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

Petrology of Basement Rocks from Palmer Ridge, NE Atlantic

J. R. Cann

Phil. Trans. R. Soc. Lond. A 1971 **268**, 605-617
doi: 10.1098/rsta.1971.0015

Phil. Trans. Roy. Soc. Lond. A. **268**, 605–617 (1971) [605]
Printed in Great Britain

Petrology of basement rocks from Palmer Ridge, NE Atlantic

By J. R. Cann
School of Environmental Sciences, University of East Anglia,
Norwich, NOR 88C

A detailed petrographic account is given of the basalts and dolerites, gabbros, amphibolites, breccias and serpentinites dredged from Palmer Ridge in the NE Atlantic, accompanied by chemical analyses of rocks and electron probe analyses of minerals. Radiometric dates on the rocks are reported. The preliminary conclusions about the geological history and structure of Palmer Ridge have been confirmed and strengthened, and certain petrological problems, in particular the physical conditions under which the amphibolites were metamorphosed, are raised.

Introduction

Palmer Ridge, near 43° N, 20° W in the NE Atlantic, forms part of a complex tectonic feature called King's Trough that extends from about $42\frac{1}{2}$° N, $19\frac{1}{2}$° W to $44\frac{1}{2}$° N, 24° W. The region was surveyed by R.R.S. *Discovery* in 1965, and in 1966 the ship returned to the area to carry out further work, one item of which was a detailed survey of a small area, 16 km by 14 km, covering the crest and flanks of Palmer Ridge. Within this small area 14 successful dredge stations were made in an even smaller area 10 km by 10 km.

The structure and geological history of the area were deduced mainly from the evidence of the rocks by Cann & Funnell (1967), to which the reader is referred for a map of the area and a detailed map of the ridge. Matthews *et al.* (1969) published an account of geophysical observations in the region, looking at the eastern end of the King's Trough complex on a larger scale and making tentative conclusions about the processes by which the structure could have developed. Ramsay (1970) has worked up the stratigraphy and palaeontology of the deep-sea consolidated oozes dredged in some numbers on Palmer Ridge and ranging in age from lower Eocene to upper Miocene and Pliocene.

The geological history of Palmer Ridge as deduced by Cann & Funnell (1967) is briefly as follows. The ocean crust in this area was formed about 60 Ma ago at the crest of the Mid-Atlantic Ridge as a complex igneous and metamorphic structure of the kind pictured elsewhere (Cann 1970). This was broken up by faulting soon after it was formed to give an irregular topography with deep-seated rocks exposed at the ocean floor, as they are today at the M.A.R. crest. The basement was then covered by an accumulation of pelagic sediments which formed apparently continuously from the lower Eocene to the lower Miocene. At about 27 Ma ago the formation of Palmer Ridge, and, by extension, the rest of the King's Trough feature, occurred. At Palmer Ridge this episode of tectonic activity was accompanied by intrusion of a serpentinite diapir along the crest of the ridge, updoming of the basement and tilting of the earlier-formed sediments, and retrograde metamorphism in the basement. On terraces near the top of the ridge thus formed, winnowed pelagic sediments have since accumulated, ranging in age from middle Miocene to the present day.

Of the 14 successful dredge stations, 10 brought up basement rocks (table 1). Of these, four contained serpentinite as their only basement rock type, two contained only gabbros, and the remaining four consisted of mixtures of rock types, amphibolites with weathered basalt (5610), weathered basalt and dolerite, gabbro and serpentinite (5978), serpentinite and gabbro (5983), and amphibolite and serpentinite (5985). Also listed in table 1 are two dredge hauls 5623 and 5636, which, though not in the detailed survey area, were made nearby and also contained basement rocks.

Thus among the basement rocks collected from Palmer Ridge are basalts, dolerites and gabbros which are most often weathered or metamorphosed, and serpentinites. This paper sets out to describe the petrology of these rocks, with particular emphasis on the metamorphic rocks which are in these hauls both very numerous and rather interesting.

Table 1. Locations of dredge hauls whose contents are described in this paper

number	position	depth/m	basement rock types
5607	42° 53.9′ N, 20° 11.8′ W	3290	serpentinites
5610	42° 50.8′ N, 20° 16.8′ W	4645	1 basalt, 2 amphibolites
5623†	43° 07.5′ N, 19° 39.5′ W	3869	1 basalt
5636†	42° 42.5′ N, 20° 14.0′ W	4939	4 basalts
5968	42° 50.3′ N, 20° 12.2′ W	5329–4604	1 serpentinite
5975	42° 54.2′ N, 20° 12.8′ W	3204–3184	serpentinites
5976	42° 53.6′ N, 20° 15.7′ W	3429–3193	1 serpentinite
5978	42° 54.6′ N, 20° 11.2′ W	3486–3098	basalt, dolerite, gabbro, serpentinite
5979	42° 50.7′ N, 20° 16.2′ W	5300–4759	gabbros
5981	42° 51.5′ N, 20° 16.5′ W	5282–4542	gabbros
5983	42° 54.4′ N, 20° 13.4′ W	3353–3231	serpentinites, breccias, gabbro
5985	42° 52.0′ N, 20° 12.4′ W	4596–3128	amphibolites, breccias

† Dredge hauls not in the area of the Palmer Ridge detailed survey.

