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DESCRIPTION OF ROCKS DREDGED FROM THE KERGUELEN PLATEAU

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ABSTRACT

This report presents descriptive and analytical detail of samples dredged from the Kerguelen Plateau on Cruise MD48 of the O/N *Marion Dufresne* in 1986, exclusive of analyses already published elsewhere (Davies et al., 1989). Dredged samples from the Kerguelen Plateau include Early Cretaceous basalt and lava breccia of transitional tholeiite composition. Isotope and incompatible element abundance ratios for these rocks are similar to ocean island basalts from the southern hemisphere Dupal anomaly region, and geochemical, geological and geophysical data are consistent with volcanic activity associated with a mantle plume. Other dredged and cored rock types include probable Early Cretaceous conglomerate and shelf limestone, Late Cretaceous chert and dolomite, Late Cretaceous - Eocene ooze, and Tertiary conglomerate. In conjunction with seismic reflection profiles the samples indicated Early Cretaceous near-shore volcanism, followed by erosion, sedimentation and subsidence through the Cretaceous; arching of the plateau at the end of the Cretaceous; subsidence through the Palaeogene; widespread emergence in the mid-Tertiary; and slow subsidence through the Neogene.

CONTENTS

INTRODUCTION

The Kerguelen Plateau, in the southern Indian Ocean, originated during the breakup of Gondwanaland. It has been suggested that the plateau includes rifted continental crust (e.g., Dietz and Holden, 1970), but most authors now favour origin by oceanic volcanism, either as thickened oceanic crust (Houtz et al., 1977) perhaps formed by excess volcanism at a slow-spreading ridge (Mutter and Cande, 1983), or as a hotspot trace (Luyendyk and Rennick, 1977; Duncan, 1978; Peirce, 1978; Morgan, 1981; Davies et al., 1989). Isotopic compositions of Cenozoic volcanics on the Kerguelen Islands provide no evidence for continental crust (Dosso and Murthy, 1980; Weis, Mennessier, et al., 1987), and limited seismic refraction data (Recq and Charvis, 1986) and the magnetic field (Bradley and Frey, 1988) suggest thick basaltic crust.

The first Kerguelen Plateau basement samples were collected in 1986 on voyage MD48 of the O/N *Marion Dufresne* (Leclaire et al., 1987; Davies et al., 1989). The samples comprise several tonnes of altered basalt, basaltic breccia and conglomerate from five dredge sites (Fig. 1, Table 1). The association of basalt with conglomerate and, at two localities, with shelf limestone, suggested a volcanic island environment, and K-Ar data indicate an Early Cretaceous age (Leclaire et al., 1987; Davies et al., 1989). Subsequently, more samples of basement basalt were collected from four sites during Ocean Drilling Program (ODP) legs 119 and 120 (Barron, Larsen et al., 1988; Schlich, Wise et al., 1988).

In this paper we present descriptive and analytical detail for the MD48 dredged samples. Descriptions of cores appear in Leclaire (1988).

BACKGROUND

The Kerguelen Plateau is 2100 km long and up to 700 km in width and thus ranks amongst the largest of submarine plateaus. The northern part of the plateau, north of about 54°S,is generally high-standing, has a partial cover of 2500-3000 m of sediment (2.5 s two-way travel time, twtt; Munschy and Schlich, 1987) much invaded by dykes and stocks (Ramsay et al., 1986), and supports the volcanic islands: Heard, McDonald, and the Kerguelen group. Dredged and piston-cored sediments indicate shoaling towards the end of the Cretaceous and partial emergence in the mid-Eocene (Frohlich, 1986), and ODP drilling indicated an unconformity in the Early Miocene (Barron, Larsen et al., 1988).

The southern part of the plateau has more subdued relief, less evidence of igneous activity, and is characterised by the development of grabens and half-grabens (Houtz et al., 1977). An elongated depression on the northeastern margin appears to be structurally a part of the plateau (Labuan Basin, Fig. 1), and there is a centrally-located north-south graben (77° Graben, Fig. 1). A sedimentary basin (Raggatt Basin, Fig. 1; Ramsay et al., 1986) contains 2500 m of sediment (2.3 s twtt; Coffin et al., 1990) resting with erosional unconformity on a partly stratified basement. Other unconformities divide the basin sediments into seven seismic sequences (Colwell et al., 1988; Coffin et al., 1990); the most marked unconformity is at about mid-sequence, the K_3P_1 unconformity of Coffin et al. (1990).

The oldest known sediment on the northern plateau is Late Cretaceous, probable-

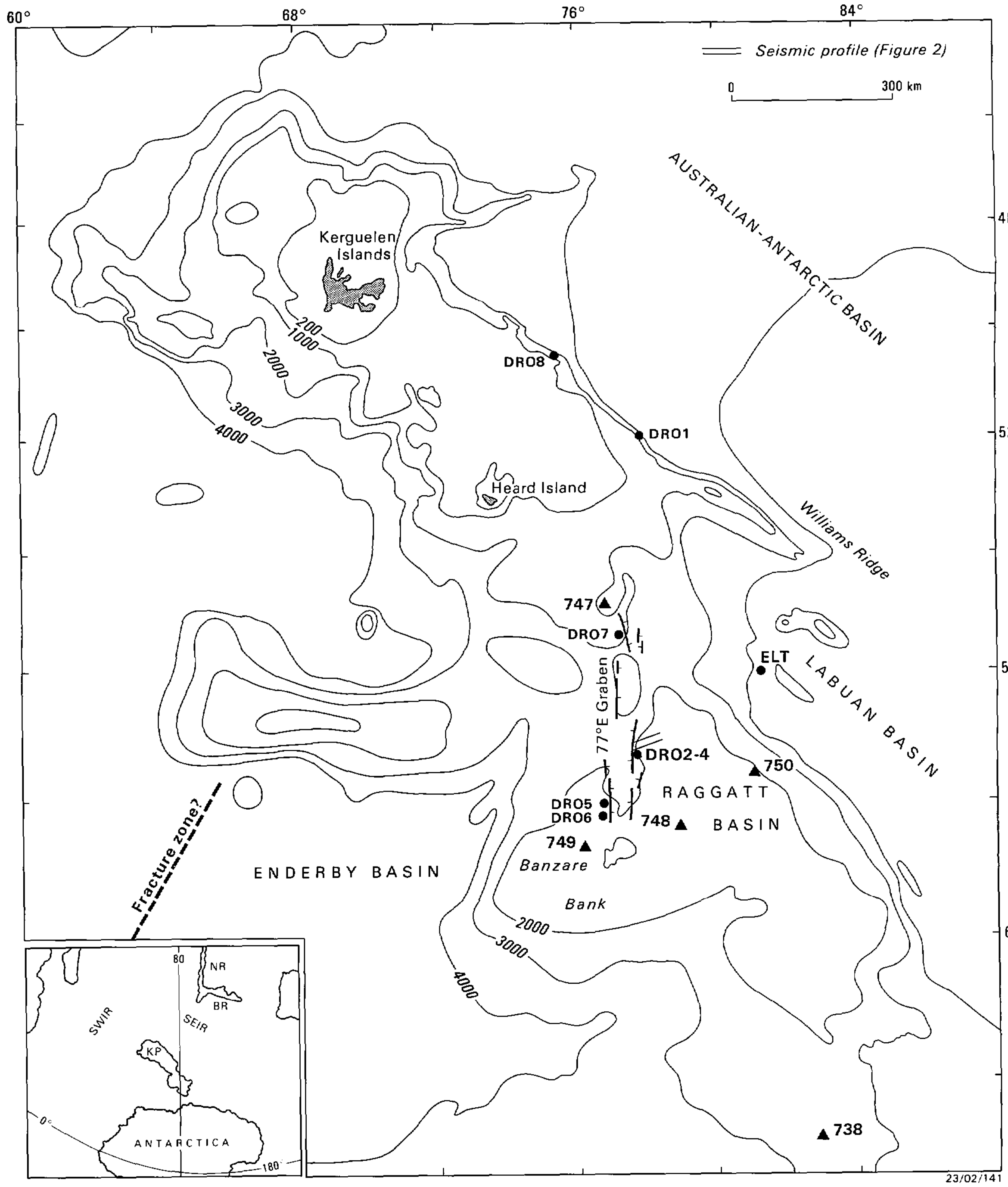

Figure 1. Bathymetric map of Kerguelen Plateau shows MD48 dredge sites 1-8 and ODP drill sites that intersected basement (see text). ELT Eltanin core 54-7. Downthrow on faults is indicated by tick. Mercator projection; scale bar correct for 55°S; isobaths in metres. Fracture zone interpreted from Seasat-derived free air gravity anomalies (Coffin et al., 1987). On locality map: KP Kerguelen Plateau, BR Broken Ridge, NR Ninetyeast Ridge, SWIR Southwest Indian Ridge, SEIR Southeast Indian Ridge.

TABLE 1: SUMMARY OF DREDGE SAMPLES

Dredge	Lat (S) Long (E) Depth (m) Tonnes	Description
1	51°58' 77°46' 2300-1600 0.2	Boulder of phlogopite melagabbro, 80 kg; phlogopite K-Ar age 12.2±0.1 Ma. Many pieces of metasomatised basalt; metasomatic minerals are quartz, andesine, K-feldspar, hornblende, minor biotite, accessory apatite, and some epidote and prehnite.
2	57°18' 77°36' 2400-1970 0.2	65% basalt, 35% limestone and 5% chert/opaline silica. Basalt is moderately altered, amygdaloidal, sparsely phyric (2.01) and feldspar-cpx glomerophyric (2.02,06,10-12), holocrystalline, 5-10% opaques. K-feldspar replaces xenocrysts of labradorite-bytownite and both are rimmed by labradorite of groundmass basalt. Shelf limestone (2.04,05) may be Early Cretaceous (a); kaolinite alteration, dissolution effects and stylolites probably indicate period of emergence (b). Some limestone is sheared. Late Cretaceous radiolaria in chert (a).
3	57°18' 77°35' 2200-2000 0.25	15% chert, remainder ice-rafted metamorphic and granitoid rocks. Chert is intensely fractured with some secondary fluor-, chlor-, and hydroxy-apatite and traces of calcareous foraminifera.
4	57°17' 77°37' 2600-2000 0.4	Mostly chert (opal-A, opal-C) with some interbedded dolomite, minor calcite and chlorapatite (a).
5	58°06' 76°55' 2200-1620 1.5	Mostly homogeneous saprolitic basalt lava, some lava breccia (5.04) and some conglomerate (5.05-07). Basalt is aphyric (5.01,02,10) and plag-cpx phyric (5.03,08,11), some with intersertal palagonite. Opaques prominent. Matrix of lava breccia 5.04 is bioclastic wackestone with glauconite peloids, benthic forams, echinoderm spines, rare bryozoa and bivalves, in matrix of micrite or phosphate after micrite; later infiltration of planktic forams into cavities (a). Conglomerate has rounded pebbles of altered basalt, lava breccia, chert and bioclastic wackestone with coral, larger forams and interclasts, phosphatised and replaced by Fe and Mn oxides; later infiltration of planktic forams into cavities; the infiltrating forams are replaced by zeolite and/or secondary clay minerals (b). K-Ar age of plag in 5.08 is 114±1 Ma; Cretaceous planktic foraminifer *Hedbergella* in matrix of lava breccia 5.04A (c).
6	58°17' 76°55' 1550-1250 1.5	Saprolitic amygdaloidal, microphyric basalt lava (6.01,02,10-13) and lava breccia (6.03,06-09,13), as in dredge 5. Matrix of lava breccia is finely recrystallised calcite, with veinlets sparry calcite and quartz, rare glauconite peloids. Basalt has sub-ophitic plag-cpx-ilm/mt, intersertal palagonite, some calcite veining. Similar to dredge 5 basalts except for absence of porphyritic basalt.

