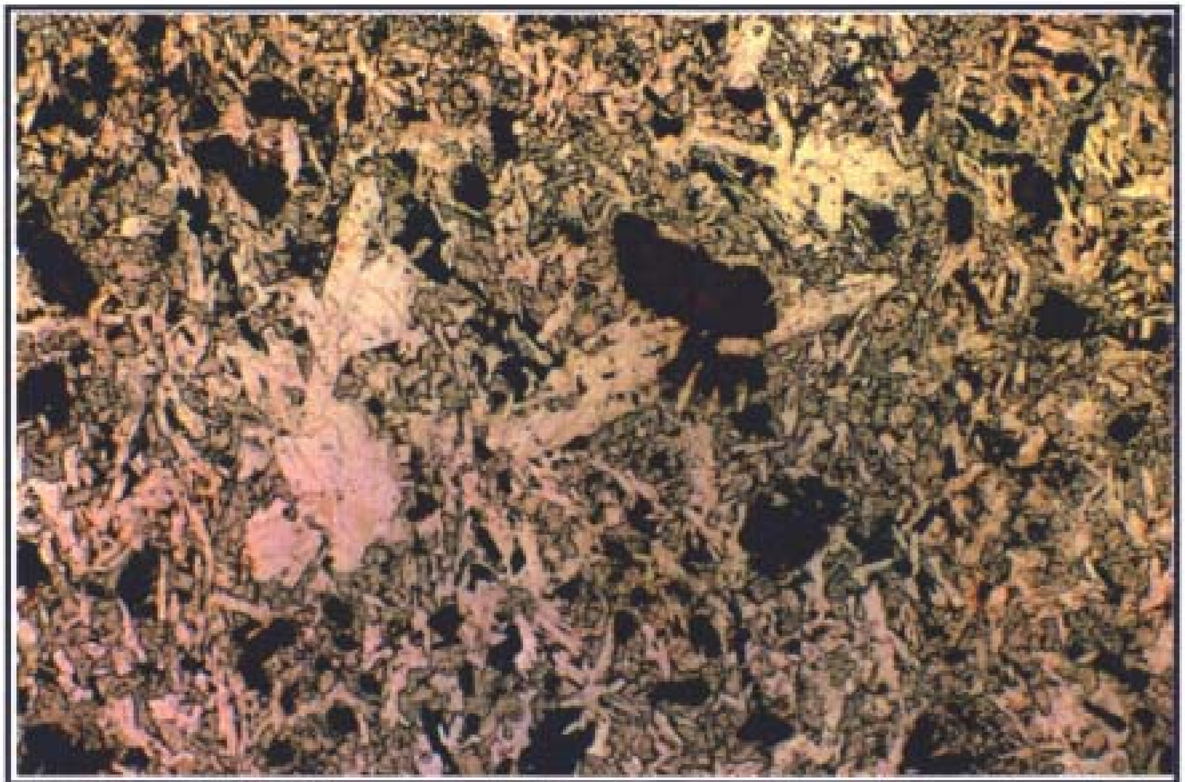


Plate 5. Basalt, 57-13/66. Glomerophyric plagioclase phenocrysts and brown olivine pseudomorphs set in groundmass of pale granular clinopyroxene, opaques and plagioclase laths. Plane polars, x63.

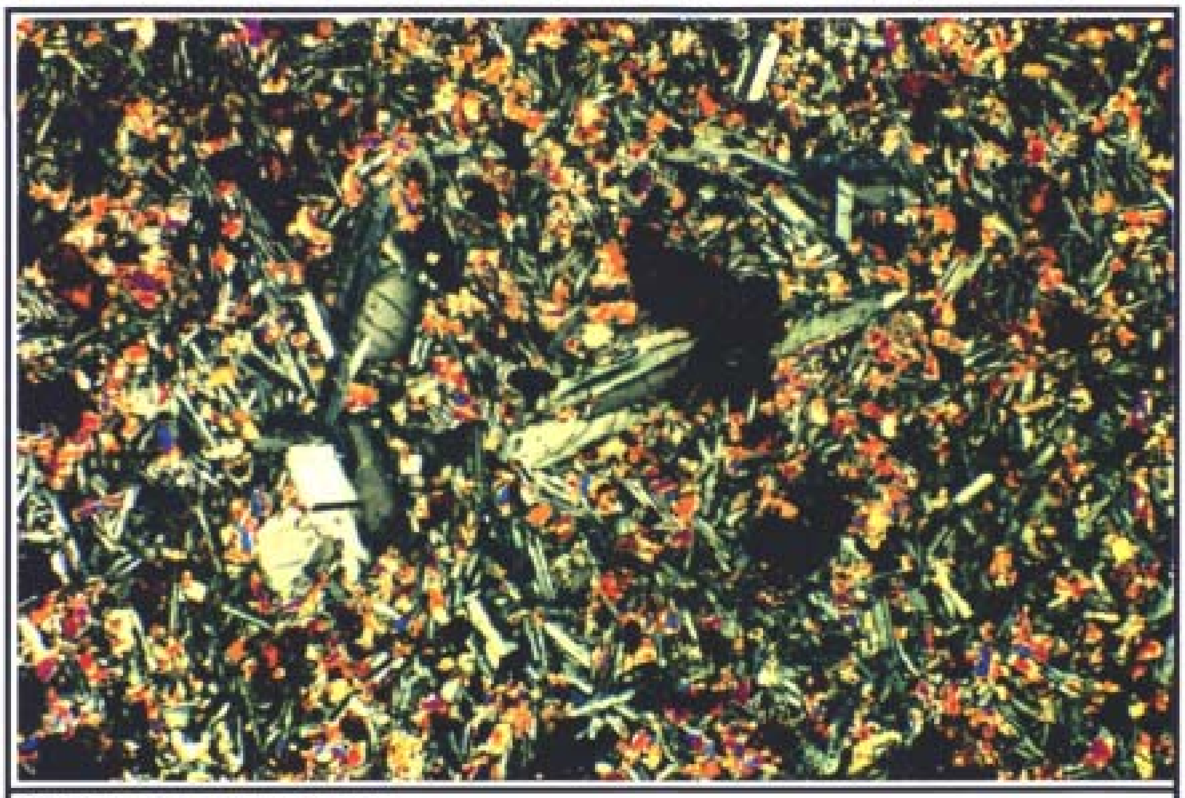


Plate 6. As plate 5, crossed polars.

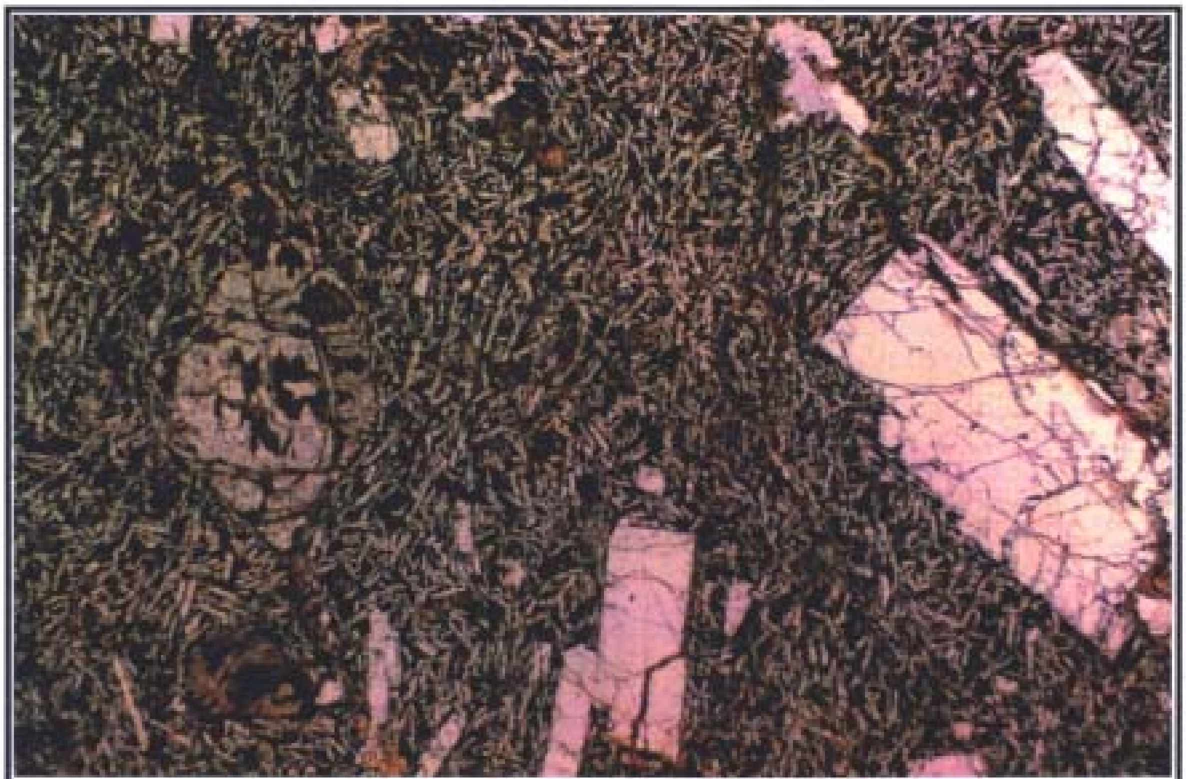


Plate 7. Plagioclase-phyric basalt, 57-14/52. General view showing plagioclase and altered olivine phenocrysts in a groundmass of plagioclase laths, opaques and altered glass. Plane polars, x25.

Plate 8. Plagioclase-phyric basalt, 57-14/52, showing alignment of plagioclase laths (trachytic texture). Plane polars, x63.