Basalts and dolerites

Basalts and dolerites were found in hauls 5610, 5623, 5636 and 5978. They are all more or less weathered. Textures vary from variolitic to doleritic, often within the same dredge haul. The finer grained varieties very often contain megacrysts (xenocrysts of Muir & Tilley 1964) of very calcic plagioclase (up to An_{85}) and olivine. The olivine is usually altered to brown weathering products, and the plagioclase sometimes shows signs of alteration. The megacrysts are set in a very fine-grained yellow to red weathered groundmass. The doleritic rocks usually give the impression of being less weathered, probably because they were more coarse grained initially. They contain laths of plagioclase (about An_{70}) and grains of augite and iron ore set in a brown weathered mesostasis. Olivine appears to have been rare in these rocks, though some of its alteration products may be indistinguishable from the mesostasis.

In table 2 are two chemical analyses of this group of rocks. 5623.1 is an aphyric, yellow weathered variolitic basalt from outside the area of the detailed survey (in fact from the north side of Peake Deep). The ratio of ferric to ferrous iron and the high-water content show it to be well weathered, and the higher than usual K_2O and low MgO are interesting in this context, confirming the results of Matthews (1970) and Hart & Nalwalk (1970) on the chemical changes that accompany such weathering.

5978.9 is a small lump of much fresher-seeming dolerite from haul 5978. The rocks of this haul are somewhat unusual, consisting of conglomerates of pebbles of pelagic ooze replaced by phillipsite, serpentinite, basalt, dolerite and gabbro. Each pebble is surrounded by a thin manganese oxide coating, and the whole conglomerate is in turn surrounded by manganese oxide to give a cohesive mass. Clearly the origin of these rocks is complex: possibly they represent fossil screes cemented by manganese oxide. 5978.9 consists of plagioclase laths, augite, iron ore and brown mesostasis. There is no sign of pseudomorphs after olivine. Megacrysts of calcic plagioclase are quite abundant. The chemical analysis shows it to be perhaps somewhat less weathered than 5623.1, but still considerably altered. The K_2O value has again been affected by this process.

Table 2. Chemical analyses of basalt, dolerite, gabbro and serpentinite

number ...	5623.1	5978.9	5979.10	5607.11	5983.20
rock type ...	basalt	dolerite	gabbro	serpentinites	
analyst ...	JRC	AJE	AJE	AJE	AJE
SiO_2	46.27	46.80	47.30	38.58	38.15
Al_2O_3	18.43	16.75	17.82	1.53	1.36
Fe_2O_3	8.47	5.97	4.45	8.18	7.34
FeO	3.10	2.54	2.76	0.51	0.14
MnO	0.13	0.21	0.15	0.10	0.08
MgO	3.97	7.91	8.12	36.26	36.42
CaO	11.56	12.55	14.33	0.08	0.43
Na_2O	2.48	1.81	2.15	0.14	0.19
K_2O	0.82	0.51	0.23	0.02	0.01
TiO_2	1.18	0.78	0.29	n.d.	n.d.
P_2O_5	0.15	0.17	0.10	0.07	0.06
H_2O^+	1.81	1.63	1.67	11.92	11.21
H_2O^-	1.66	2.70	0.80	2.18	3.52
CO_2	—	0.16	0.23	0.20	0.15
Cr_2O_3	—	0.05	0.09	0.43	0.43
NiO	—	n.d.	n.d.	0.43	0.46
	100.03	100.54	100.49	100.63	99.97
parts/10^6					
Rb	10	—	—	—	—
Sr	80	—	—	—	—
Y	35	—	—	—	—
Zr	60	—	—	—	—
Ni	75	—	—	—	—
Cu	120	—	—	—	—
Zn	120	—	—	—	—
Ga	15	—	—	—	—

Analysts: JRC, J. R. Cann; AJE, A. J. Easton. Trace elements by X-ray fluorescence analysis.

Table 3 gives the results of four electron probe analyses of augites from this rock. They are all close to $Wo_{42}En_{48}Fs_{10}$, and no great amount of zoning was apparent. No calcium-poor pyroxenes were observed.

Gabbros

Apart from two hauls (5979 and 5981) which contained only gabbros, and were made close together at the foot of the slope from Palmer Ridge into Freen Deep, hauls 5978 and 5983 also contained fragments of gabbro.

The gabbros of hauls 5979 and 5981 are essentially similar and can be described together. They consist of blocks of rather plagioclase-rich gabbro sometimes weathered but not metamorphosed, sometimes metamorphosed to hornblende gabbros, and sometimes partly metamorphosed. The partly metamorphosed blocks show that the metamorphic effects proceeded inwards from cracks and joints in the gabbro. One or two of the blocks have cracks running through them, on either side of which the metamorphic effects are visible for a few centimetres and beyond which the rock is unmetamorphosed.