7	55°18' 77°28' 2265-1865 0.4	Most is conglomerate of moderate to large boulders of saprolitic basalt partly cemented by Mn oxides after carbonate. Typical basalt is red (hematitic), sparsely amygdaloidal to scoriaceous, intersertal, with celadonite alteration and calcite and Mn oxides in amygdales. Typical basalt lava and lava breccia of dredges 5 and 6 also present.
8	50°19' 74°49' 2175 0.25	60% Neogene unaltered porphyritic basalt (8.01-03, 05,07,10,13,14); 30% saprolitic older basalt probably from outcrop (8.04, 11); remainder is white, vuggy, low density, soft conglomerate with pebbles of altered basalt and white former foram limestone (no longer calcareous) in grey matrix of crystal tuff and clay. Forams in limestone pebbles are planktic, Miocene or younger (d). Upper Cretaceous sediment was cored previously up-slope from dredge 8 (see text).

(a) Bassias et al., 1987
(b) R.E. Garrison, pers. comm., 1987
(c) F. Vieban and C. Darmedru-Ducreux, pers. comm., 1987
(d) D.J. Belford, pers. comm., 1986.

TABLE 2 Potassium-argon age determinations

Sample	%K	Radiogenic ^{40}Ar ($x10^{-10}$ moles/g)	Radiogenic ^{40}Ar/Total^{40}Ar	Age* Ma
05.08	0.372	0.7545	0.727	114$\pm$1
plag.	0.369			
01.06	7.37	1.7036	0.802	13.3$\pm$0.1
phlog.	7.39	1.6995	0.804	13.2$\pm$0.1

*Error limits are for analytical uncertainty at one standard deviation.

Constants: $^{40}K = 0.01167$ atom %
$\lambda_\beta = 4.962 \times 10^{-10} y^{-1}$
$\lambda_\varepsilon = 0.581 \times 10^{-10} y^{-1}$

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Santonian, (87-84 Ma?) ooze, piston-cored from the northeastern flank (Wicquart and Frohlich, 1986; time scale of Kent and Gradstein, 1985). Oldest known sediment on the southern plateau is Late Cenomanian (94-91 Ma) chalk, piston-cored from the northeastern margin (Quilty, 1973; ELT in Fig. 1). ODP legs 119 and 120 recovered reworked Cenomanian microfossils (97-91 Ma) at site 750, Early Turonian sediment (91-90 Ma) at site 738, Early Santonian (87-85 Ma) at site 747, probable Late Campanian (78-75 Ma) above a basalt flow at site 748, and earliest Eocene (55 Ma) at site 749 (Barron, Larsen et al., 1988; Schlich, Wise et al., 1988).

The plateau was once contiguous with Broken Ridge, which now lies more than 1800 km to the northeast, the two having separated by spreading along the Southeast Indian Ridge. The oldest known sediment on Broken Ridge is Turonian and there is a marked angular unconformity in the mid-Eocene, 48-43 Ma (Peirce, Weissel, et al., 1988). Kerguelen Plateau split from Broken Ridge in the Cretaceous (Mutter and Cande, 1983) or Eocene (Peirce, Weissel et al., 1988) and rapid separation began at Anomaly 18 or 19 time, 40-43 Ma ago (Houtz et al., 1977; Mutter and Cande, 1983; Royer and Sandwell, 1989; time-scale of Berggren et al., 1985). Cenozoic volcanic activity in the Kerguelen Islands from Eocene to Late Quaternary, 40 Ma to 10,000 years (Giret and Lameyre, 1983; Nougier et al., 1983), and on Heard and McDonald Islands possibly from late Eocene-Early Oligocene and certainly from Late Miocene-Early Pliocene to the present day (Quilty et al., 1983), is thought to indicate the presence of a hotspot (Luyendyk and Rennick, 1977; Duncan, 1978; Peirce, 1978; Morgan, 1981).

ANALYTICAL METHODS

All sample types identified from macroscopic characteristics were thin sectioned. Minerals were analysed using a fully automated *camebax* (CAMECA) *microbeam* electron probe microanalyser at the Australian National University (method of Ware, 1981). Accelerating voltage was 15 kV and beam current generally 30 nA. Alteration minerals were identified by X-ray diffraction using a Siemens DACO MP (Cu K_α) diffractometer coupled with a DIFRAC/AT automatic identification interface in the Laboratoire de Geologie, Museum National d'Histoire Naturelle (MNHN), Paris. Three least-altered samples were analysed for major and trace elements by X-ray fluorescence spectrometry (XRF) at La Trobe University, using methods of Norrish and Hutton, 1969; Norrish and Chappell, 1977), and for Sc, Cr, Co, rare earth elements, Hf, Ta and Th by instrumental neutron activation analysis at Massachusetts Institute of Technology, method of Ila and Frey (1984). The same three samples were re-run for Nb and Zr by XRF at Bureau of Mineral Resources (BMR), Canberra, with good agreement with La Trobe results. Seven samples, apparently more altered, were analysed for Ti, Nb, Zr and Y by XRF at MNHN, Paris. Sr and Nd isotope compositions were determined at the Australian National University, following the method described in McCulloch and Chappell (1982), with uncertainty in $^{147}Sm/^{144}Nd = \pm0.2\%$ and Nd ±0.2 units (2 sigma). During the period of data collection the $^{143}Nd/^{144}Nd$ value for BCR-1 = 0.512650$\pm$4 and for La Jolla = 0.511873$\pm$2. K-Ar age of plagioclase in DR05.08 was determined at AMDEL, Adelaide (Table 2).

For Sr isotope analyses, in particular, the effects of pervasive seawater alteration are a serious problem. To minimise these effects, mineral separates (clinopyroxene and plagioclase) were prepared and analysed for two of the samples, and whole-rock powders were leached in 4N HCl for several hours prior to analysis.

LOCATION AND DESCRIPTION OF SAMPLES

Dredge localities and summary descriptions of samples are given in Table 1 and a detailed description of each dredge haul is given in Appendix 1. Bulk samples are stored at MNHN Paris, and selected pieces at BMR Canberra.

A large quantity of altered basalt, probably from basement, was dredged at four localities on the 77 E Graben (localities 2,5,6,7; Fig. 1, Table 1) and at one locality on the northeastern margin of the northern plateau (locality 8, Fig. 1. Table 1). In addition, Middle Miocene phlogopite gabbro and metasomatically-altered basalt of unknown age were dredged at locality 1, and rounded, transported boulders of unaltered, probably Neogene, basalt at locality 8 (Table 1). The younger basalt at locality 8 and the gabbro and metasomatically-altered basalt at locality 1 are not discussed further.

The largest hauls of basement basalt were in dredges 5 and 6. In both, about 1.5 tonnes of lava and lava breccia were recovered. Basalt from dredges 2, 5, 6 and 8 is blocky and has the appearance of material dredged from outcrop or from a talus slope below outcrop. Basalt from dredge 7, on the other hand, is mostly from a conglomerate of medium to large rounded boulders, patchily cemented by Mn oxides and calcite.

Most of the several tonnes of basalt collected in dredges 5, 6 and 8 is a brown, moderately altered, sparsely microphyric to aphyric and holocrystalline basalt, with scattered fine amygdales; microphenocrysts are plagioclase and clinopyroxene. The same rock type is also present in dredges 2 and 7. Samples 6.14 and 8.04 were selected for analysis as being representative of this material, and sample 2.12 was selected as representative of the dominant basalt type in dredge 2 - a finely glomerophyric basalt with plagioclase laths to 1 mm (analytical results were reported by Davies et al., 1989). Samples 5.08 and 5.11, a more coarsely glomerophyric basalt that was found only in dredge 5, were selected for K-Ar dating of plagioclase separates (Table 2) and for Nd and Sr isotope analysis of mineral separates and whole-rock (Davies et al., 1989). Unique to dredge 7 is a red-brown, coarsely amygdaloidal to scoriaceous, sparsely plagioclase-phyric and intersertal basalt with amygdales up to 15 mm across comprising up to 25 percent of the rock: this rock was too altered for analysis. All of the basalts have 5-10 percent opaques, in most cases a mixture of Ti-magnetite and ilmenite.

All of the basement basalts are moderately to severely altered with development of smectite, smectite/illite mixed clays, and celadonite; these minerals are consistent with reaction with sea water (Bassias et al., 1987). Alteration of basalts from dredge 2 includes partial replacement of labradorite/bytownite xenocrysts by K-feldspar and development of zeolites (stelerite and analcite or stilbite and clinoptilolite), rhodocrosite, chlorapatite, dioctahedral smectite, well-crystallised illite-smectite, illite, palygorskite and pyrophyllite as well as chlorite and chlorite-vermiculite. Very rare and small (to 6 microns) K-feldspar partially replaces plagioclase phenocrysts in

5.08/5.11.

AGE CONTROL

A single determination of K-Ar age for plagioclase from plagioclase-phyric basalt in dredge 5 gave an age of 114±1 Ma (Table 2; Leclaire et al., 1987; Davies et al., 1989), or Aptian-Albian in the biostratigraphic time scale of Kent and Gradstein (1985). Cretaceous foraminiferids were found in the matrix of associated basaltic breccia. The radiometric age is compatible with the age of oldest dredged and drilled sediment. The same age may be assumed for the petrographically similar basalts of nearby dredge 6, and basalt from dredge 2 is likely to have similar age, given the continuity of basement character between the three sites as indicated in seismic reflection profiles (Ramsay et al., 1986; Coffin et al., 1990). The age of basalt in dredge 8 is thought to be pre-Santonian, i.e., pre-87 Ma, because Late Cretaceous (probable-Santonian) sediments were cored immediately up-slope (Wicquart and Frohlich 1986). The age of basalt in dredge 7 also is probably pre-Santonian be cause Lower Santonian sediment was recovered at nearby ODP site 747 (Schlich, Wise, et al., 1988).

RESULTS

Mineral Chemistry

In such altered rocks, determination of the composition of unaltered minerals is a direct means of inferring magma composition. Analyses of minerals in the MD48 basalts point to a general transitional tholeiitic to tholeiitic character. Mineral data are presented graphically in Davies et al. (1989). Selected analyses are presented in Tables 3-6.

In most samples plagioclase tends to have high Or content, indicating relatively high K_2O in the primary magma (Table 3); Or content is comparable with or higher than Or content of plagioclase of alkali basalts of the Hawaiian Islands (Davies et al., 1989). Exceptions are the dredge 7 basalts in which Or content is uniformly low. Phenocryst cores are typically labradorite An_{70-52}, ranging to bytownite An_{77} in dredges 2, 5 and 7. Phenocryst rims and groundmass plagioclase are labradorite and andesine, An_{68-33}.

Plots of clinopyroxene compositions clearly demonstrate an affinity with tholeiitic and transitional basalts (Davies et al., 1989). Phenocryst cores are diopsidic augite with only 10-15 percent ferrosalite molecule, but rims and groundmass grains typically show Fe enrichment to ferro-augite and, rarely, sub-calcic ferro-augite (Table 4). Generally, trends are similar to those for transitional basalts of the Kerguelen Islands, but some rim and groundmass clinopyroxenes in dredge 5 and all in dredge 7 trend to depletion in Ca, and thus mimic the trend of pyroxenes in Hawaiian tholeiites (Davies et al., 1989).

Plagioclase and clinopyroxene compositions show that the lavas of dredge 2 are less fractionated than those of dredges 5, 6 and 8 (early-formed plagioclase is more calcic and Mg/Fe in clinopyroxene is higher). The more primitive character of dredge 2 basalt is borne out by whole-rock major element chemistry (Davies et al., 1989). Mineral compositions in dredge 7 basalts suggest tholeiitic character.