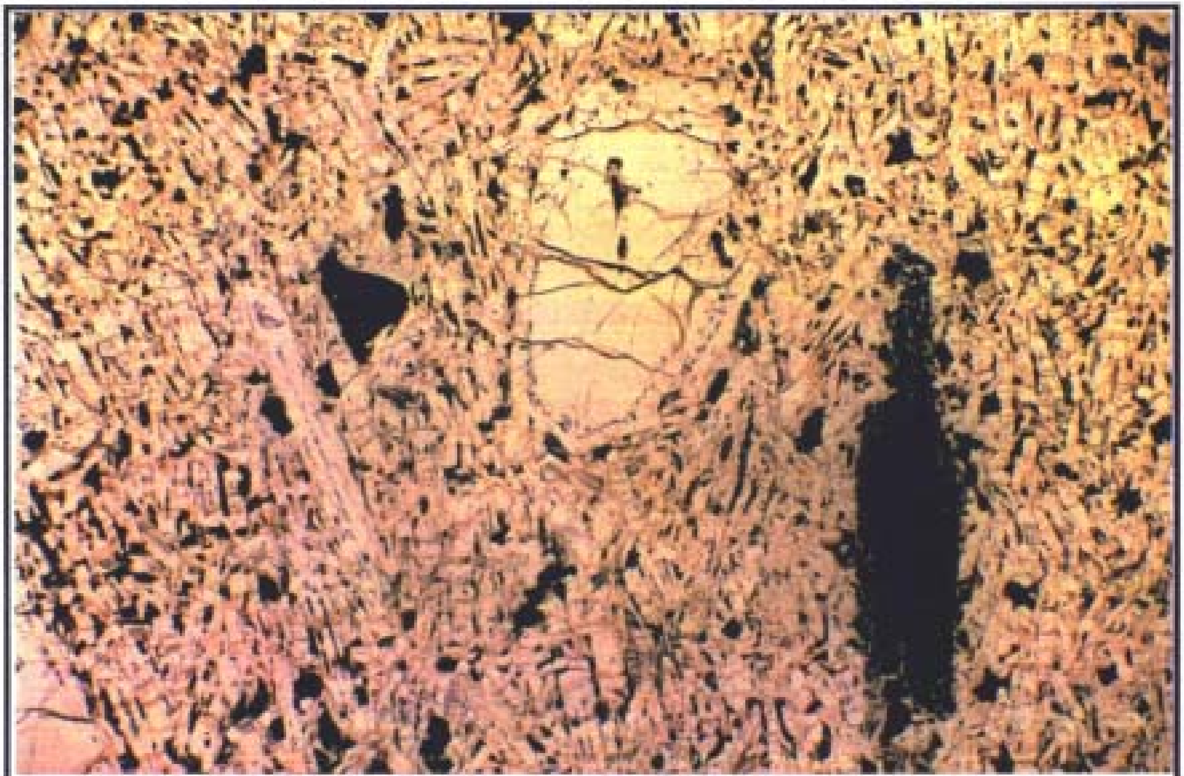


Plate 9. Trachyte, 57-14/53. Dominated by feldspar, both as groundmass and minor phenocryst phases. Large cluster of opaques (towards right) is altered biotite. Plane polars, x63.

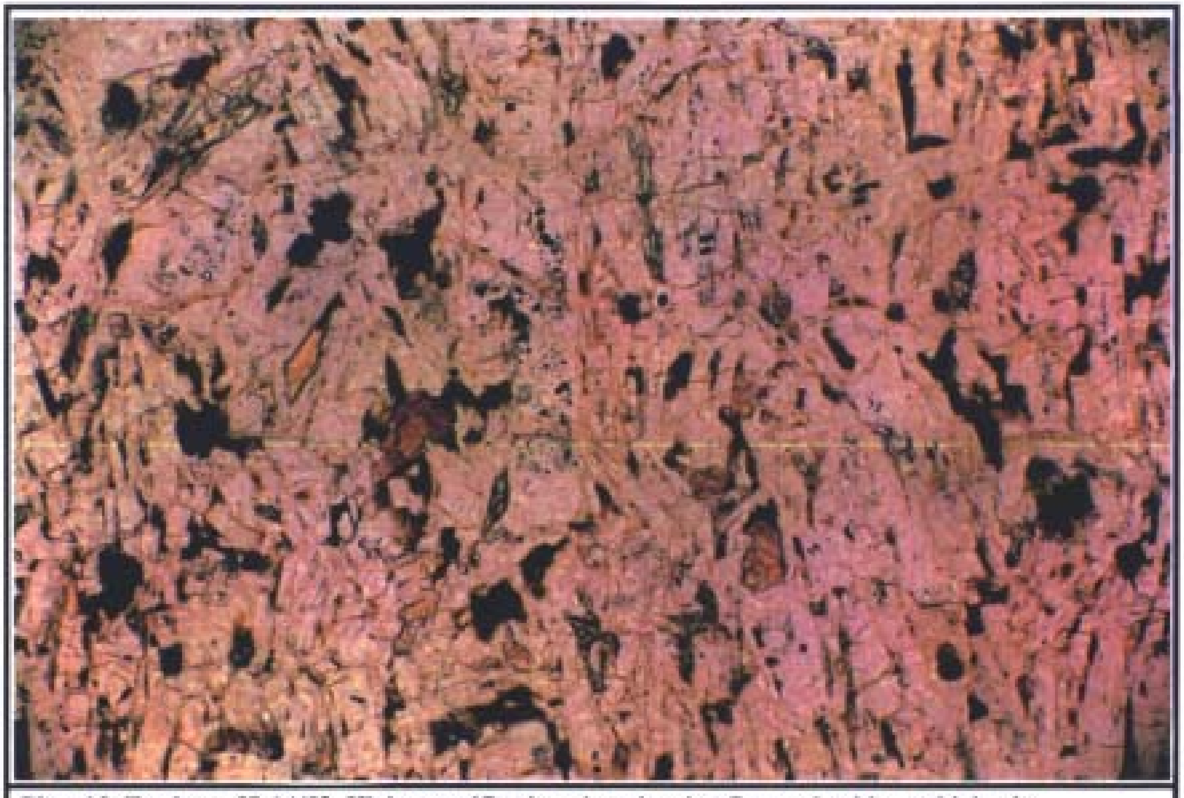


Plate 10. Trachyte, 57-14/53. High-magnification view showing fine-grained interstitial pale brown ?amphibole and pale green ?clinopyroxene. Plane polars, x160.

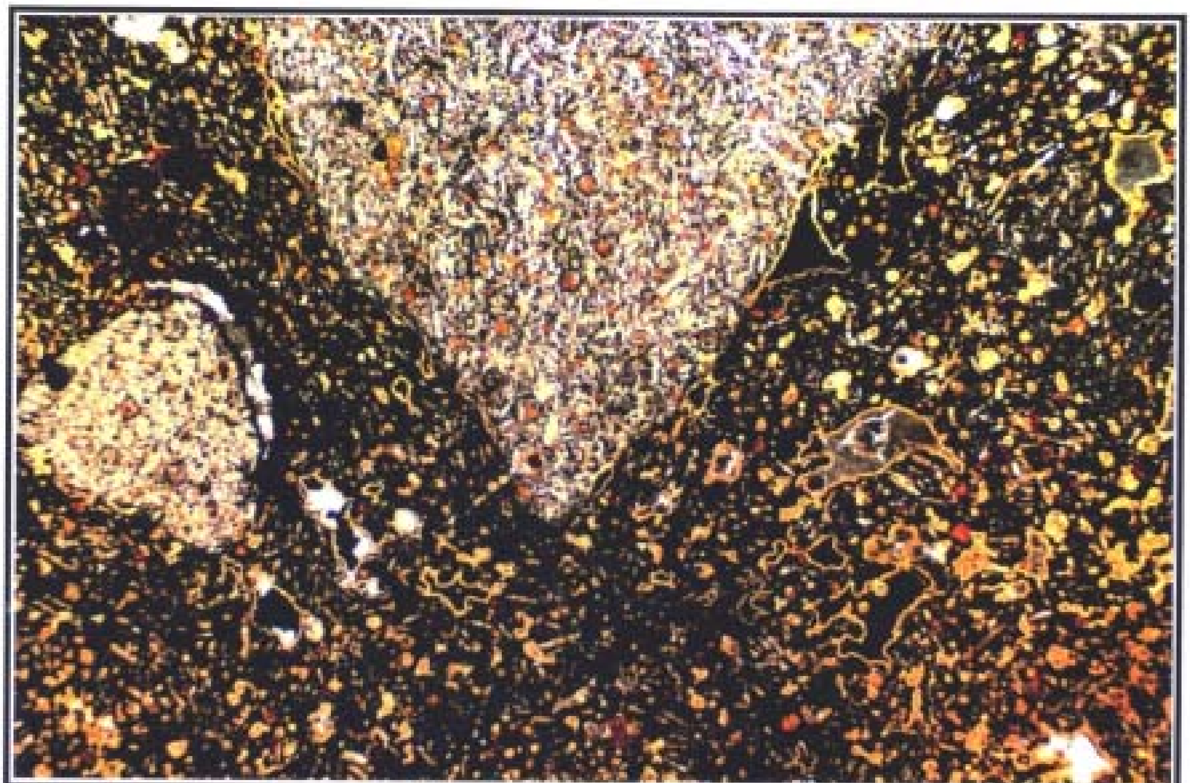


Plate 11. Basaltic agglomerate, 58-14/8. General view showing subangular lithic basaltic clast set in highly altered and highly vesicular glassy framework. Plane polars, x25.

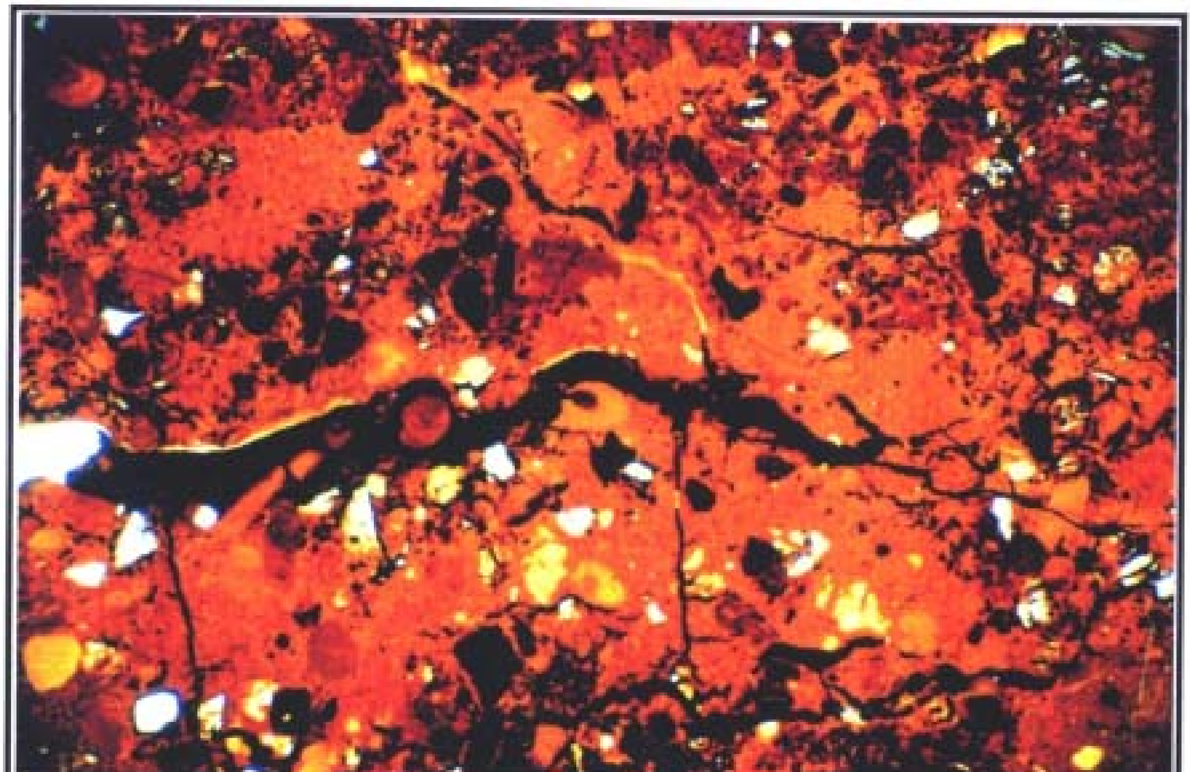


Plate 12. Iron/manganese alteration zone, 58-14/31. Deep red-brown crust developed on limestone due to seafloor weathering. Ghosts of glaucony and bioclasts can be observed. Plane polars, x63.

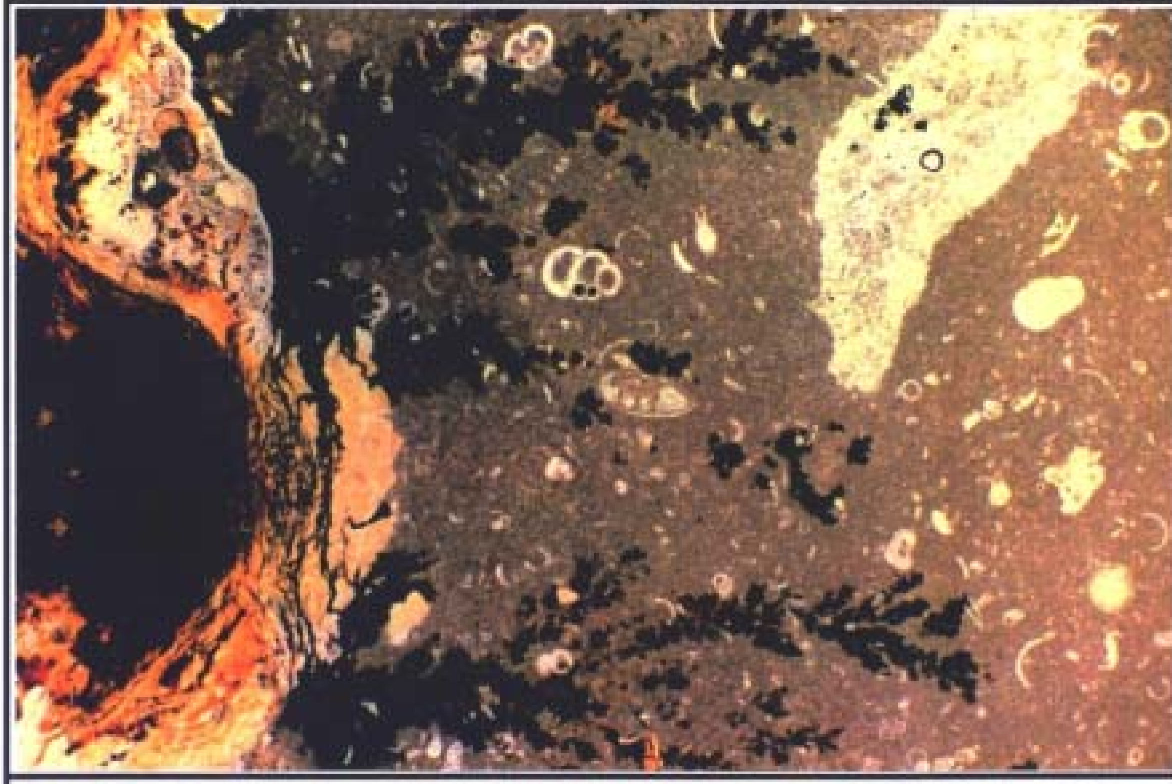


Plate 13. Iron/manganese alteration zone, 58-14/31. View shows interface between limestone and weathered zone, with dendritic development extending into limestone. Plane polars, x63.

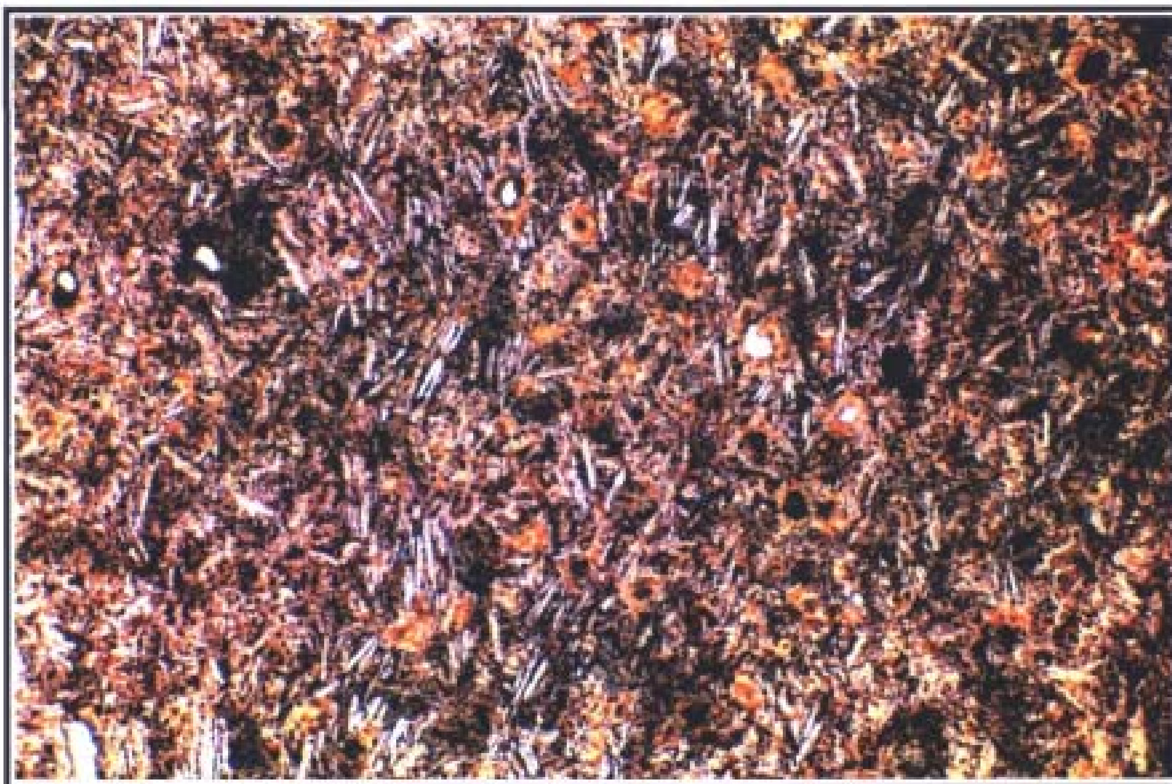


Plate 14. Benmoreite, 58-14/42. General view showing its very fine grained, sparsely vesicular nature. Plagioclase laths show a subtrachytic texture. Plane polars, x63.

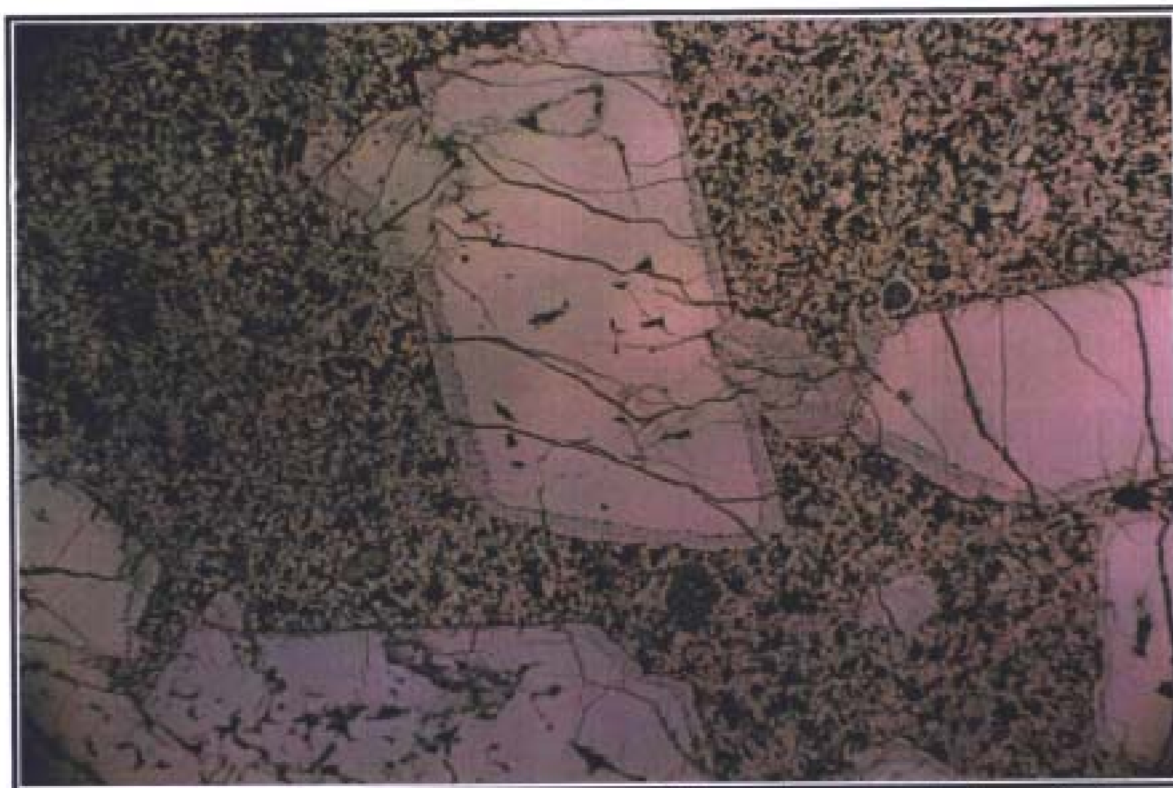


Plate 15. Feldspar-phyric trachyte, 58-14/51. Large zoned feldspar phenocrysts set in finer-grained feldspar-pyroxene-opaque groundmass, with altered interstitial glass. Plane polars, x25.

Plate 16. Feldspar-phyric trachyte, 58-14/51. Partially resorbed ?basalt xenolith. Plane polars, x160.