TABLE 3 REPRESENTATIVE ANALYSES OF FELDSPARS

	1	2	3	4	5	6	7	8	9
P_2O_5							0.25		
SiO_2	49.45	52.86	50.93	57.86	53.78	57.15	51.89	55.42	64.20
TiO_2	0.13	0.08	0.10	0.08	0.11	0.07	0.08	0.07	<0.03
Al_2O_3	32.20	29.19	30.94	25.86	28.64	26.11	29.35	26.93	18.69
FeO*	0.42	1.05	0.42	0.77	0.56	0.64	0.86	1.00	0.04
MgO	0.16	0.21	0.12	0.12	0.09	<0.03	0.45	0.13	<0.03
CaO	15.64	12.26	13.20	8.08	10.71	7.98	12.88	9.25	<0.02
Na_2O	2.45	3.91	3.64	6.24	4.98	6.10	4.24	5.56	0.42
K_2O	0.10	0.61	0.12	0.45	0.30	0.69	0.15	0.48	16.17
TOT	100.55	100.16	99.48	99.47	99.18	98.73	100.15	98.84	99.52
An	77.5	61.1	66.2	40.6	53.3	40.2	62.2	46.5	00
Or	0.5	3.6	0.7	2.7	1.8	4.1	0.8	2.9	96.2

1 - Core of megacryst in 86DR02.12; **2** - Groundmass lath in 86DR02.12; **3** - Core of megacryst in 86DR05.11; **4** - Rim of megacryst in 86DR05.11; **5** - Core of microphenocryst in 86DR06.12; **6** - Rim of same microphenocryst in 86DR06.12; **7** - Groundmass 40 micron lath in 86DR07.14; **8** - Rim of microphenocryst in 86DR08.04; **9** - K-feldspar megacryst (replaces plagioclase megacryst) in 86DR02.12.

TABLE 4 REPRESENTATIVE ANALYSES OF CLINOPYROXENE

	1	2	3	4	5	6	7	8
P_2O_5				0.30	0.20	0.37		
SiO_2	52.73	50.58	50.11	49.73	51.70	50.50	51.20	50.34
TiO_2	0.64	1.09	1.29	0.83	0.40	0.92	0.60	0.80
Al_2O_3	2.15	2.93	1.92	1.08	1.7 9	3.42	2.68	1.33
Cr_2O_3	0.44	0.67	<0.04	0.04	0.54	0.21	0.83	0.24
FeO*	7.23	8.81	15.69	18.64	7.53	8.11	7.61	17.15
MnO	0.19	0.25	0.34	0.41	0.21	0.23	0.19	0.42
NiO	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.06	<0.05
MgO	17.94	15.78	12.31	10.46	16.84	14.64	17.08	12.33
CaO	18.94	19.04	18.16	17.50	18.42	20.42	19.35	16.82
Na_2O	0.20	0.24	0.28	0.34	0.48	0.27	0.22	0.21
TOT	100.46	99.39	100.10	99.33	98.11	99.09	99.89	99.63
Mg#	81.6	76.2	58.3	50.0	80.0	76.2	80.0	56.2
en	0.504	0.459	0.360	0.312	0.491	0.432	0.484	0.362
fs	0.114	0.143	0.258	0.312	0.123	0.135	0.121	0.282
wo	0.382	0.398	0.383	0.376	0.386	0.433	0.394	0.355

Mg# = 100 molar mg/(mg+fe*); en, fs, wo = molar mg/(mg + fe + ca) etc.

1 - Core of 0.7 mm phenocryst in 86DR02.12; **2** - Core of 0.3 mm phenocryst in 86DR05.11; **3** - Rim of 0.5 mm phenocryst in 86DR05.11; **4** - Groundmass 20 micron lath in 86DR06.11; **5** - Microphenocryst 0.14 mm in 86DR06.12; **6** - Groundmass 50 micron lath in 86DR07.14; **7** - Core of equant 0.12 mm microphenocryst in 86DR08.04; **8** - Microphenocryst lath 0.12 mm in 86DR08.04.

TABLE 5: ILMENITE AND TI-MAGNETITE

Sample	1	2	3	4	5	6	7	8
SiO_2	<0.2	0.03	0.12	0.05	0.14	<0.02	0.19	<0.02
TiO_2	50.51	51.44	51.78	53.16	33.43	28.46	26.94	23.41
Al_2O_3	<0.04	<0.04	<0.04	<0.04	3.68	1.10	1.56	1.23
V_2O_3	0.30	0.29	0.54	0.26	0.28	0.40	1.08	0.63
Cr_2O_3	0.07	<0.03	0.08	0.04	2.32	0.04	0.20	0.06
FeO*	42.73	46.80	44.71	43.73	50.86	60.87	64.33	68.37
MnO	3.81	1.11	0.37	0.67	0.47	3.46	1.97	0.42
NiO	<0.04	<0.04	<0.04	<0.04	0.14	<0.04	<0.04	<0.04
MgO	0.38	0.41	1.28	1.73	4.77	<0.03	0.21	0.89
CaO	0.20	0.05	0.15	0.18	0.62	0.08	0.09	0.18
TOT	98.00	100.13	99.03	99.84	96.69	94.40	96.59	95.19

1 - 4 ILMENITE:
1 Ilmenite in glomerophyric basalt 86DR02.06; 2 Ilmenite in coarsely plagioclase-phyric basalt 86DR05.11; 3 Ilmenite laths in cotectic intergrowth with plagioclase in microphyric basalt 86DR06.14; 4 Ilmenite laths in basalt 86DR08.04.

5-8 TI-MAGNETITE:
5 Ti-mt inclusion in cpx 86DR01.06; 6. Ti-mt in coarsely plagioclase-phyric basalt 86DR05.08; 7 Ti-mt in groundmass of microphyric basalt 86DR06.14; 8 Ti-mt in altered quenched basalt 86DR07.14.

TABLE 6. OTHER MINERALS

Sample	1	2	3	4	5	6	7	8	9
SiO_2	46.25	48.41	37.34	53.51	36.04	47.46	44.57	37.90	29.71
TiO_2	0.43	0.16	<0.03	0.18	6.27	0.08	<0.03	<0.03	1.78
Al_2O_3	9.68	6.21	<0.03	0.87	14.57	5.39	22.89	23.83	17.16
Cr_2O_3	<0.04	0.04	<0.04	<0.04	0.06	<0.03	<0.04	<0.04	0.04
FeO	16.46	17.94	26.55	16.11	10.18	16.26	1.51	12.07	21.83
MnO	0.24	0.34	0.42	0.47	0.04	<0.03	<0.03	0.17	0.09
NiO	<0.05	<0.05	0.13	0.06	<0.05	<0.04	<0.04	<0.05	0.08
MgO	11.97	11.37	36.16	27.31	16.53	5.37	<0.03	<0.03	16.85
CaO	11.64	12.21	<0.02	1.04	<0.02	0.31	25.43	23.40	0.43
Na_2O	0.86	0.43	<0.02	<0.02	0.53	0.68	<0.02	<0.02	0.03
K_2O	0.20	0.18	<0.01	<0.01	9.27	7.32	<0.01	<0.01	0.43
TOT	97.74	97.28	100.60	99.54	93.49	82.87	94.40	97.37	88.44

1 **Amphibole** 0.8 mm in uralitised basalt 86DR01.05; 2 **Amphibole** 0.25 mm in uralitised basalt 86DR01.08; **3 Olivine** 0.5 mm in cumulus gabbro 86DR01.06; **4 Orthopyroxene** 0.05 mm in gabbro 86DR01.06; **5 Phlogopite** in gabbro 86DR01.06; **6 Celadonite** in basalt 86DR05.08; **7 Prehnite** in uralitised basalt 86DR01.08; **8 Epidote** in uralitised basalt 86DR01.08; **9 Prismatic chlorite** in uralitised basalt 86DR01.05.

Ilmenite is intimately associated with Ti-magnetite (Table 5) in most samples. Ti-magnetites contain 18-26% TiO_2 and rarely as much as 0.9% ZnO by weight, and some Ti-magnetite and ilmenite contains up to 3.4% MnO. The high MnO values reflect mobilization of Mn during cooling and hydrous alteration. Plots of $\log(Mg/Mn)_{mt}$ vs. $\log(Mg/Mn)_{il}$ confirm that in almost all cases co-existing magnetite and ilmenite are not in equilibrium (*see* Bacon and Hirschmann, 1988). Phlogopite in the cumulus gabbro 86DR01.06 is remarkable for high TiO_2 content.

Major Element Abundances
Three samples were selected as least altered and analysed for major and trace elements, including rare earth elements (REE). The major element contents (Table 2 in Davies et al., 1989) are similar to ocean island basalts that are transitional between ocean island tholeiites and alkali basalts (Basaltic Volcanism Study Project, 1981), and thus support the interpretation of magma chemistry based on mineral chemistry (above). However, all three samples are significantly altered, with total water in the range 3.15-5.6 percent, and FeO/Fe_2O_3 of 0.3 to 0.9. Because of this alteration, abundances of many elements, especially mobile elements such as alkali metals and alkaline earths, do not represent magma compositions.

We calculated CIPW norms for each rock, assuming anhydrous composition and Fe_2O_3/FeO ratio 0.2. On this basis, all three samples are hypersthene normative, consistent with original tholeiitic chemistry. Mg numbers calculated on the same basis suggest that 2.12 is the least fractionated of the three, as is also suggested by mineral compositions. Sample 2.12 also appears to be the most alkalic, but the high K_2O may be due entirely to late-stage interaction with sea water (see below). The low Mg number of 8.04 is probably due to loss of MgO during altera tion. Evidence for this is the high Co, Cr and Ni content of 8.04 relative to the other two samples, and the magnesian character of the clinopyroxene phenocrysts in 8.04 (Table 4).

Trace Element Abundances
Trace element abundances in the three analysed basalts are presented in an expanded incompatible elements and REE diagrams by Davies et al. (1989). Anomalous peaks for certain elements suggest enrichment in those elements during late stage alteration. For example, high K and Rb in 2.12 are consistent with the development of secondary K-feldspar, and the high P in 8.04 reflects late introduction of apatite (confirmed by electron probe). Anomalously high La in 6.14 may be due to late alteration.

Abundance data for the more immobile elements probably reflect significant differences in parental magma composition. For example, sample 2.12 has markedly lower HREE content and a higher LREE/HREE ratio than the other samples. The sub-parallel chondrite-normalized REE patterns of 6.14 and 8.04 (Davies et al., 1989) are surprising considering that the two sites are separated by 800 km and are located on the tectonically distinct southern and northern sectors of the Kerguelen Plateau. However, in detail, these two samples are also geochemically different. Sample 6.14 is generally enriched in immoble incompatible elements (Zr, Hf, LREE, Th) relative to sample 8.04 but has lower Nb and Ta. Trace element data additional to those reported by Davies et al. (1989) are presented in table 7.

TABLE 7 Analyses of immobile elements in other MD48 basalts

Sample	Ti	Nb	Zr	Y	Zr/Nb
2.01	11519.7	7	132	25	18.9
2.02(1)	13278.0	14	150	26	10.7
2.02(5)	-	18	189	33	10.5
2.11	10792.1	13	127	18	9.8
5.01	10185.8	10	104	31	10.4
5.02	9700.8	6	98	22	16.3
6.06	12853.6	11	129	26	11.7

Notes: 2.02(1) and 2.05 are petrographically similar to 2.12 (see Davies et al., 1989, Table 6). 2.11 and 6.06 are clasts from lava breccias. 5.02 is an altered aphyric basalt. Analyst: Y. Bassias.

Nd and Sr Isotopes

Isotopic data for basement basalts from dredges 5, 6 and 8 are presented elsewhere (Table 3 and Figure 8 in Davies et al., 1989). Initial $^{144}Nd/^{143}Nd$ and $^{87}Sr/^{86}Sr$ ratios are calculated at an age of 114 Ma, the K-Ar age of plagioclase from sample 5.08. Initial $^{87}Sr/^{86}Sr$ ranges from 0.70411 to 0.70563 and initial ε_{Nd} from 2.0 to -3.5. The Nd and Sr isotope values are inversely correlated, and the extreme Sr isotope values are defined by analysis of unaltered mineral separates (clinopyroxenes from 5.11 and 8.04). This suggests that the effect of seawater hydrothermal alteration on the initial $^{87}Sr/^{86}Sr$ ratios was minimised by sample pretreatment (acid leach).

Acknowledgments and Dedication

HLD thanks N.G. Ware for assistance with the operation of the electron microprobe and M.B. Duggan and D.J. Wyborn for advice on mineral chemistry data processing.