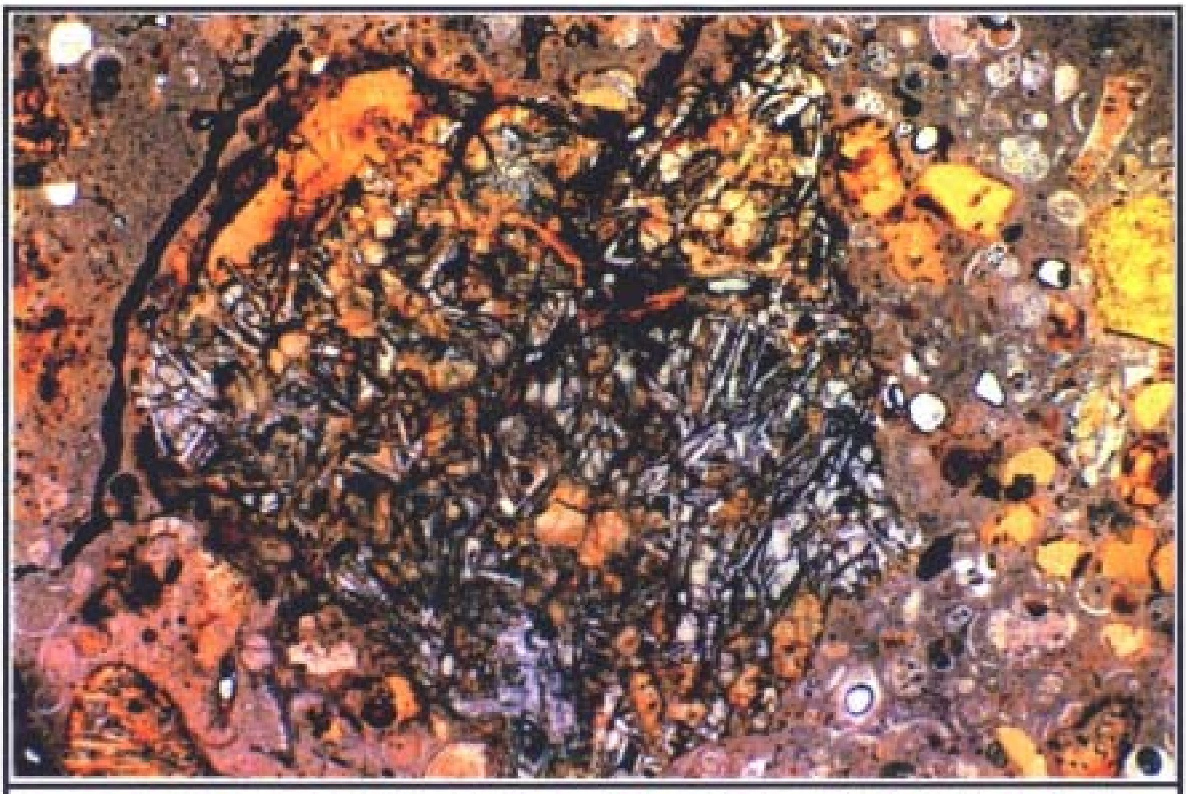


Plate 17. Conglomerate, 58-14/57. Partially glauconitised basaltic clast set in glauconitic bioclastic limestone. Plane polars, x63.

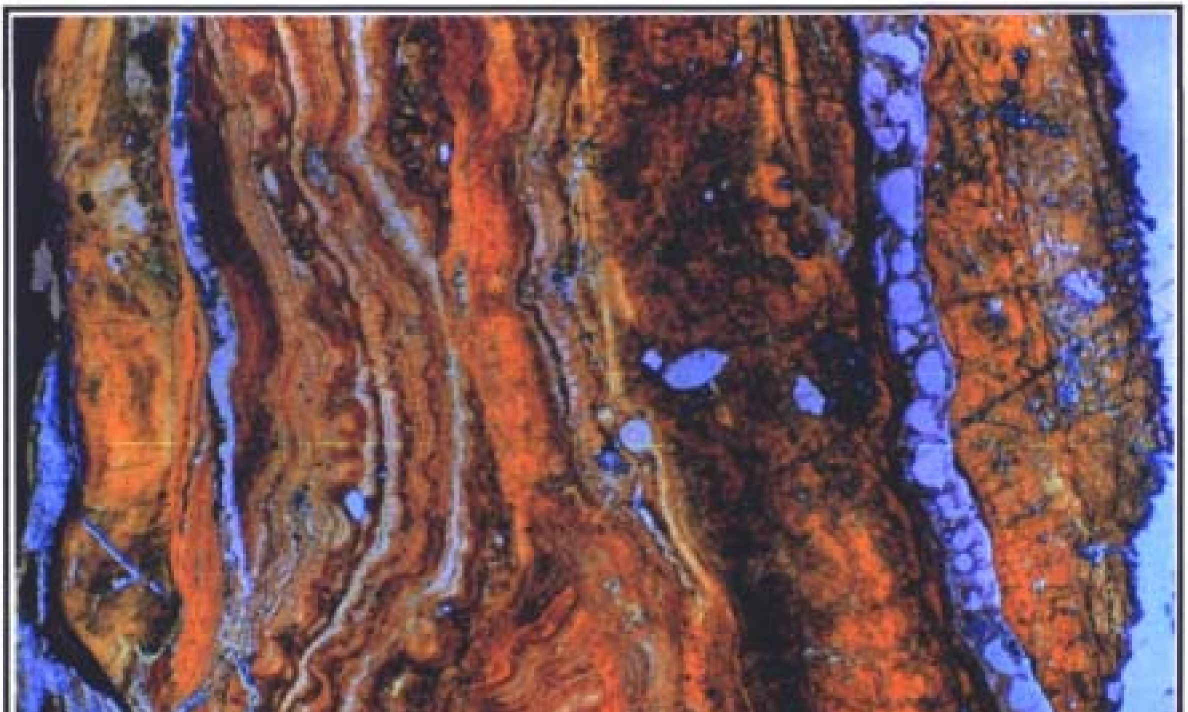


Plate 18. Conglomerate, 58-14/57. Ferroan crust resulting from seafloor weathering processes. Glaucony horizon near top (right frame) marks interruption of weathering. Plane polars, x63.

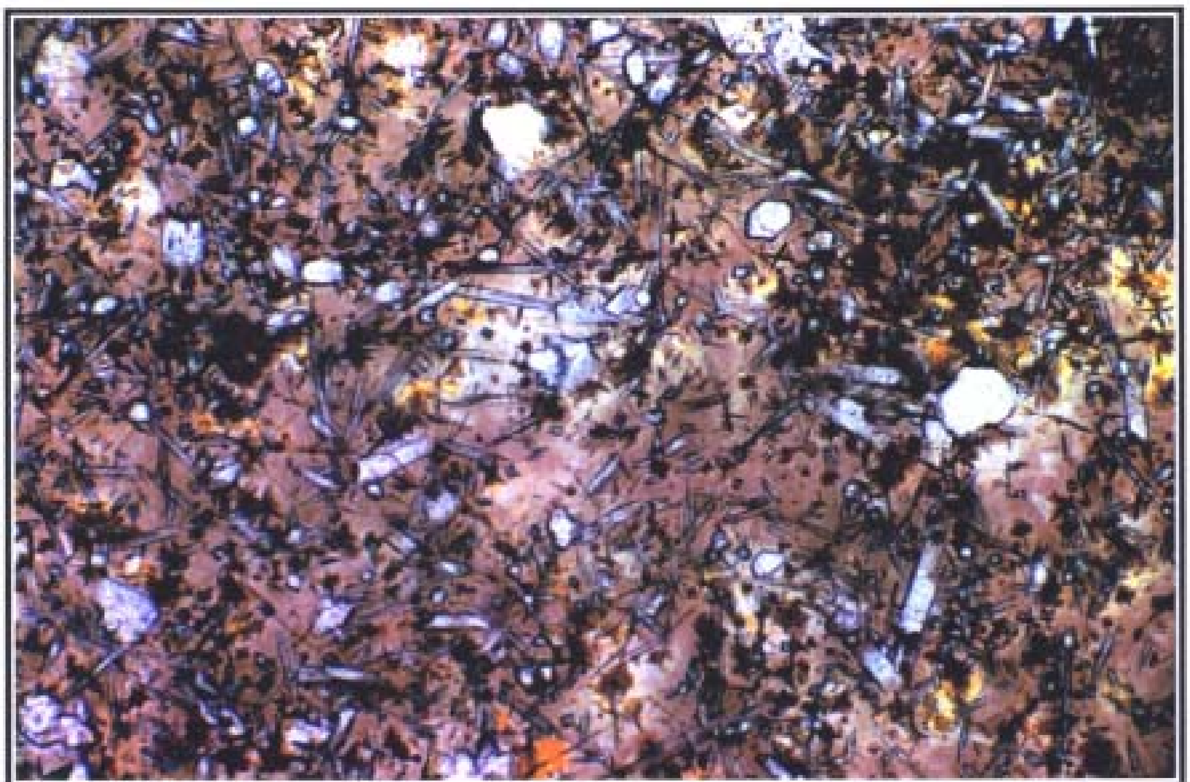


Plate 19. Phono-tephrite, 59-11/12. Consisting of elongate to acicular clinopyroxene in pinkish brown isotropic glass. Yellow patches and darker areas represent greater alteration. Plane polars, x160.