This volume is humbly dedicated to the memory of Lucien Leclaire, formerly Director of the Laboratoire de Geologie of the Museum National d'Histoire Naturelle, and Chief Scientist on voyage MD48/NASKA.

REFERENCES

Bacon CR, Hirschmann MM (1988) Mg/Mn partitioning as a test for equilibrium between coexisting Fe-Ti oxides. Amer Mineral 73:57-61

Barron J, Larsen B, Shipboard Scientific Party (1988) Leg 119 studies climatic history, Geotimes 33(7):14-16.

Basaltic Volcanism Study Project (1981) Basaltic volcanism on the terrestrial planets, Pergamon Press, New York.

Bassias Y, Davies H, Leclaire L, Weis D (1987) Basaltic basement and sedimentary rocks from the southern sector of the Kerguelen-Heard Plateau: new data and their Meso-Cenozoic paleogeographic and geodynamic implications, Bull Mus Natn Hist Nat Paris 9:367-403.

Berggren WA, Kent DV, Flynn JJ, Couvering JA (1985) Cenozoic geochronology, Geol Soc Amer Bull, 96:1407-1418.

Bradley LM, Frey H (1988) Constraints on the crustal nature and tectonic history of the Kerguelen Plateau from comparative magnetic modelling using MAGSAT data, Tectonophysics 145:243- 251.

Coffin MF, Davies HL, Haxby WF (1986) Structure of the Kerguelen Plateau province from Seasat altimetry and seismic reflection data, Nature 324:134-136.

Coffin MF, Munschy M, Colwell JB, Schlich R, Davies HL, Li ZG (1990) ODP Leg 120 Scientific Party, Seismic stratigraphy of the Raggatt Basin, southern Kerguelen Plateau: tectonic and paleoceanographic implications, Geol Soc Amer Bull 102:563-579.

Colwell JB, Coffin MF, Pigram CJ, Davies HL, Stagg HMJ, Hill PJ (1988) Seismic stratigraphy and evolution of the Raggatt Basin, southern Kerguelen Plateau, Marine Petroleum Geol, 5:75-81.

Davies HL, Sun S-s, Frey FA, Gautier I, McCulloch MT, Price RC, Bassias Y, Klootwijk CT, Leclaire L (1989) Basalt basement from the Kerguelen Plateau and the trail of a Dupal plume. Contrib Mineral Petrol 103:457-469.

Dietz RS, Holden JC (1970) Reconstruction of Pangaea: breakup and dispersion of continents, Permian to present, J Geophys Research 75:4939-4966.

Dosso L, Murthy VR (1980) A Nd isotopic study of the Kerguelen Islands: inferences on enriched oceanic mantle sources, Earth Planet Sci Lett, 48:268-286.

Duncan RA (1978) Geochronology of basalts from the Ninetyeast Ridge and continental dispersion in the eastern Indian Ocean, J Volc Geothermal Research 4:283-305.

Frohlich F (1986) Sedimentary phosphates occurrence on the Kerguelen- Heard Plateau (Indian Ocean), C R Acad Sc Paris 303:167-170.

Giret A, Lameyre J (1983) A study of Kerguelen plutonism: petrology, geochronology, and geological implications, in: Antarctic Earth Science, R.L. Oliver, P.R. James and J.B. Jago, eds., pp. 646-651, Austral Acad Sci, Canberra.

Houtz RE, Hayes DE, Markl RG (1977) Kerguelen Plateau bathymetry, sediment distribution, and crustal structure, Marine Geol 25:95-130.

Ila P, Frey FA (1984) Utilization of neutron activation analysis in the study of geologic materials, Atomikernenergie Kerntectnick 44:710-716.

Kent DV, Gradstein FM (1985) A Cretaceous and Jurassic chronology, Geol Soc Amer Bull 96:1419-1427.

Leclaire L (1988) MD48/NASKA a bord du "Marion Dufresne" 21 fevrier - 26 mars 1986. Terres Australes et Antarctiques Francaises Rapports des campagnes a la mer 86-01.

Leclaire L, Bassias Y, Denis-Clocchiatti M, Davies H, Gautier I, Gensous B, Giannesini P-J, Patriat P, Segoufin J, Tesson M, Wannesson J (1987) Lower Cretaceous basalt and sediments from the Kerguelen Plateau, Geo-Marine Lett, 7:169-176.

Luyendyk BP, Rennick W (1977) Tectonic history of aseismic ridges in the eastern Indian

Ocean, Geol Soc Amer Bull, 88:1347-1356.
McCulloch MT, Chappell BW (1982) Nd isotopic characteristics of S- and I-type granites, Earth Planet Sci Lett, 58:51-64.
Morgan WJ (1981) Hotspot tracks and the opening of the Atlantic and Indian Oceans, in: The Sea, 7, The Oceanic Lithosphere, C. Emiliani, ed., pp. 443-487, Wiley, New York, N.Y.
Munschy M, Schlich R (1987) Structure and evolution of the Kerguelen-Heard Plateau (Indian Ocean) deduced from seismic stratigraphy studies. Marine Geol 76:131-152
Mutter JC, Cande SC (1983) The early opening between Broken Ridge and Kerguelen Plateau, Earth Planet Sci Lett, 65:369-376.
Norrish K, Chappell BW (1977) X-ray fluorescence spectrometry, in: Physical Methods in Determinative Mineralogy, 2nd ed., J. Zussman, ed., pp. 201-272, Academic Press, London.
Norrish K, Hutton JT (1969) An accurate X-ray spectrographic method for the analysis of a wide range of geological samples, Geochim Cosmochim Acta 33:431-453.
Nougier J, Pawlowski D, Cantagrel JM (1983) Chrono-spatial evolution of the volcanic activity in southeastern Kerguelen (T.A.A.F.). In: Oliver RL et al. (eds) Antarctic Earth Science. Austral Acad Sci Canberra, pp 640-645.
Peirce JW (1978) The northward motion of India since the Cretaceous. Geophys J Roy Astr Soc 52:277-311
Peirce J, Weissel J, Shipboard Scientific Party (1988) Leg 121 traces rifting and hotspots. Geotimes 33(11):9-11
Quilty PG (1973) Cenomanian-Turonian and Neogene sediments from northeastern Kerguelen Ridge, Indian Ocean. J Geol Soc Austral 20:361-371.
Quilty PG, Shafik S, McMinn A, Brady H, Clarke I (1983) Microfossil evidence for the age and environment of deposition of sediments of Heard and Macdonald Islands, in: Antarctic Earth Science, R.L. Oliver, P.R. James and J.B. Jago, eds., pp. 636-639, Austral. Acad. Sci., Canberra.
Ramsay DC, Colwell JB, Coffin MF, Davies HL, Hill PJ, Pigram CJ, Stagg HMJ (1986) New findings from the Kerguelen Plateau. Geology 14:589-593.
Recq M, Charvis P (1986) A seismic refraction survey in the Kerguelen Isles, southern Indian Ocean. Geoph J Roy Astr Soc 84:529-559.
Royer J-Y, Sandwell DT (1989) Evolution of the eastern Indian Ocean since the Late Cretaceous: constraints from GEOSAT altimetry. J Geophys Research 94:13755-13782.
Schlich R, Wise W, Shipboard Scientific Party (1988) Ocean Drilling Program - That sinking feeling, Nature 334:385-386.
Ware NG (1981) Computer programs and calibration with the PIBS technique for quantitative electron probe analysis using a lithium-drifted silicon detector, Computers and Geoscience 7:167-184.
Weis D, Mennessier J-P, Gautier I, Cantagrel J-M (1988) Geochimie isotopique des Terres Australes (Archipel des Iles Kerguelen), Actes Coll Recherche Francaise dans les Terres Australes, Strasbourg, pp.357-368.
Wicquart E, Frohlich F (1986) The sedimentation on the Kerguelen-Heard Plateau. Relationships with the evolution of the Indian Ocean during Cenozoic, Bull. Soc. Geol. France 11(4):569-574.

APPENDIX: DESCRIPTION OF MD48 DREDGED ROCKS BY H.L. DAVIES, I. GAUTIER, Y. BASSIAS AND R.E. GARRISON

DREDGE 01

Northeast margin of plateau, 51°57.75'S, 77°45.74'E, 1600 m approximate depth, day 61.

Summary. The dredge contained a single large piece of melagabbro (01.06); a number of moderate-size (to 45 cm), sub-angular, apparently faceted, pieces of silicified and propylitised lava, without Mn oxide coating (01.01, 2, 3, 4, 7, 9, 10, 13); and a sack of smaller pieces. Of the entire sample, only a few pieces carried any notable thickness of Mn oxide coating and can be regarded as probably *in situ*. The rock types with Mn oxide coating (up to 2 cm thick) are closely fractured propylitic basalt (01.05, 8, 11,); they make up less than 5 percent of the sample. The very large (about 80 kg) boulder of melagabbro has a Mn oxide coating which is up to 0.5 cm thick; probably this rock was *in situ*.

Conclusions. Rocks which probably crop out at this site are propylitically altered basalt with a thick MnO coating, and melagabbro. The latter is a residium from differentiation of basaltic magma (see below), and probably is a sub-volcanic intrusive - many dykes or stocks are apparent on seismic reflection profiles of the northern sector of the plateau. The silicified and propylitised volcanics may have been ice-rafted, presumably from a source within the Kerguelen Plateau.

Description of samples — All sample numbers have prefix 86DR

01.01 Feldspar-phyric trachyte, scattered mafic phenocrysts entirely made over to chlorite; much alteration to hematite, chlorite and epidote (red and green colours).

01.02 Similar to 01.01.

01.03 Feldspar-phyric trachyte with extreme alteraition and replacement by quartz, calcite and hematite.

01.04 Feldspar-phyric trachyte with extreme replacement by quartz, and some hematite and chlorite.

01.05 Amygdaloidal aphyric holocrystalline basalt, moderate propylitic alteration and epidote-chlorite-calcite veining. Primary minerals are plagioclase laths to 0.2 mm (45% of the rock), finely granular sub-equant clinopyroxene to 0.32 mm (50%), and fine opaques (0.01-0.02 mm, 5%); amygdales are chlorite + zeolite and, less commonly chlorite + quartz, up to 2 mm across, and make up 5 percent of the rock.

This is a former porphyritic 'basalt' that has been completely metasomatically replaced by andesine, hornblende, quartz, minor biotite and accessory apatite; fine magnetite and ilmenite may be primary. Primary texture is not preserved except for the outline of former plagioclase phenocrysts.

Amphibole (Table 6) occurs throughout the groundmass as fine laths (0.1-0.2 mm), randomly oriented, and forms larger grains which may be pseudomorphs of former pyroxene. Compositions of larger and smaller amphibole grains are not notably different.

Plagioclase in groundmass is An 46-48 Or 0.2-4, and in phenocrysts is An 40 to An 40 to An48, Or 0.3-1.0; possibly the groundmass plagioclase is generally a little more calcic than the phenocryst plagioclase - neither is primary. Fine biotite with chlorite alteration (Table 6) is associated with some of the coarser andesine and clinopyroxene. Quartz, similarly is associated with the coarser mineral phases, and may also be present in the groundmass. Epidote occurs within some large plagioclase grains, and in veinlets with quartz and calcite. Magnetite forms 5-10 per cent of the rock, and is accompanied by some ilmenite. Apatite needles occur within plagioclase.

01.06 Large piece of melagabbro, about 80 kg. "Top" is rounded and carries partial coating of Mn oxide up to 0.5 cm thick. Lower surfaces planar as though controlled by jointing. Part is olivine-plagioclase cumulate with post-cumulus clinopyroxene, remainder may be ol-pl-cpx cumulate, with large clinopyrozene grains (to 1 cm) and large interstitial grains of iron oxide. Large oikocrysts or phlogopite (up to 1.5 cm) appear to be localised on former irregular fractures, as though from reaction of late magmatic fluids with already-crystallised gabbro.

This is a medium to coarse-grained phlogopite melagabbro, with prominent clinopyroxene. The rock is a cumulate, characterised by a complex sequence of crystallisation which began with olivine and was followed by plagioclase and Ti-magnetite; augite; plagioclase; orthopyroxene, magnetite and ilmenite; and phlogopite. Apatite is present within phlogopite.

Olivine occurs as sub-rounded equant grains, 0.5-2.0 mm, with prominent cracks but no alteration; composition is Mg 68.5-70.8; some grains have a thin rim of orthopyroxene (see below). Augite grains tend to be large and sub-rectangular, 2-4 mm, and to have a dark cloudy appearance due to irregularly-distributed fine opaques; composition is uniformly En44 Fs12 Wo44. The grains appear to have formed early, though not before olivine, and to have continued to grow through later stages of crystallisation. They contain inclusions of plagioclase and Ti-magmetite, magnetite and ilmenite. Plagioclase typically forms laths, 0.5-1.0 mm, which are twinned and strongly zoned from An 65 Or 1.0 cores to An 50 Or 1.6 rims. One smaller grain which was completely enclosed in augite is bytownite, An 84 Or 0.2, presumably a grain of early-formed plagioclase, protected from later reaction with melt by the enclosing pyroxene. Orthopyroxene is present as narrow rims on olivine, and as small discrete grains, and has composition Mg 73.2 Ca 1.3. The large grains of opaque minerals are mostly magnetite, but some are ilmenite; smaller grains of both magnetite and ilmenite are present; titanomagnetite was found only as an inclusion in augite, and possibly was an early-formed phase. Magnetite contains 1.3 per cent $Cr_2 0_3$. Phlogopite is intergranular and encloses the other minerals as oikocrysts 4-6 mm across. It has a strong red-brown colour, is titanium-rich, and is intimately associated with magnetite. Where in contact with augite, it appears to have scavenged fine opaques from the augite. Mg/Fe ratio is 2.9, TiO_2 6.5 per cent, and K_2O 9.3 per cent by weight (Table 6).

K-Ar age: 13.3±0.1, 13.2±0.1 Ma, phlogopite (Table 2).

01.07 Elongated sub-angular block about 45 x 22 x 15 cm, of pale-coloured, hard volcanic rock without MnO coating (or only 0.1 mm) is chloritised and silicified volcanic breccia of angular lava clasts (various types of lava) in matrix of finer angular lava fragments; matrix includes some feldspar phenocrysts to 0.5 cm.

01.08 Sparsely feldspar-phyric flow-textured metasomatised 'basalt', now entirely made over to albite, K-feldspar, quartz, hornblende, magnetite and some ilmenite, epidote and some prehnite. The rock is similar to 01.05 but has fewer amy doles, a darker colour, and is seen in thin section to be finer-grained, and to have a higher proportion of coloured minerals, and fewer phenocrysts. Groundmass is about 50 percent hornblende, 35 per cent plagioclase (and possibly quartz), and 5- 10 per cent magnetite.

The hornblende differs from that in 01.05 in being more strongly pleochroic, from yellow to bluish-green, and has a more tremolitic composition (Table 6). Plagioclase microphenocrysts have been replaced by albite, K-feldspar, and some epidote; albite also replaces groundmass plagioclase laths and is present in veinlets, together with quartz, calcite, epidote and prehnite (Table 6). Quartz and prehnite also occur irregularly through the rock, possibly in former vesicles. Opaques are prominent and are mostly magnetite, with some ilmenite.

01.09 Silicified, chloritised and hematitic volcanic breccia similar to 01.07.
01.10 Similar.

01.11 Fractured dark-coloured basalt similar to 01.08 and 05 has thick (to 2 cm) MnO coating.

01.12 Medium-grained syenogabbro. No MnO coating. This is a more felsic variant of 1.06, but contains the same minerals (olivine, cpx, phlogopite). Both plagioclase and clinopyroxene are up to 4 mm; some of the plagioclase is cloudy (like the cpx) due to fine inclusions of opaques.

01.13 Silicified former felsic lava or fine-grained intrusive rock, fine dark mineral dispersed throughout, has later fossiliferous limestone as fracture fillings.

01.14 Red scoriaceous hornblende-phyric 'basaltic' lava has fine sedimentary carbonate throughout. Hornblende is unaltered and could be dated, but rock may be not in situ. The red lava is probably former glass of felsic composition, and is entirely altered to clay.

Comment
The two samples 01.05, 01.08 were *in situ*, as was indicated by MnO coating more than 2 cm thick. Both are of metasomatised 'basalt' (not enough primary minerals

are preserved to permit a more precise name) and are characterised by ubiquitous fine hornblende and sodic (or relatively sodic) plagioclase. 01.05 os remarkable also for the presence of apatite, and 01.08 for K-feldspar. Both have a relatively high content of magnetite.

The phlogopite melagabbro, 01.06, or related intrusives, may be the source of fluids which have metasomatically altered the nearby basalts 01.05 and 01.08.

DREDGE 02

77° Graben, 57°18′S, 77°36′E, 2200-2400 m water depth.

160-200 kg of rock was recovered from an estimated depth of 2200-2400 m on a west-facing scarp at position 1630 hours on BMR47 Line 19. The largest single rock fragment was a rounded boulder of karstified limestone measuring about 100 x 60 x 50 cm (02.04). Next largest was a sub-rectangular block of hematitic quartzite, roughly 60 x 40 x 20 cm (02.03). Another notable rock fragment was a gently-arched thin slab of basalt, 50 x 30 x 3 cm (02.01).

Numerous smaller fragments were a mixture of altered basalt and possible intrusive (02.02, 6, 10, 11, 12) and limestone, and minor opaline silica/chert (02.07,8). The basalt is fine-grained and extensively altered to saprolite. Much of it was initially mis-identified as siltstone or argillite.

None of the red quartzite (02.03) was found amongst the finer fragments of the dredge haul and it was concluded that the quartzite was exotic, presumably ice-rafted.

The proportions of the rock types assumed to be *in situ* were approximately 60% basalt, 35% limestone and 5% chert/opalline silica.

Sample Descriptions — **All sample numbers have prefix 86DR**

02.01 Gently arched slab of basalt (initially thought to be sediment) with Mn oxide coating to 1 mm.

This is a sparsely feldspar-phyric intersertal basalt, made up of laths of plagioclase, clinopyroxene and ilmenite, up to 0.5 mm long, in a groundmass of palagonite and, locally, much zeolite. Plagioclase is strongly zoned, from An70 (cores of microphenocrysts) to An 62 Or 3 (rims of same) and An 49 Or 3 (rims of groundmass plagioclase). The high orthoclase content of the labradorite and andesine-labradorite is unusual. The few pyroxene laths which are sufficiently unaltered for analysis have variable composition, from En 48 Fs 13 Wo 38 to En 32 Fs 32 Wo 36, with moderate amounts of TiO_2, $A1_20_3$ and Cr_20_3. The groundmass palagonite has relatively high K_20 at around 2.1%, and low Na_2O and TiO_2 (both around 0.1%); Mg/Mg+Fe* is 52.

The high Or content of plagioclase, the high levels of K_20 in palagonite, and the variable composition of clinopyroxene all indicate alkaline transitional alkaline basalt affinity.

02.02 Pink-brown, altered, amygdaloidal basalt; about 20% amygdules typically of dark green celadonite as an outer rim around and brown zeolite? The same two minerals also occur in veinlets. In other fragments of this rock type are plagioclase phenocrysts (up to 1 mm) and rare brown laths, probably alteration after pyroxene; plagioclase microlites and fine opaques in groundmass; opaques are unusually high proportion, say 5-10%. In thin section see plagioclase, altered clinopyroxene, opaques, celadonite dispersed and in amygdules with colourless and brown zeolites. Another thin section of 02.02 is glomerophyric basalt (plagioclase- clinopyroxene with possible olivine pseudomorphs), with a partly flow-textured groundmass which includes considerable K-feldspar. Phenocrysts are up to 1.5 mm and comprise 15% of the rock; plagioclase is zoned and all are somewhat altered. Groundmass is plagioclase (40%), clinopyroxene to 0.5 mm (15%), intersertal K-feldspar (15%), acicular opaques to .2 mm (10%) and argillic alteration (20%). Many moderate-size boulders of this (see also 02.06, 10, 11, 12).

02.03 Pink arkosic quartzite : larger (1 mm) rounded quartz grains in finer pink-coloured groundmass of mixed grains. One large block, probably exotic.

02.04 Pink bioclastic limestone forms large karstified boulder with very thin and incomplete Mn oxide coating. Pelecypods, crinoid fragments; grain-size 1-4 mm. Some smaller fragments of same rock type.
Micropalaeontology (D.J. Belford, pers. comm., 1986): Echinoid spines, algae, bryozoa mollusca, fragments of benthonic foraminifera, coral. Age not known

02.05 Same rock type as 02.04 but sheared. Many pieces of this.
Micropalaeontology by D.J. Belford (pers. comm., 1986): Algae, bryozoa, mollusca, very rare benthonic foraminifera (unidentifiable). Age probably Tertiary. Environment : Outer shelf.

Lack of cheilostome bryozoa suggests older than Cenomanian (B. Walter, Lyon, pers. comm., 1987)

02.06 This represents the altered basalt which makes up about 60 per cent of dredge haul 02. It is a glomerophyric rock with xenocrysts of labradorite/bytownite, K-feldspar and minor albite set in a host rock of K-rich labradoreite, augite, and Ti-magnetite dominant over ilmenite. The xenocrysts are partly replaced by K-feldspar and albite. Other alteration minerals include prominent celadonite.
Groundmass has some fluidal texture defined by plagioclase laths, with fine clinopyroxene and much fine opaques. Xenocrysts are moderately altered grains to 2.5 mm, 10% of rock. Groundmass plagioclase microphenocrysts to 0.25 mm and flow-aligned finer laths (30%); K-feldspar sub-equant, 0.1-0.15 mm (20%); clinopyroxene 0.05 mm, moderately altered (20%); opaques rectangular grains 0.02 mm (10%); clay alteration (20%).

Plagioclase in the xenocrysts is An 67-75 Or 1; it is closely associated with, and appears to have been replaced by, K-feldspar, some of which has about 8 per cent of albite molecule. The xenocrysts are rimmed by labradorite, An 57-64 Or 2, which appears to have formed by reacton of xenocryst with host rock melt; labradorite (An 63 Or 4) also forms veinlets which cut across some xenocrysts. Plagioclase laths in the host rock are An 58-59 Or 2-6. Augite has composition around En 49 Fs 13 Wo38, with slight Fe enrichment towards grain boundaries.

02.07 Slab of brown opaline silica with white alteration (dehydration, recrystallisation) above and below. Some pieces have up to 8 mm of Mn oxide coating.

02.08 Chert or opaline silicia, white, translucent, some fine trace fossils.

02.09 Fine-grained siliceous sediment, peculiar ashflow-like texture, altered, yellow-white colour (only one small piece of this). Reversed 3rd & 4th peaks XRD-Q, nontronite 15R. Trace of calcite.

02.10 Breccia of medium-grained trachybasalt (02.02-type), angular centimetric clasts in brown non-calcareous matrix which includes glass shards or small trace fossils. Only one piece.

02.11 Breccia of altered felsic lava clasts in matrix of the same dark green celadonite and brown zeolite? that elsewhere occupy amygdules. Only one piece. XRD nomalous strong peaks @ 2.51 and 2.83A - cristoballite?

Note micro-faults in some cherts.

02.12 Altered 'basalt'; no amygdales. Rock and minerals similar to 02.06, with the exception that celadonite is more prevalent. Megacryst plagioclase is An 70-78 Or 1, and host rock plagioclase is An 59-66 Or 3-4. K-feldspar is present as megacrysts in glomeroporphs, and as small (.03 mm) areas within megacryst plagioclase. K-feldspar is a late-stage alteration product, no doubt related to interaction with sea water. It selectively replaces the more calcic megacryst plagioclase.

DREDGE 03

77° Graben up slope from Dredge 02, 57°18'S, 77°35'E, 2200-2000 m water depth.