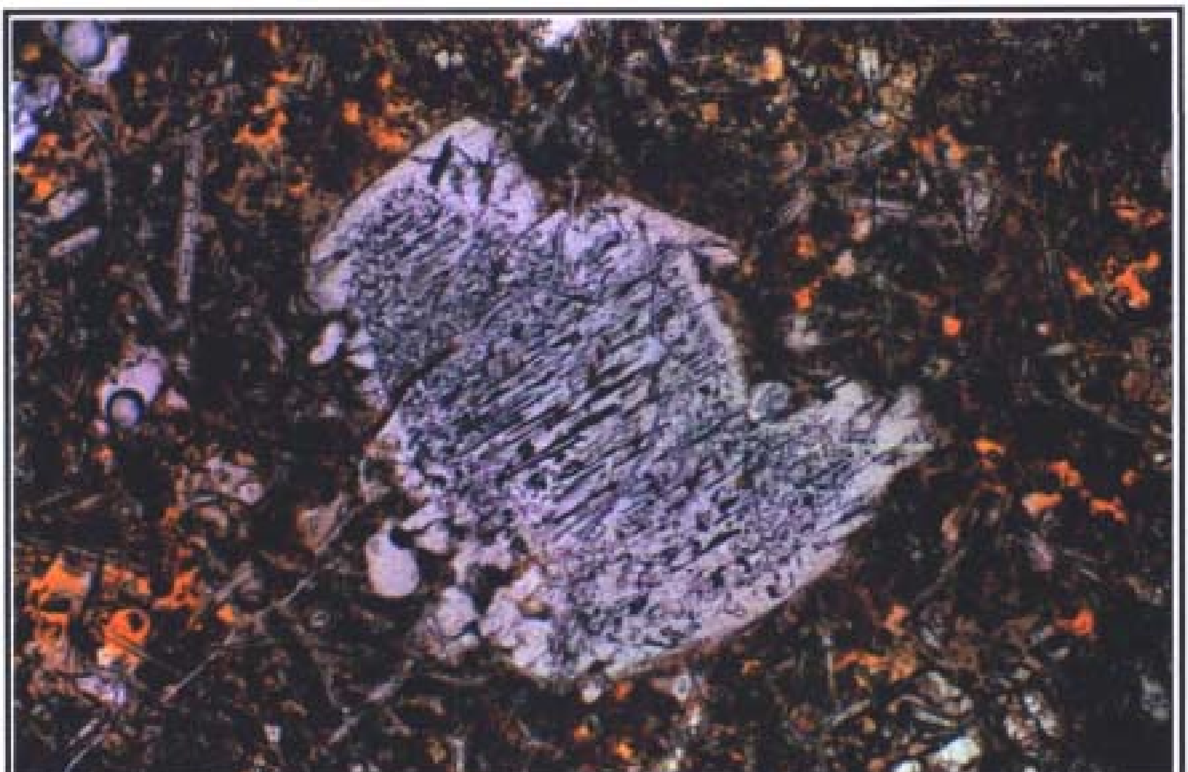


Plate 20. Phono-tephrite, 59-11/12. Rare clinopyroxene phenocryst, showing inner ?altered core and outer clear zone probably with similar composition to elongate/acicular pyroxene. Plane polars, x160.

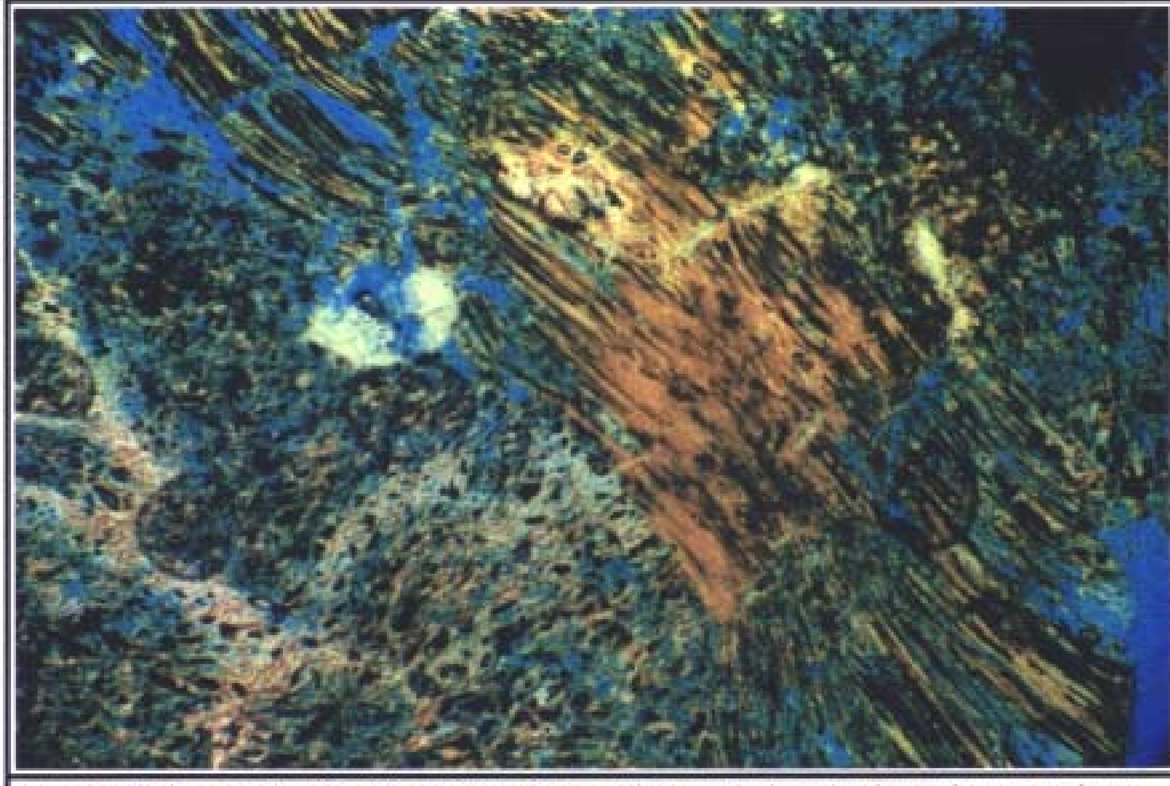


Plate 21. Vitric andesitic tuff, 94/3, 112.50-112.54 m. Highly vesicular colourless to brown pumiceous shards and minor feldspar phenocrysts. Blue dye impregnation shows high porosity. Plane polars, x160.

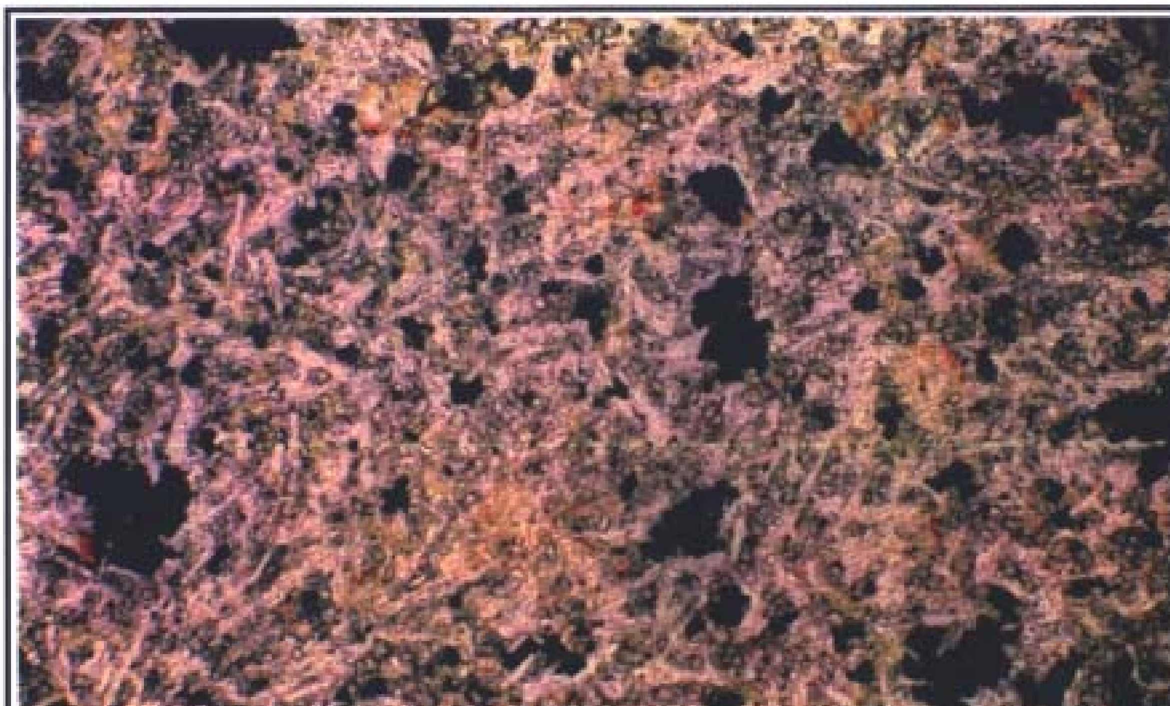


Plate 22. Basalt pebble, 94/3, 171.14-171.20 m. General view showing fine-grained nature, lack of trachytic texture and colourless granular pyroxene. Plane polars, x160.

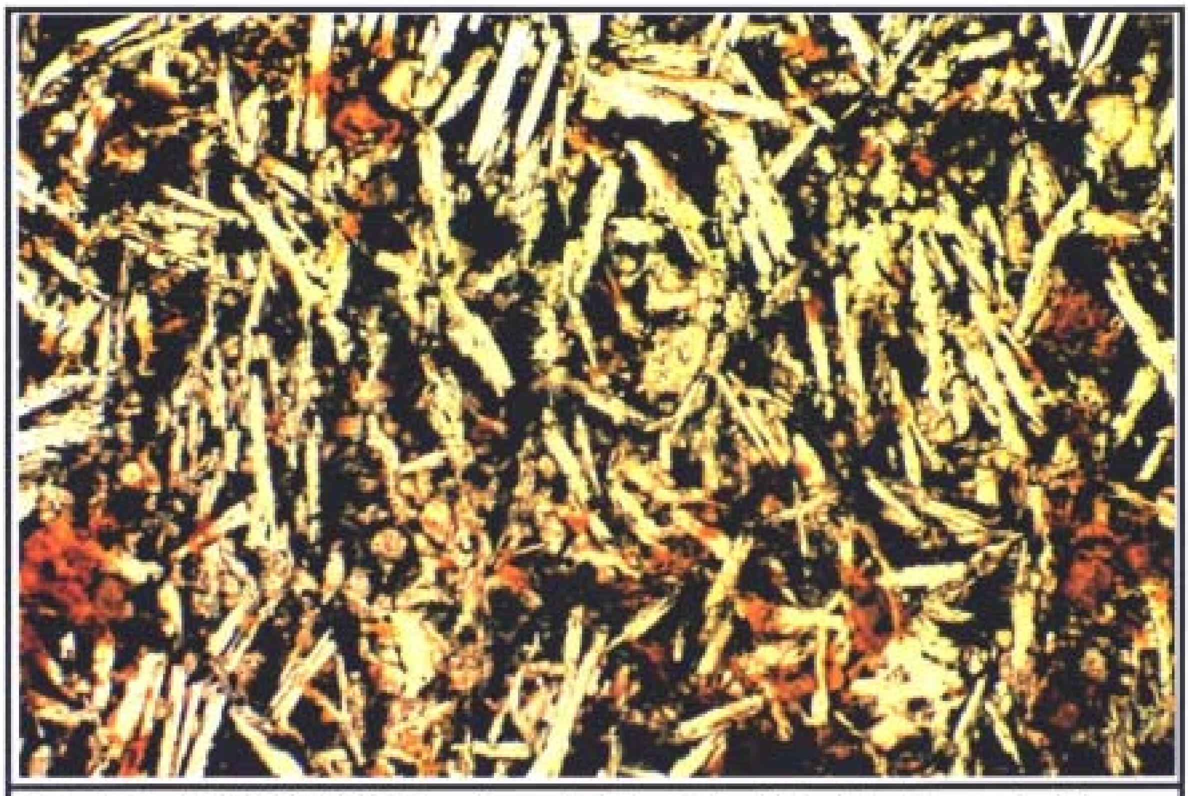


Plate 23. Basalt, 94/3, 208.12-208.15 m. Shows plagioclase laths with trachytic texture and pale brown clinopyroxene in highly altered groundmass. Plane polars, x160.

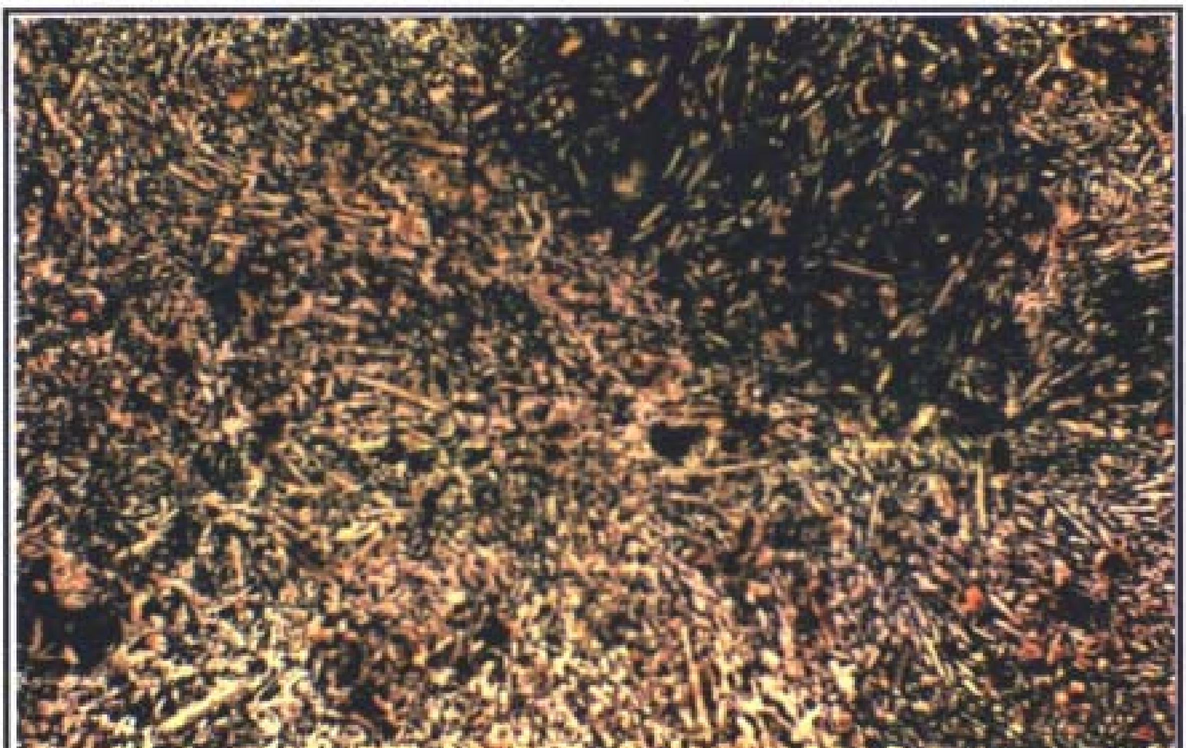


Plate 24. Hawaiite, 94/5, 29.21-29.25 m. General view showing very fine grained nature and textural inhomogeneity due to partial resorbtion of slightly coarser basalt clasts. Plane polars, x63.

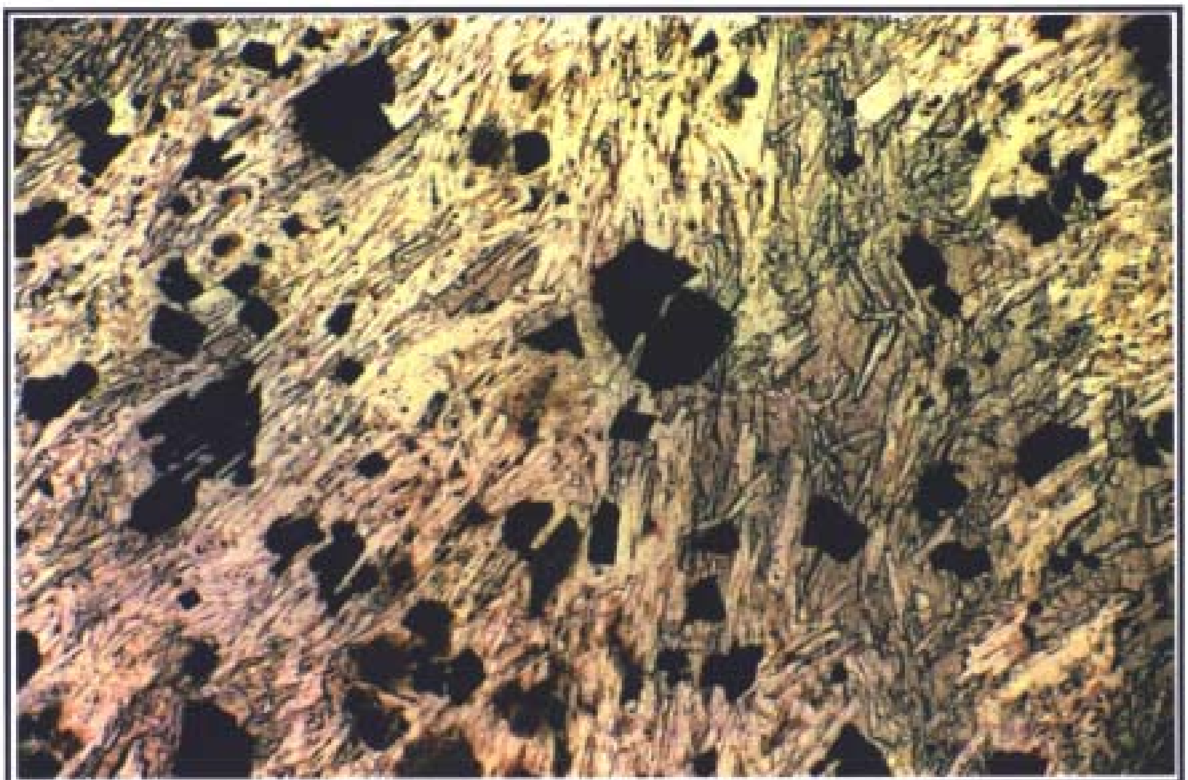


Plate 25. Hawaiite, 94/7, 22.25-22.57 m. Showing ophitic clinopyroxene, opaques and trachytic plagioclase laths. Plane polars, x160.

BRITISH GEOLOGICAL SURVEY

MARINE REPORT SERIES
TECHNICAL REPORT WB/95/11C
VOLUME 5: APPENDIX 5
COMMERCIAL-IN-CONFIDENCE

ROCKALL CONTINENTAL MARGIN PROJECT
FINAL GEOLOGICAL REPORT

TECHNICAL REPORT WB/95/11C
VOLUME 5: APPENDIX 5
SEISMIC LINES AND GRAVITY AND MAGNETIC MAPS

K Hitchen

Geographical index:
Hebrides Shelf, Rockall Trough, Rockall Bank, George Bligh Bank, Rosemary Bank and Anton Dohrn seamounts.

Subject index:
Multichannel Seismic Reflection Profiles, Bouguer Gravity Data, Marine Magnetic Data

Production of report was funded by:
BGS and a consortium of Oil Companies

Bibliographic reference:
Hitchen, K. 1995. Seismic Lines and Gravity and Magnetic Maps. Volume 5, Appendix 5 of Stoker, M S, and Hitchen, K. 1995. Rockall Continental Margin Project: Final Geological Report. *British Geological Survey Technical Report* WB/95/11C.

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EH9 3LA

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EXPLANATORY NOTES

Seismic profiles D2 and D15

Two seismic profiles from the 'grid' area (sub-area A), on the western margin of the Rockall Trough (for location see Fig 1.2, volume 1), have been selected to illustrate the geology of the area.

Line D2 is a strike line parallel to the eastern margin of Rockall Bank. The line is clear of lower Tertiary lavas (hence reflector D is not seen) but shows many sills intruded into the presumed Upper Cretaceous succession. These tend to mask reflections from deeper levels.

Line D15 is a dip line from Rockall Bank into Rockall Trough. It illustrates the major basin-bounding fault, the limit of the lower Tertiary basalts and numerous sills.

Both lines illustrate the major, early late Eocene, basin-wide unconformity (reflector C, yellow) and the more areally-restricted, and slightly younger reflector B (turquoise). Reflector A (mid-Miocene) is not imaged on these data as it is too close to the sea bed.

From:
Hitchen, K. 1995. Seismic Lines and Gravity and Magnetic Maps. Volume 5, Appendix 5 of Stoker, M. S. and Hitchen, K. 1995. Rockall Continental Margin Project: Final Geological Report. *British Geological Survey Technical Report* WB/95/11C.

Reflector A (mid-Miocene)
(not resolved in this data)

Reflector B Late late Eocene

Reflector C Early late Eocene

Reflector D Top Basalt
(Late Paleocene-Early Eocene)

Igneous intrusions

Possible fluid migration structures

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Reflector A (mid-Miocene) (not resolved in this data)

Reflector B Late late Eocene

Reflector C Early late Eocene

Reflector D Top Basalt (Late Paleocene-Early Eocene)

Igneous intrusions

Possible fluid migration structures

Gravity map

This is compiled from data acquired for this study on the 1992 and 1993 seismic acquisition cruises, the data purchased from Mobil and some BGS data in the region east of 10°W. A regional field (dashed contours) has been removed to compensate for the thinning of the crust under the Rockall Trough.

Gravity highs are associated with the Anton Dohrn and Geikie igneous complexes, an intrusion within the George Bligh Bank and the metamorphic basement of Rockall Bank. The N-S aligned gravity high in the centre of the Rockall Trough, north of Anton Dohrn, may be due to highly intruded and attenuated crust which almost reached the rifting stage. The gravity low at approximately 57°N 13°45'W is coincident with the eastern side of Rockall Bank and may be caused by a sub-basalt sedimentary succession.

Magnetic map

This is compiled solely from the data acquired on the 1992 seismic acquisition cruise. There is little control on the pattern of the anomalies at the eastern edge of the map.