About 240 kg of rock was recovered from near the top of the west-facing scarp at the 1630 hours mark on BMR47 Line 19, in a water depth of about 2000-2200 m, directly up-slope from Dredge 02. The sample was dominated by large boulders (maximum size 45 x 40 x 30 cm) of granite, granitic gneiss, amphibolite and red quartzite. Most of these were faceted, had little or no MnO coating, and may be assumed to be of exotic (ice-rafted) origin. About one-sixth of the sample was made up of sub-angular pieces of chert (maximum size 25 x 20 x 15 cm) with thick (to 1 cm) MnO coating; this was assumed to be in situ. Most of the chert was white and very finely granular, as though dehydrated and re-crystallised; no organic remains were seen.

03.01 Chert

03.10 Pink quartzite

DREDGE 04

77° Degree Graben, base of scarp below sites 02 and 03, 57°17'S, 77°37'E, 2600-2400 m depth.

300-400 kg of rock was collected from a water depth of 2400-2600 m at or near the base of the west-facing scarp at about the 1630 hour mark on BMR47 Line 19. Almost the entire sample was chert, with minor interbedded (and separate fragments) of finely (1 mm) re-crystallised dolomite; all carried a thick Mn oxide crust (up to 1 cm). The chert is typically of brown opalline silica with white alteration on margins, as noted in previous dredge hauls. The re-crystallised carbonate consisted of fine euhedra, trapezoidal in section, with some curved crystal faces, set in a milky amorphous matrix and, less commonly, in opaline silica ('chert'). Largest piece of chert was a slab about 100 x 75 x 18 cm.

Other material in the sample included two boulders of the altered basalt which was encountered in Dredge 02, and is characteristic of Dredges 05 and 06, and one piece of presumably ice-rafted granite.

04.01 The carbonate rhombs have curved faces, a characteristic of dolomite. Composition is ca:mg 12:10, with negligible fe. The groundmass is 51-52% $Si0_2$ and 4-5% $A1_20_3$ with Fe, Mg, K, Na oxides each 0.5-1.5% each and $T10_2$ 0.2-0.3%
Fine inclusions in the cores of the rhombs give the illusion of zoning but repeat analyses show no systematic chemical zoning between core and rim. Specifically there is no increase in Fe content. Poorer stoichiometry in rim.
Note : The sample numbered 04.01 in the MNHN collection is an altered basalt plagioclase-cpx-phyric, with prehnite alteration

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DREDGE 05

77° Graben, 58°06.74'S, 76°54.54'E, approximate water depth 2200 m, day 67.

About 1.5 tonnes of rock was dredged from an east-facing scarp on the west flank of the 77° Graben, a few km north of the BMR47 free-fall grab site. The sample is dominantly of limonitic saprolitic basaltic lava, some of which is coarsely porphyritic. This occurs principally as (a) large angular blocks of the saprolitic lava, but includes (b) some volcanic breccia of angular lava clasts in calcite matrix (50 per cent matrix), and, less commonly, (c) a conglomerate of lava cobbles and rare chert in bioclastic limestone matrix.

The calcareous matrix of the volcanic breccia (b) includes trace fossils but is mostly finely recrystallised calcite, and is unlikely to yield diagnostic microfossils. The matrix of the conglomerate (c), on the other hand, is richly organic, and should yield age-diagnostic fossils. The matrix of the conglomerate is bioclastic limestone. It includes corals, bivalves, and foraminiferas. It is partly ex-solved, and the cavities lined with opaline silica. The comglomerate is younger than the breccia, as is indicated by the presence of cobbles of the volcanic breccia in the conglomerate. The lava and volcanic breccia are too altered for isotopic age determination, but the fossiliferous limestone of the conglomerate may contain diagnostic foraminifers.

05.01 Argillically-altered aphyric intersertal basalt with prominent opaques. Primary minerals are plagioclase (0.1 mm laths, about 50% of rock), granular clinopyroxene, now mostly altered (about 30%), opaques (about 10%) and intersertal glass (now entirely smectite; about 10%). About 25% of the rock is altered to clay minerals. K-feldspar was not confirmed but may be presen in groundmass (see 05.02). The rock looks like the typical 'trachyandesite' of BMR47 grab samples from same general region. The latter contained some unaltered oligoclase and andesine phenocrysts, tending to high K content, but no other minerals sufficiently unaltered for analysis by microprobe (Colwell et al., 1988).

05.02 Sub-ophitic intersertal medium-grained trachybasalt with what appear in hand speciment to be prominent acicular opaques. The rock is probably a coarser equivalent of lava 05.01. Primary minerals are plagioclase laths (to 0.3 mm, 35%), sub-equant clinopyroxene to 0.3 mm and as microphenocrysts to 0.5 mm (about 25%), acicular opaques to 0.3 mm, intersertal glass, now entirely smectite (20%), fine K-feldspar in groundmass, and some argillic alteration. Plagioclase compositions range from An 60 Or 1 in cores to An 47 Or 2 and An 34 Or 4 in rims. Clinopyroxene composition is around En 50 Fs 15 Wo 35, with slight Fe enrichment on rims and in groundmass grains (51/18/31). Ilmenite and some Ti-magnetite are prominent opaques.

05.03 Plagioclase-phyric sub-ophitic intersertal trachybasalt, closely related to 05. 01 and 02. Plagioclase occurs as broad prisms up to 6 mm and, in the groundmass, as laths to 0.5 mm (50%), clinopyroxene as sub-equant grains to 0.5 mm (30%), opaques to 0.3 mm (5%), and smectite after intersertal glass (15%).

5.04 Volcanic breccia of angular basalt clasts in matrix of finely re-crystallised calcite; matrix is 50% of rock; trace fossils poorly preserved. Clasts include basalt types similar to 05.01, 02 and 03.

05.04A Basalt minerals are: Plagioclase An_{53}, cpx Mg:Fe:Ca 49.1 : 13.5 : 37.4, ilmenite. The matrix is a bioclastic wackstone of recrystallised calcite with spicules, echinoderm plates, rare bryozoa debris and bivalves. The matrix includes the age-diagnostic foraminifer Hedbergella and small benthic forams.

05.04B Basalt clast has plagioclase (An_{64}) and Ti-magnetite; groundmass is 90% fluor-apatite, some is clear, some murky, cleavage makes fine meshwork. Some of groundmass is calcite, clear, recrystallised. Small black blebs are Mn oxide and yellow blebs are glauconite.

Comment on 05.04B by R.E. Garrison: 05.04B is similar to 5.09. One major difference is that the original biomicritic sediment was only partly phosphatized and much carbonate remains; for example, nearly all of the abundant echinoderm spikes are beautifully preserved as large single crystals, which is what one would see in an uncrystallized limestone. Phosphatizations seem to have preferentially replaced the fine-grained carbonate matrix, but in parts of the rock even this is preserved. Several generations of phosphatization are evident.

Like specimen 05.09, there was a later influx of infiltrated sediment which contains fairly well preserved planktic forams (which a micropalaeontologist might be able to identify and date), leading me to believe this was a relatively deep water sediment.

Other grains present are glauconite peloids, basalt clasts, forams (some unreplaced, sitting in a phosphatized matrix; these are benthic forams of first generation sediment as opposed to the planktic forams of the infiltrating carbonate).

At least three generations of phosphatization are evident, indicating slow sedimentation rates. Some glaucophane is replaced by phosphate, indicating less oxic conditions.

05.05 Conglomerate: rounded pebbles of saprolitic trachybasalt in matrix of bioclastic limestone; rare pebbles of chert, fine volcanic breccia of 04 type, and finely recrystallised limestone of 04 type. The limestone matrix includes fragments of coral and small bivalves and probably large foraminifera. Small cavities and fissures in limestone are lined with agate; some cavities partly filled with unconsolidated fine calcareous sediment. Rock has 2 mm Mn oxide coating.

By electron probe, matrix is entirely fluorapatite (F = 5%). Apatite has replaced forams also. By XRD matrix is apatite, dolomite and unidentified mineral (strong peak 3.60A), with some Mn oxide. The basalt clasts include plagioclase An_{65} and Ti-magnetite, and some zeolite(?).

Micropal:
Planktonic foraminifera, echnoid spines, Mollusca, unidentifiable Globigerinidae.
Age : Definite Tertiary (D.J. Belford, pers. comm., 1986)
Diatoms & radiolaria in cavities. One cavity filled with radiolaria, could be very young (R.C., Ga, 1987).

Comments on 05.05 by R.E. Garrison, 1987: 05.05 is like specimens above (05.04B), except more strongly altered. Very little primary carbonate sediment has been preserved - most was phosphatized. Extensive ferruginization (Fe-Mn oxide??) has replaced parts of the rock. An interesting aspect is the presence of a large grain (indicated by pink marker pen) of glauconitized Foraminiferal sediment - most of the forams look like planktic forams. This may have been a deeper water ooze that became replaced by glauconite.

The basic pattern is the same as in the samples above, i.e. shallow water carbonate (mostly foramins and intraclasts - relatively few echihoderms) became phosphatized; later infiltration of carbonate ooze containing planktic forams. An interesting variation is that in at least one patch, the infiltrated carbonate sediment (including the forams) appears to have been replaced by zeolites and/or secondary clay minerals.

05.06 Probably the same conglomerate but matrix entirely replaced by MnO.

05.07 Typical conglomerate has much matrix removed presumably by later dissolution.

05.08 05.03-type porphyry fragment selected for possible radiometric age determination, but is clearly too altered. This is the same coarsely porphyritic basalt that is characteristic of Dredge 02 - see also 05.11. It consists of andesine/labradorite megacrysts (to 6 mm) in a matrix of andexine/labradorite, very variable clinopyroxene, ilmenite and Ti-magnetite, and alteration minerals, including prominent celadonite (Table 6).

Plagioclase composition in megacrysts is An 52 Or 2 to An 41 Or 2 on rims, and in groundmass is An 48-52 Or 2. Clinopyroxene composition ranges as follows : En 24-41 Fs 22-42 Wo 34-37.

05.09 Bioclastic limestone, partly replaced by MnO. Amorphous matrix is 90% apatite. The collection of apparently detrital grains at A is of quartz, glauconite, clay, apatite.

Comments on 05.09 by R.E. Garrison:
Phosphatized skeletal limestone with ghost-like outlines of corals, possible calcareous algae, echinoderm spikes, foraminiferal tests, peloids, and intraclasts in a finely-crystalline matrix of carbonate and fluorapatite. The original sediment would probably have been a biomicrite in the classification of R.L. Folk. It looks as though it contained relatively shallow water fossil assemblages (eg coral, echinodemia, - the latter rather abundant), but I suppose it could have been redeposited into deeper water. Also present are scattered clasts of fragmented basalt, and sparse feldspar and glauconite grains. Some patches of finely crystalline carbonate are also present. Some of the basaltic rock fragments appear to have dissolved and the resulting vugs are partly infilled by zeolites and secondary, finely crystalline carbonate (noted above); the cavities contain foram; probably a carbonate ooze (deep water?) infiltrated into cavities after phosphatization.

There appear to be at least two generations of glauconite : (1) an earlier generation which is cemented into the phosphatized limestone, (2) a latter generated which is infiltrated, along with unphosphatized carbonate, into vugs. There are also a few phosphate peloids associated with the latter kind of glauconite. Opaque material (Fe-Mn oxides??) coat and partly replace many of the grains, fossil and otherwise, in the phosphatized limestone.

Let me make a speculative scenario for this rock (unconstrained by any knowledge of the overall setting!)
(1) deposition of shallow-water carbonate sediment on 2 shoulders submerged seamounts.
(2) subsidence and non-deposition because the seafloor sinks below the zone of

maximum carbonate productivities.

(a) First within the OXIC zone, so that Fe-Mn oxides start to coat and replace grain line vigs.

(b) Then into the suboxic zone (e.g. edge of the oxygen minimum zone) where glauconite forms.

(c) Then into the oxygen minimum zone, or some other low oxygen water mass, where phosphatization takes place.

(d) Then below the low oxygen water mass (below 0_2min. zone) where pelagic carbonate was deposited and infiltrated into vugs.

At some stage associated with or prior to stage (d) there was dissolution of basaltic rock fragments, then precipitation of zeolite into the vugs, then infiltration of pelagic ooze (+ some glauconite, phosphate and feldspar) grains into the vugs thus produced. Finally, this infiltrated ooze became partly recrystallized to calcite and/or dolomite (fine to coarse euhedral rhombs).

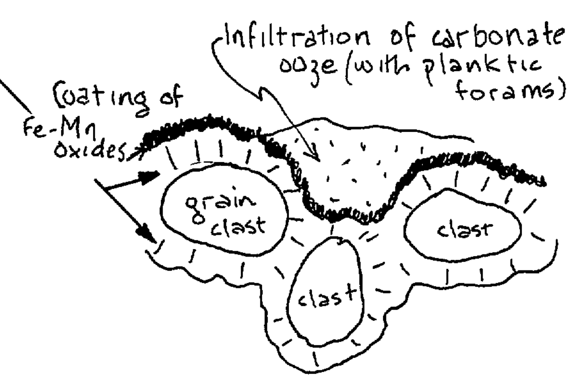
I think the actual diagenetic story is somewhat more complicated. For example, some of the fossil fragments (corals, echinoderms) were partly dissolved, and the resulting vugs became partly lined by a reddish-brown, laminated material which is birefrigent and resembles palagonite (can palagonite be precipitated from pore fluids? This material is clearly void-filling cement); also zeolites were precipitated in such vugs.

It may be that there were few or no basaltic glass fragments in this rock, and that all of the vugs resulted from dissolution of carbonate fossils.

This is a very interesting rock; more could be learned from additional study, if this seemed worthwhile.

5.09 is like 5.05 except that echinoderms are very rare. Infiltrated carbonate sediment contains both planktic forams and radiolaria, hence appears definitely a deeper water facies than the phosphatized limestone (which here however contains both benthic and planktic foraminifera). A particularly interesting aspect here is that there are well developed rim cements which appear to be phosphatized.

Isopachous rim cement = submarine cement; probably originally a carbonate cement (possibly overlain by zeolites) - it now appears to be partly or entirely phosphatized. The significance of this is that it suggests that carbonate cementation (submarine) preceded the main phase of phosphatization.



General comment on 5.04B, (breccia), 5.05 (conglomerate) and 5.09 (bioclastic limestone) by R.E. Garrison:

These are complex rocks. They seem to have started out as shallow-water deposits which then subsided through different diagenetic and sedimentological zones, e.g., glauconite = suboxic zone, phosphate = suboxic to anoxic zones; there is a suggestion that these deposits subsided through the oxygen minimum zone and into deeper water where planktic foram oozes were deposited (infiltrating into vugs and other cavities). Overall an interesting if complicated story (especially the multiple generation of phosphatization in 05.04B.

05.10 05.01-type lava, least altered

This is the altered aphyric quench basalt which is the dominant rock type in Dredge 05; it may be related to the porphyritic basalt (05.08, 05.11) but indications are that it is more akin to a true basalt, whereas the porphyry has higher Na and K (as indicated by plagioclase compositions, prevalence of celadonite, and by approximate analysis of the groundmass of 05.10 by traversing the rastered beam across the polished section).

Plagioclase microphenocrysts are labradorite/bytownite An 70-73 Or 0.4, with labradorite rims An 60 Or 1-2. One groundmass plagioclase is An 54 Or 1. Clinopyroxene was too altered for analysis. Opaques are ilmenite and Ti-magnetite. Small amygdales are smectite (Mg, Al, Si peaks).

05.11 05.03-type porphyry

Coarsely plagioclase-phyric intersertal basalt, of the same type as 05.03 and 05.08. Prominent plagioclase megacrysts, 2 mm long, form about 40 per cent of the rock, and are set in a groundmass of finer plagioclase laths (0.2 mm), sub-ophitic equant clinopyroxene (0.5 mm), acicular ilmenite and some Ti-magnetite, and fibrous chloritic alteration, with fine opaques, probably after palagonite.

The plagioclase megacrysts are strongly zoned from labradorite cores (An 65 Or 1) to andesine rims (An 40 Or 2.6); groundmass plagioclase ranges from labradorite (An 55 Or 1) to andesine (An 40 Or 2.6). Clinopyroxene compositions are variable around En 45 Fs 14 Wo 41 and show some Fe enrichment on rims (Fs 18-26). A very little K-feldspar is present as small patches (to 6 microns) of late-stage alteration within labradorite megacrysts, and there is up to 0.8 per cent of K20 in the chloritic fibrous alteration noted above.

<u>DREDGE 06</u>

77°E Graben, 58°16.89'S, 76°55.31'E, approximate depth 2650 m, day 68.

About 1.5 tonnes of rock was dredged from the east-facing scarp on the west flank of the 77° Graben, between the sites of 05 and the BMR free-fall grab locality. The sample was predominantly large (say 30-50 cm) blocks of limonitic saprolitic trachybasalt of the 05 type, including some minor breccia of angular lava fragments in finely-recrystallised calcite matrix.

Sample descriptions **All sample numbers have prefix 86DR**

06.01 A single 30 cm slab of dark green saprolitic amygaloidal lave, very fine-grained basaltic texture; mostly saprolite; amygdules are the familiar green celadonite outer shell and brown zeolite core. The slab has little or no Mn oxide coating. Rock is about 40 per cent argillically altered, includes plagioclase laths; 5% amygdules.

06.02 Altered trachybasalt of Dredge 05 type with much plagioclase and prominent opaques. Plagioclase prominent laths 0.2-0.3 mm (50%), some flow texture; opaques acicular 0.2-0.3 mm (10%) locally ophitically enclose plagioclase; alteration brown smectite (935%) and colourless lowbirefringence material (5%).

06.03 Breccia of lava clasts (to 3 cm) in matrix of finely recrystallised calcite. All lava clasts are saprolite; most common is linonitic very fine-grained formerly-vesicular and vitrophyric trachybasalt (?) with prominent laths of plagioclase to 0.1 mm (50%) and hematitic/limonitic saprolitic groundmass; some clasts less altered have fine opaques.

06.04 Exotic block of leucocratic granitic gneiss with sillimanite.

06.05 Exotic block of hornblende granite.

06.06 Breccia of trachybasalt(?) clasts in matrix of finely-recrystallised calcite, similar to 06.03 with the exception that the matrix includes finer (millimetric) volcanic fragments (shards). All volcanics entirely saprolitic. Glass shards in carbonate matrix are palagonite with moderately high K_20. Basalt clasts have plagioclase and altered cpx. Matrix and recrystaliized matrix are calcite.

06.07 Similar to 06.06; note trace fossil. Amygdale in basalt has quartz in centre, fine rim of calcite, wider rim of zeolite? (isotropic; Fe Mg A1 Si peaks). Matrix is mostly very fine grained calcite, with sparry calcite veining; some Si in matrix. A veinlet is ribbon quartz with later (central) calcite veinlet. Glauconite grain, green.

06.08 Similar to 06.03, 06 and 07, but matrix is 80 per cent of rock. Fine basalt clasts in carbonate matrix. Matrix is entirely calcite. Plagioclase in basalt is An_{52}.

06.09 Similar to 06.06, 07, 08.

06.10-13 are examples of different varieties of saprolitic lava:

06.10. Amygdaloidal, some amygdules have quartz in core, groundmass may have primary minerals.

06.11 No amygdules, groundmass may have primary minerals. Limonitic saprolitic sparsely phyric (plagioclase, clinopyroxene) 'basalt' makes up much of Dredge 06. Sample 06.11 was selected for analysis as representing some of the least altered material.

Plagioclase microphenocrysts are labradorite (An 65 Or 1) with andesine-labradorite rims (An 48 Or 2); groundmass plagioclase includes well-formed labradorite laths (An 48 Or 2-4). A single clinopyroxene microphenocryst is augite En 47 Fs 14 Wo 39, but groundmass clinopyroxene microphenocrysts are consistently more iron-rich, e.g., En 34 Fs 30 Wo 36. Opaques are acicular ilmenite and equant grains of Ti-magnetite.

06.12 Saprolitic finely holocrystalline 'basalt' with rare augite microphenocrysts, and sparse vesicles which are lined or filled with carbonate. Plagioclase groundmass laths are K-rich laberadorite (An 53-56 Or 2-4), with rims and finer grains of andesine (An 37-40 Or 4). Groundmass c;linopyroxene is too altered for analysis; microphenocrysts are En 48 Fs 13 Wo 39. Opaques are acicular ilmenite. Rough estimate of whole-rock chemistry traversing polished section beneath rastered probe beam indicates K_20 0.8%, and Mg# (100Mg/Mg+Fe) = 21.

06.13 Calcite-veined finely amygdaloidal lava.

Notes: Explosive lava breccia is 06.03, 6, 7, 8, 9, 13.

06.14 Typical Dredge 6 lava, selected from a large block as being least altered. In thin section it is a sparsely micro-porphyritic, sparsely vesilular intersertal 'basalt', with minor calcite veining. Plagioclase, clinopyroxene and ilmenite (and Ti-magnetite) occur as intergrown laths and appear to have crystallised together. Plagioclase and clinopyroxene form rare microphenocrysts, and palagonite is intersertal.

Plagioclase microphenocrysts and groundmass laths are andesine/labradorite: microphenocrysts An 51 Or 2 with rims An 41 Or 3, and groundmass laths An 48 Or 2-3. A clinopyroxene microphenocryst is En 49 Fs 16 Wo 35 (47-15-38 on rim), and groundmass clinopyroxenes are richer in iron: typically En 40 Fs 22 Wo 37. Ilmenite forms prominent acicular grains, and Ti-magnetite smaller and less common equant grains. Vesicle size is around 3 mm.

Approximate analysis of intersertal palagonite indicates some potassium (around 2% K_20), and Mg# (100 Mg/Mg+Fe) = 25. See Davies et al. (1989) for full analysis.

General Comments on Basalts of DR05 and 06

The three samples from Dredge 06 are similar, and confirm that the lavas in this dredge haul are a homogenous collection. The Dredge 06 lavas also are broadly similar to the aphyric lavas of Dredge 05 (as represented by 05.10), with the exception that in 05.10 plagioclase compositions were generally more calcic; e.g. there is no andesine in 05.10 but there are andesine rims and small grains in Dredge 06 samples.

Considered as a group, and including the porphyritic lavas of Dredge 05, the lavas of Dredges 05 and 06, like those of Dredge 02, show some degree of alkali enrichment, and all have prominent opaques. Approximate analyses of groundmass and of palagonite indicate that they are ferrobasalts. This was confirmed by full analyses (Davies et al., 1989).

DREDGE 07

55°18.65'S, 77°27.93'E, approximate depth 1800 m, day 71.

Summary. About 400 kg of rock was dredged from the northern end of the 77° Graben at a point about 300 km north of Dredges 05 and 06. Most or all of the *in situ* material (as indicated by MnO coating 2 cm thick) is a conglomerate of moderate to large boulders (up to 50 x 20 x 15 cm) of saprolitic lava, cemented by Mno and, in places by carbonate. The most common lava type is red (hematitic), formerly high-vesicular to scoriaceous, very fine-grained or glassy, felsic lava, now mostly saprolite (2, 14, below); commonly the vesicles are filled with carbonate or other filling, of various colours. In thin section, this rock is seen to be very similar to the basalt of dredge hauls 05 and 06. Also present is the typical altered basalt and basalt lava breccia with fine calcite matrix, as was found in Dredge 05 and 06. The dredge haul also included a number of large faceted blocks of exotic rock (quartzite, gneiss, etc.).

Sample descriptions — **All sample numbers have prefix 86DR**

07.01 Same as the limonitic saprolitic basalt typical of Dredges 05 and 06. Plagioclase laths to 0.2 mm (45%), clinopyroxene 0.05 mm too altered to probe (15%), opaques 0.02 mm (5 %), colourless intersertal K-feldspar (?) (15%), fine limonite (20%).