Trends of anomalies, aligned NW-SE across the Rockall Trough, can be observed. These may reflect the deep structure of the basin (?terrane boundary, ?transfer faults). The pattern of the anomalies does not coincide with the limit of the basalts as mapped from seismic data.

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ROCKALL CONTINENTAL MARGIN PROJECT

FILTERED MIGRATION

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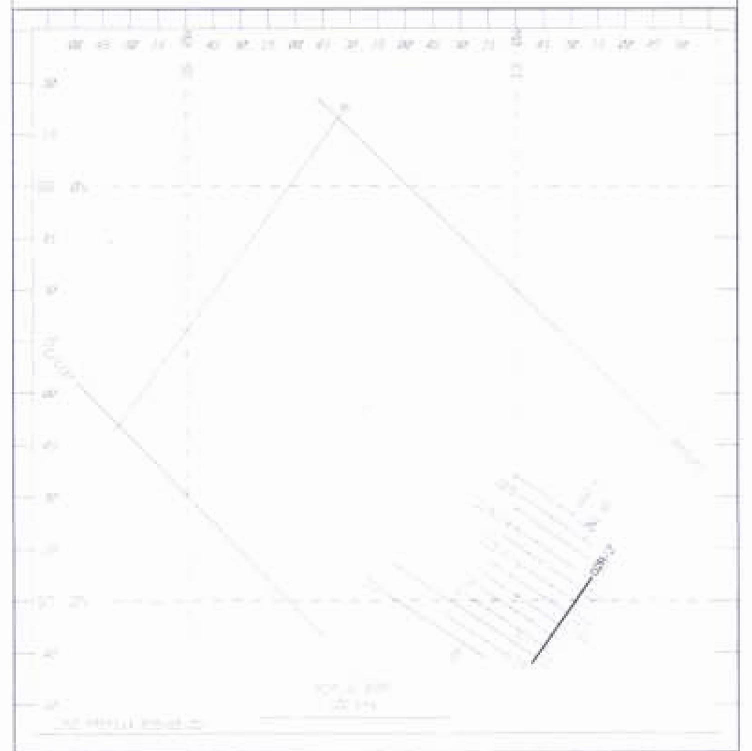
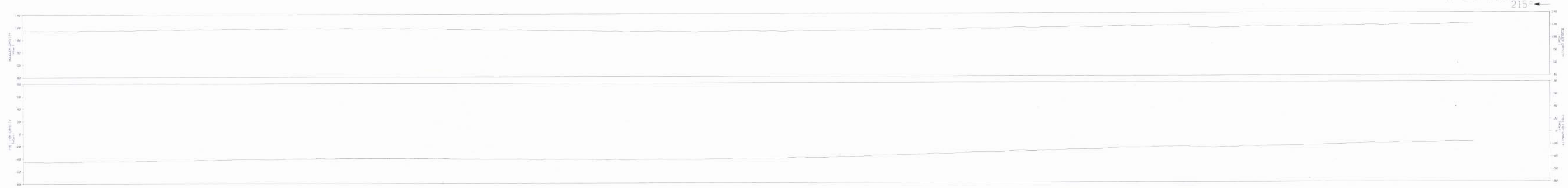
SP RANGE : 2427-555/555-101
DIRECTION : 215°





From:
Hitchen, K. 1995. Seismic Lines and Gravity and Magnetic Maps. Volume 5, Appendix 5 of Stoker, M. S. and Hitchen, K. 1995. Rockall Continental Margin Project: Final Geological Report. *British Geological Survey Technical Report* WB/95/11C.

Reflector A (mid-Miocene) (not resolved in this data)
Reflector B Late late Eocene
Reflector C Early late Eocene
Reflector D Top Basalt (Late Paleocene-Early Eocene)
Igneous intrusions
Possible fluid migration structures

WATER DEPTHS UNRELIABLE

British Geological Survey

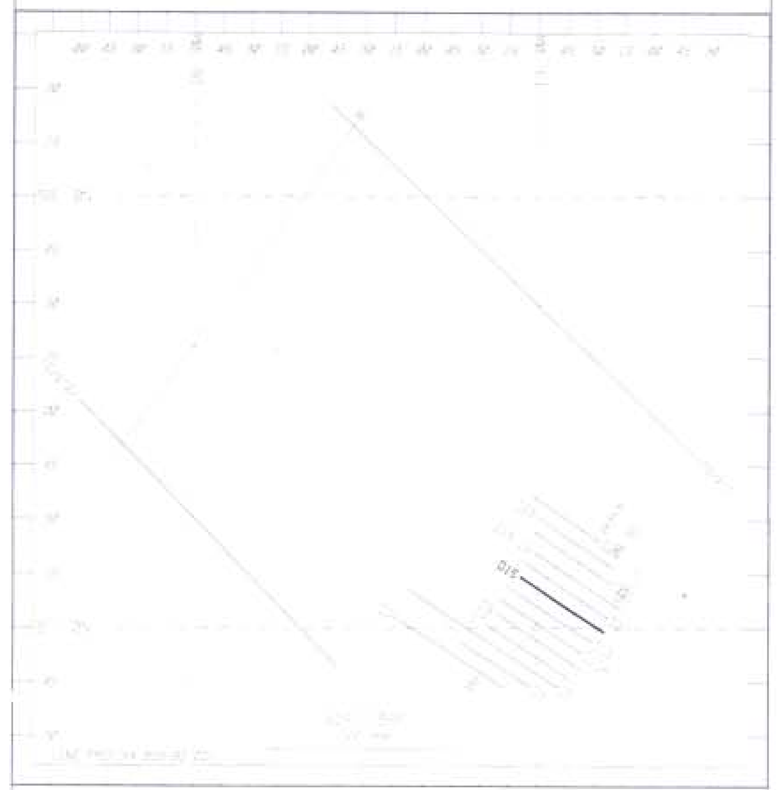
ROCKALL CONTINENTAL MARGIN PROJECT

FILTERED MIGRATION

LINE : BGS-93/02-015

SP RANGE : 101 - 2225

DIRECTION : 124°



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Bibliographic reference:
Hitchen, K. 1995. Seismic Lines and Gravity and Magnetic Maps. Volume 5, Appendix 5 of Stoker, M S, and Hitchen, K. 1995. Rockall Continental Margin Project: Final Geological Report. *British Geological Survey Technical Report* WB/95/11C.

Reflector A (mid-Miocene) (not resolved in this data)

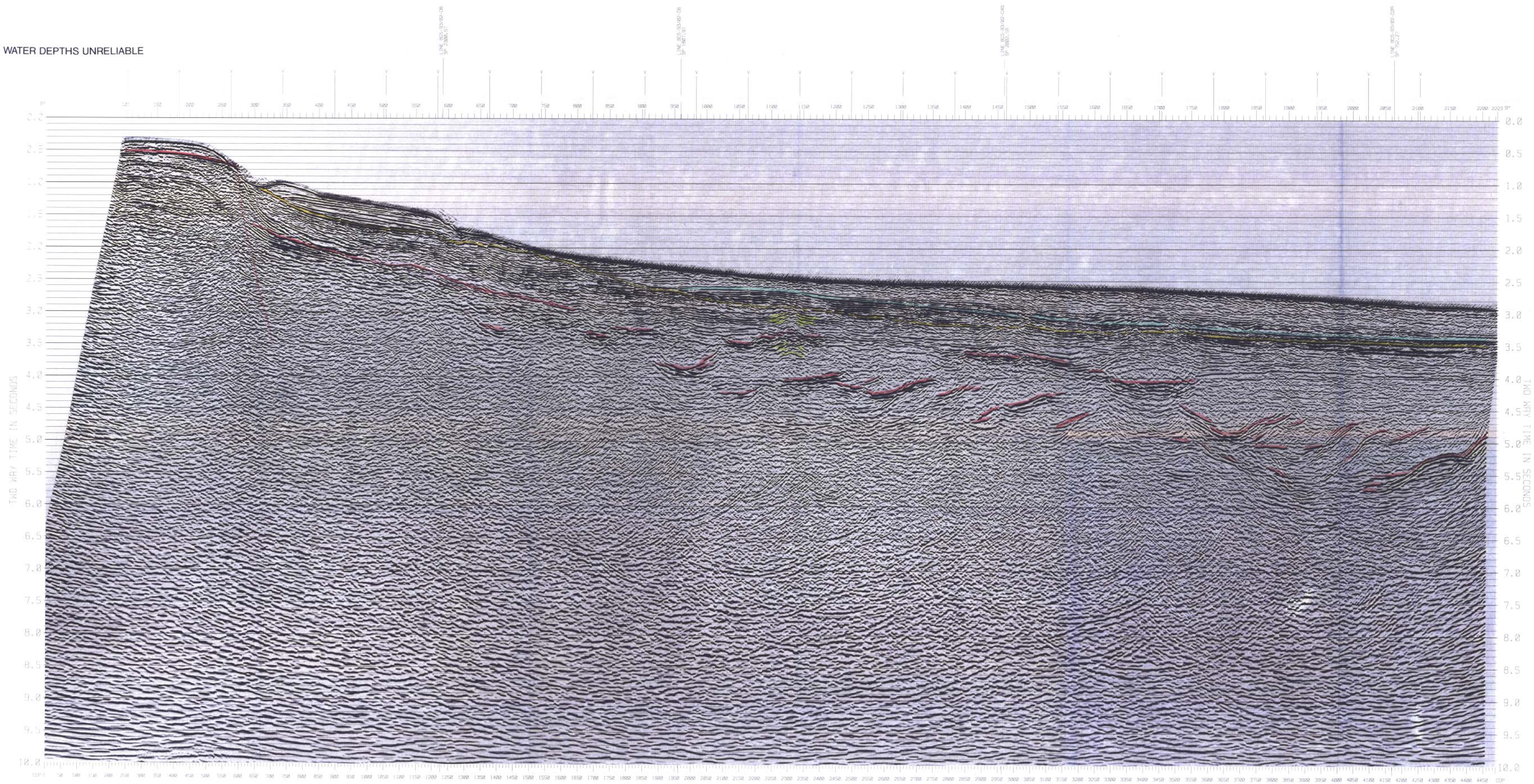
Reflector B Late late Eocene

Reflector C Early late Eocene

Reflector D Top Basalt (Late Paleocene-Early Eocene)