07.02 Amygdaloidal sparsely phyric ophitic intersertal basalt with purple colour due to hematite alteration. This is the most common rock type in dredge 07. Plagioclase to 0.1 mm (30%), clinopyroxene equant to 0.2 mm, K-feldspar cloudy alteration interstitial (10%), opaques to 0.02 mm (5%), smectite after intersertal glass (20%), hematite (10%); zeolite in amygdale 2 mm across.

07.03 Scoriaceous saprolitic formerly-glassy lava clasts in matrix of finely-recrystallised calcite, which includes finer volcanic clasts. Vesicles are lined with green celadonite.

07.04 Similar to 07.03 but with high proportion of calcite, and fine clasts of altered lava. Matrix has foraminifers; is entirely calcite, very fine grained and partly recrystallised. Scattered grains of clay (?) with rectangular cleavage, 0.3 mm, has Na, K. A1, Si peaks (illite?). Plagioclase in basalt is An_{53}.

07.05 Typical green-grey amydaloidal lava, which characteristically has thick Mn oxide crust.

07.06 Phyric trachybasalt or mugearite; phenocrysts of clinopyroxene, plagioclase to 1.5 mm, and opaques to 0.15 mm, in trachytic (flow) textured groundmass of crystals to 0.05 mm with occasional rhombs of K-felspar and much argillic alteration.

Clinopyroxene phenocrysts are rimmed with fine grains of hornblende (?), apparently reacion with melt.

07.07 Superficiallty similar to 07.06 but with amygdules of calcite. In thin section is seen to be plagioclase-phyric intersertal coarse trachybasalt. Labradorite(?) phenocrysts to 2.5 mm with phyllosilicate alteration on cracks and commonly unaltered core and rim with alteration between; groundmass of sub-ophitic plagioclase laths and equant clinopyroxene, both to 0.2 mm, with opaques to 0.1 mm. Intersertal yellow phyllosilicate with moderate birefringence probably is smectite after glass. Amygdales to 10 mm, some of zeolite, others of carbonate with, in one case, euhedral zeolite enclosed. Rock is 15% phenocrysts, 10% amygdules. Groundmass is 40% plagioclasem 20% clinopyroxene, 30% smectite, 10% hematite.

Plagioclase phenocrysts are An 68-76 Or 0.2-1.0, with rims An 65 Or 1; groundmass plagioclase is An 58 Or 1. Groundmass clinopyroxene is typically En 45 Fs 16 Wo 39. Celadonite is colourless.

07.08 Red quartzite (exotic)
07.09 Felsic gneiss (exotic)
07.10 Biotite-feldspar gneiss (exotic)
07.11 More-massive gneiss (former intrusive?) (exotic)
07.12 Marble (exotic)
07.13 Quartz-feldspar-biotite gneiss (exotic)

07.14 Amygdaloidal hematitic saprolitic trachybasalt lava of the 07.02-type, some unaltered plagioclase. This is another sample of the typical amygdaloidal lava of Dredge 07, and is similar to 07.07 except for a lack of phenocrysts, some indication of flow texture, and a higher degree of alteration. Calcite and Mn oxides form prominent (to 2 cm amygdules. There is smectite alteration of clinopyroxene, and most opaques are altered. No celadonite was detected but the red-brown ferromagnesian alteration mineral characteristic of 07.07 is present.

Plagioclase is labradorite An 62 Or 1, and clinopyroxene is augite with uniform composition around En 44 Fs 16 Wo 41. Potassium is present in the smectite alteration, and as very local potassic alteration of plagioclase (hydromuscovite?).

Comment
The characteristic 'basalt' of Dredge 07 differs from those of Dredges 02, 05 and 06 in the absence of any clear indication of alkali enrichment.

DREDGE 08

50°18.90'S, 74°48.75'E, from base of northeastern margin of plateau, day 74.

Summary. About 250 kg of rock was dredged from the lower part of the northeastern flank of the Kerguelen Plateau, down-slope and a short distance SSE of the location of MD35 Late Cretaceous chalk. The sample was mostly made up of large sub-angular boulders, 30-50 cm across, with little or no Mn oxide coating. Of these about 60 per cent were what appeared to be unaltered Neogene-Quaternary porphyritic basalts (08.01, 2, 3), and 30 per cent sub-rectangular blocks of soft altered basalt with sub-parallel parting (08.04, 11). The remainder of the sample was made up of rounded and near-spherical boulders of porphyritic basalt, and irregularly shaped fragments of a soft and vuggy white rock, of low density. The latter was the only rock-type to carry a measurable coating of Mn oxides (3-4 mm).

The altered basalt (08.04) is too soft to have been transported far and is almost certainly from outcrop or a colluvial apron. The white rock (08.12) also was probably *in situ*. The several large blocks of porphyritic basalt all have broadly similar composition and thus may have come from the one source - perhaps an exposure of dyke-rock or lava up-slope. The rounded boulders are of generally similar porphyritic basalt and are either from fluvial or littoral sediments within the Neogene (Serie superieure), or were ice-rafted from the Kerguelen Islands region.

The white rock (08.12) is mostly vuggy and soft and difficult to identify. One piece, perhaps less altered, consists of (a) lava fragments in a matrix of (b) white former limestone. Solution cavities in the former limestone have been filled with (c) translucent, probably formerly calcareous, fine sandy sediment. The white former limestone (b) contains a rich fauna of planktonic and benthonic foraminifera, all entirely replaced by silica and white clay.

The altered basalt (08.04) is a medium-grained rock (0.3 mm) which initially comprised plagioclase and clinopyroxene in approximately equal proportions, with opaques to 0.1 mm, but is now much altered to smectite (some possibly after glass). It is broadly similar to the basalt thought to be in situ in Dredge 01 (01.05), but without the propylitic alteration of the latter.

Comments

The apparent stratigraphic position of the altered basalt, the high degree of alteration, and, to a lesser extent, the sub-parallel parting, are all reminiscent of the basement lavas of the southern Kerguelen Plateau. We conclude, tentatively, that the rock represents volcanic basement of the northern plateau. It differs from the southern basement in having no obvious alkaline characteristics.

The white former limestone is of special interest, both because it is a possible age-diagnostic indicator of a (pre-Late Cretaceous?) sub-aerial erosional unconformity and shallow marine sedimentation, and also because of its subsequent history of carbonate ex-solution and infilling of cavities with sandy (tuffaceous) sediment.

Sample Descriptions — All samples numbers have prefix 86DR

08.01, 2, 3 are sub-angular boulders with little or no MnO coating, probably Neogene volcanics or intrusives from up-slopem but possibly ice-rafted.

08.01 Phyric basalt (plagioclase, clinopyroxene) with high proportion of opaques (about 20%) - probably ilmenite as indicated by note white alteration).

08.02 Olivine-augite-phyric basalt, unaltered, transported. Minerals are olivine (Fo74); brown cpx (en 42 fs 12 wo 46 with Al_2O_3 4-5.8% and TiO_2 2%), not zoned; and plagioclase $An_{45}Or_1$, $An_{59}Or_5$, $An_{66}Or_3$, note high Or; prominent seriate ilmenite with 6% MgO.

08.03 Unaltered plagioclase-phyric fine basalt, much fine opaques, Mn oxide coating to 1 mm; transported. Plagioclase is strongly zoned An_{87}-An_{57}, groundmass An_{54}; cpx is pigeonitic and zoned to Fe-rich rims, en:fs:wo 69:27:4 -> 53:38:9; Ti-Magnetite has 13% $T10_2$, 1% MgO

08.04 Medium-grained, sparsely microporphyritic basalt of equal proportions of plagioclase laths and subequant clinopyroxene to 0.3 mm, with opaques to 0.1 mm, much altered to smectite. This rock is quite friable and makes up about 30 per cent of the dredge haul, and is in the form of sub-rectangular blocks (with sub-parallel parting) which appear to have been torn from outcrop.

Plagioclase microphenocrysts are labradorite (An 54-64 Or 0.7-1.5) with andesine or andesine- labradorite rims (An 47-52 Or 1.5-3.0); groundmass laths have a similar compositional range - An 45-64 Or 1.3-2.4. Clinopyroxene compositions are mostly around En 43 Fs 18 Wo 39 with iron content ranging to Fs 13 and Fs 28. Opaques are acicular ilmenite and some Ti-magnetite.

08.05 Olivine-clinopyroxene-plagioclase-phyric basalt with high proportion of opaques; olivine entirely altered.

08.06 Granitic gneiss (exotic)

08.07 Holocrystalline to intersertal basalt of unaltered plagioclase (0.5 mm, 40%), clinopyroxene (0.2 mm, 40%), and opaques (0.2 mm, 10%) with 10% smectite after intersertal glass. Transported. Plag laths 0.1 mm, An 58 Or1.5; cpx to 0.15 mm, tends pigeonitic: en:fs:wo 60:33:7 zoned to 34:32:34; equal amounts of Ti-magnetite and ilmenite, both stable.

08.08 Cataclastic mafic schist, greenschist facies, with quartz veining (exotic).

08.09 Biotite-hornblende-garnet-feldspar gneiss (exotic).

08.10 Intersertal sparsely glomerophyric, near-holocrystalline, sub-ophitic basalt similar to 08.07, with plagioclase to 1 mm (50%), clinopyroxene to 0.3 mm (30%), opaques to 0.3 mm (7-10%), and smectite after glass (10%).

08.11 Altered basalt, same as 08.04.

08.12 Soft, low density, vuggy white rock with 0.3-0.4 mm of MnO coating, partly a conglomerate of small pebbles of lava in a matrix of former limestone in which planktonic and benthonic foraminifera are preserved. Former solution cavities in the former limestone are partly filled with later fine sandy sediment, possibly once calcareous, and probably containing foraminifera. Much of the material does not

show the conglomerate texture; perhaps it has been more completely altered.
The volcanic breccia/conglomerate consists of

(i) white rounded clasts of (planktonic) foraminiferal former limestone (now not calcareous), and

(ii) grey matrix of crystal tuff with amorphous material (clay).

Matrix (ii) fills solution cavities in (i). All has been replaced by silica and clay.

Microprobe results:
(i) White foraminiferal clasts are K-Al-Si and Al-Si clays;
(ii) Amorphous matrix is K-Al-Si clay.
Tuff grains are (a) much alkali feldspar Or53 Ab43 An4; (b) plagioclase Or6 Ab51 An43; and (c) pigeonitic cpx, en:fs:wo 41:38:21.
XRD results (at BMR):
Both (i) and (ii) contain kaolinite, minor feldspar, and mixed layer clays.
Age:
D J Belford (pers. comm., 1986) found abundant planktonic foraminifera Globigerinidae. Globigerinoides quadrilobatus group - ?triloba. Not older than Miocene. These were in (i), the rounded clasts of former limestone. The diatoms also are of Miocene aspect (50% probability).

Supporting a Neogene (Miocene?) age, the minerals of the tuffaceous matrix are similar to the minerals in the rounded boulders (08.02, 08.03). The tuff and the rounded boulders may all originate from one Neogene volcanic and erosional event.

08.13 Olivine-pyroxene-phyric basalt

08.14 Relatively unaltered glomerophyric intersertal(?) basalt of plagioclase and minor clinopyroxene; the plagioclase is strongly zoned and exhibits strain effects (cracking, undulose extinction, broken grain boundaries) which suggest movement of near-crystalline magma. Groundmass basalt adjacent to and within the glomerocrysts is finer-grained than elsewhere, presumably because of fine re-crystallisation under stress.

Plagioclase phenocrysts are labradorite (An 78 Or 0.2) with andesine rims (An 37 Or 3.2); groundmass plagioclase is intermediate between these compositions at An 54 Or 2. Clinopyroxene phenocryst is En 46 Fs 14 Wo 40, but groundmass clinopyroxene is more iron-rich: around En Fs 21 Wo 39. Plagioclase phenocrysts contain brown inclusions in crystallographic orientation. Parts of groundmass are altered to yellow-brown and red-brown smectite - this is not necessarily after glass, but could be.