Igneous intrusions

Possible fluid migration structures



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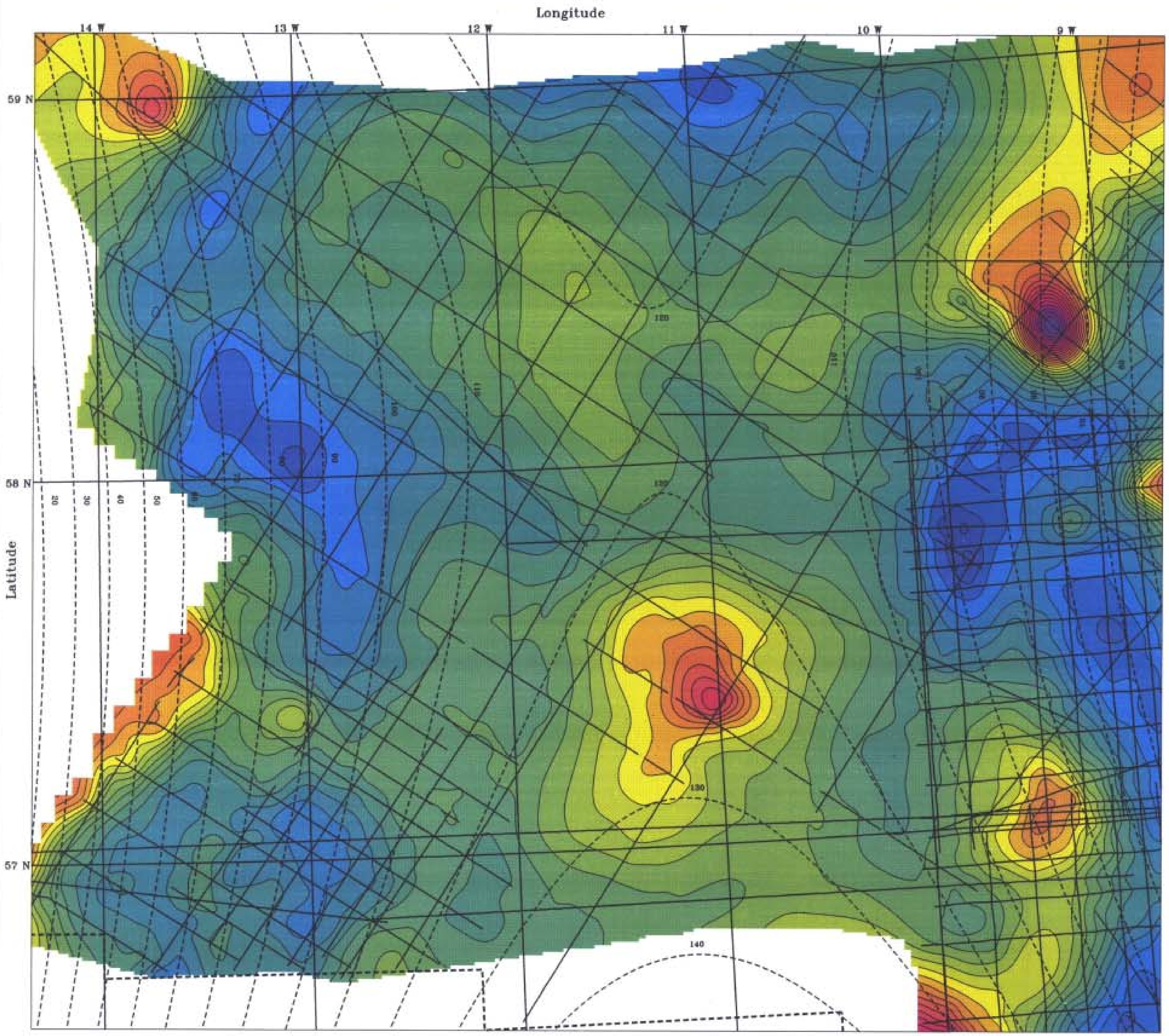
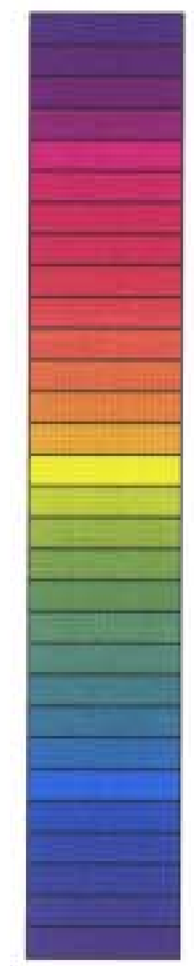


ROCKALL GEOPHYSICS
BOUGUER GRAVITY DATA
Residual (2nd order)

mGal



Gravity Data:
Bouguer gravity data network adjusted, and reduced using a density of 2.67 Mg m-3. Grid interval 1.0 km. Ship tracks plotted where data were used in gridding.

Dashed line is United Kingdom median line.

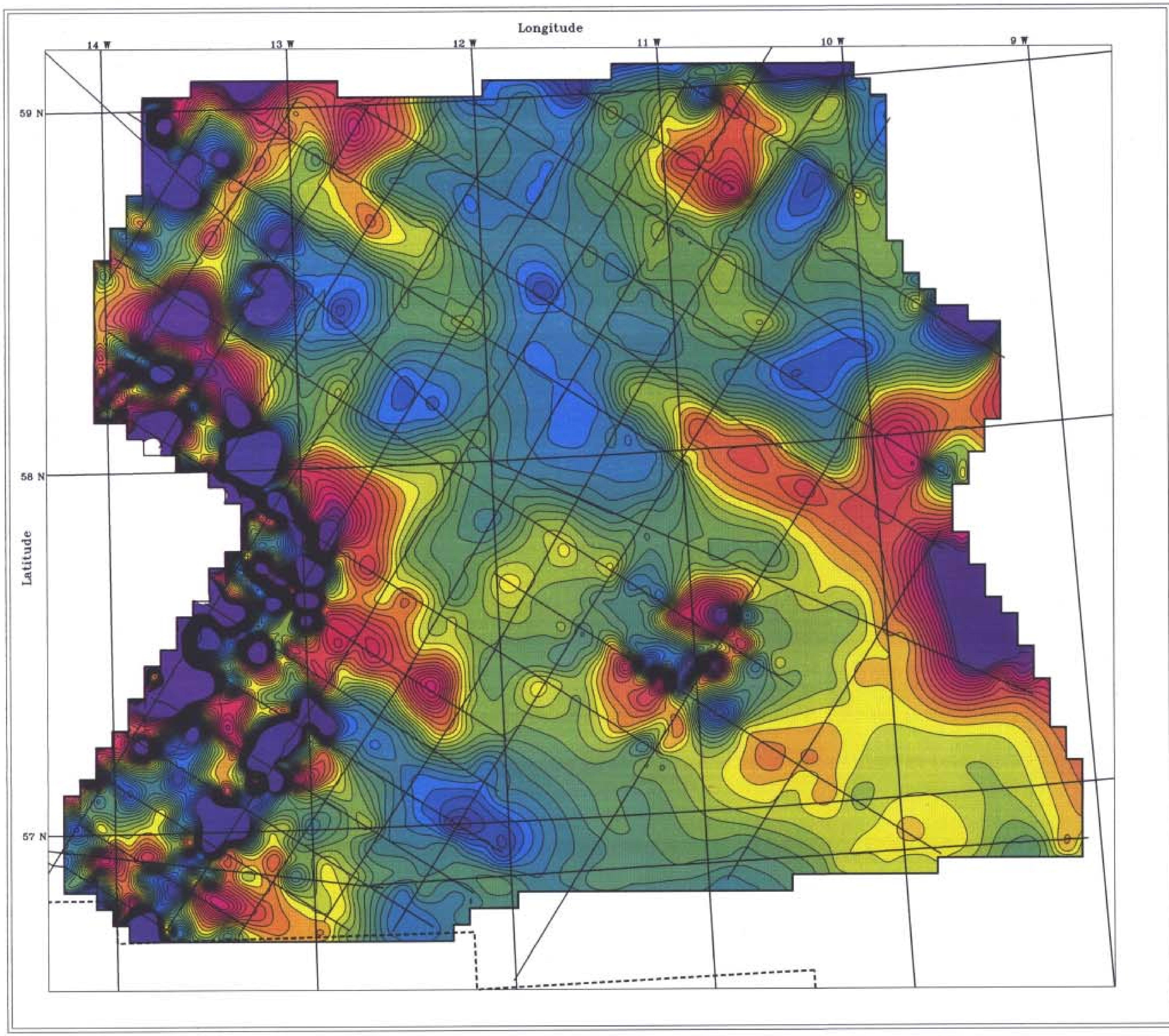
Grid Transformations:
2nd order trend surface removed (dashed contours).

Display Parameters:
5 mGal. fixed contour interval (for values -50 to 150).

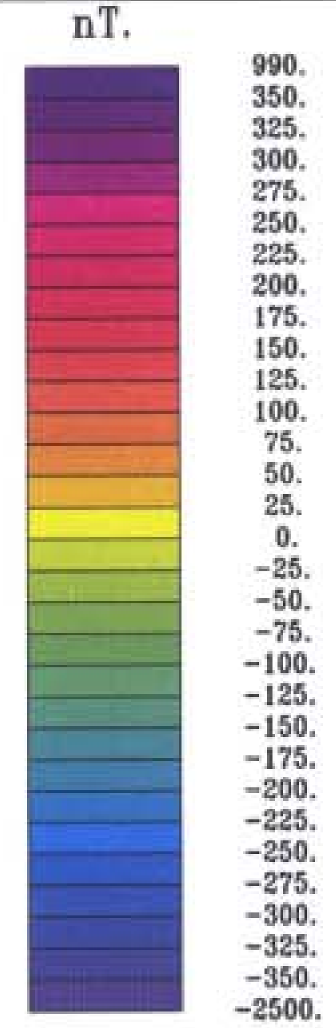
Mike Sankey, Regional Geophysics Group, Edinburgh
April 1995.

Scale 1:1000000

From:
Hitchen, K. 1995. Seismic Lines and Gravity and Magnetic Maps. Volume 5, Appendix 5 of Stoker, M. S. and Hitchen, K. 1995. Rockall Continental Margin Project: Final Geological Report. *British Geological Survey Technical Report* WB/95/11C.



ROCKALL GEOPHYSICS MARINE MAGNETIC DATA



Marine Magnetic Data:
This marine magnetic data has been fully network adjusted and corrected to the BGGM92 reference field, diurnal corrections were applied using one hourly mean values from Eskdalemuir Observatory.
A 5x5 km unsmoothed grid was created using the Interactive Surface Modeling program (ISM 7.0) by Dynamic Graphics Inc. The grid was imported into COLMAP→P (developed by Regional Geophysics Group, BGS) to create this image.
Ship tracks plotted where data was used in gridding.

The bold dashed line in south-west of area is the United Kingdom median line.

Display Parameters:
25 nT. constant contour interval (from -350 to 350 nT.)

Mike Sankey, Regional Geophysics Group, Edinburgh
March 1995.

Scale 1:1000000