TABLE 3. PARTIAL ELECTRON PROBE ANALYSES OF PYROXENES FROM THE DOLERITE, 5978.9

	1	2	3	4
SiO_2	50.74	51.50	50.75	49.66
Al_2O_3	2.63	2.64	2.62	2.61
FeO	6.43	7.89	5.90	5.51
MgO	16.85	16.38	16.38	15.65
CaO	19.32	19.18	19.99	20.49
cations for 6 oxygens				
Si	1.94	1.94	1.94	1.95
Al	0.12	0.12	0.12	0.12
Fe	0.21	0.25	0.19	0.18
Mg	0.96	0.92	0.93	0.91
Ca	0.79	0.78	0.82	0.84
Wo	40	40	42	43
En	49	47	48	47
Fs	11	13	10	10

TABLE 4. PARTIAL ELECTRON PROBE ANALYSES OF MINERALS FROM THE GABBRO, 5979.10

	1	2	3	4	5	6
		augite		opx.	hb.	plag.
SiO_2	50.39	51.16	52.37	53.29	45.62	48.91
Al_2O_3	2.62	2.68	2.46	1.25	8.57	32.05
FeO	7.16	4.36	5.48	13.63	9.48	—
MgO	15.52	17.49	18.31	27.25	15.35	—
CaO	19.46	20.14	19.73	2.25	11.41	14.84
cations for 6 oxygens						
Si	1.95	1.94	1.94	1.96	—	—
Al	0.12	0.12	0.11	0.05	—	—
Fe	0.23	0.14	0.17	0.42	—	—
Mg	0.89	0.99	1.01	1.49	—	—
Ca	0.81	0.82	0.78	0.09	—	—
Wo	42	42	40	4	—	—
En	46	51	51	75	—	—
Fs	12	7	9	21	—	—

opx. = orthopyroxene, hb. = hornblende, plag. = plagioclase.

The unmetamorphosed gabbros contain large plates of calcic plagioclase (about An_{75}; see table 4), large partly ophitic areas of augite, more or less rectangular crystals of faintly pleochroic orthopyroxene and large areas of brown weathering products of olivine. Olivine is scarcely ever found fresh in these rocks except when it occurs as small crystals wholly embedded in plagioclase. Surrounding the regions composed of alteration products after olivine, where they come into contact with plagioclase, are corona-like reaction rims, apparently composed of amphibole. These rims seem to be a primary phenomenon, not related to the metamorphism, and probably reflect a subsolidus reaction of the olivine with the plagioclase.

The augite shows some odd features. Where crystals of augite come into contact, they commonly develop wide areas of vermicular intergrowth of one crystal with another. Electron probe studies show that both components of the intergrowth have the same composition, and that both are always augite. This kind of vermicular intergrowth does not seem to have been previously described, and its origin is not at all clear.

Table 2 gives a chemical analysis of one of the specimens of unmetamorphosed gabbro (5979.10). Its plagioclase-rich character is plain from this. It is also clear that, even though this is the freshest available specimen, it has suffered appreciably from weathering, as the pseudomorphs after olivine indicate. Table 4 gives the results of electron probe analyses of augite, orthopyroxene and plagioclase. An analysis of one of the rare crystals of hornblende that indicate the onset of metamorphic changes in this rock is also given. The analyses of augite are very close to those of the dolerite 5978.9 (table 3), about $Wo_{41}En_{50}Fs_9$. One analysis was made of the coexisting orthopyroxene and this gave a composition of $Wo_4En_{75}Fs_{21}$. The partial analysis of the amphibole showed it to be a fairly typical green hornblende.

As the metamorphic changes begin, the olivine and the orthopyroxene are the first minerals to be affected, being replaced by flaky aggregates of very pale green pleochroic clinoamphibole, probably actinolite. At a later stage the augite is affected, and is replaced by large single crystals of light green pleochroic hornblende (see the analysis in table 4). The plagioclase shows little sign of being attacked, even in the most severely metamorphosed rocks, retaining its rectangular plate-shaped crystals and its calcium-rich composition. Clinozoisite is seen in veins cutting the metamorphosed gabbros, but is never found replacing plagioclase. Thus the end result is a hornblende gabbro, consisting of calcic plagioclase, green hornblende and flaky aggregates of actinolite after olivine and orthopyroxene. The brown weathering products after olivine are absent from such rocks.

In some of the gabbros, intense shearing along well-defined planes leads to the formation of local mylonite textures in the rocks.

Two of the conglomerates of 5978, described above, were found to contain pebbles of gabbro, one of them about 5 cm across. This specimen was of anorthositic gabbro, very rich in plagioclase of composition An_{65} which has been replaced in part by an unidentified phase, possibly a zeolite. Specimen 5983.38 is also a fragment of gabbro, in a haul which is otherwise almost entirely composed of serpentinite. This gabbro is slightly crushed, and contains plagioclase, now extensively replaced by muscovite (see section on amphibolites), and some relict augite, though most of the ferromagnesian minerals have been replaced by chlorite, epidote and hornblende.

Amphibolites

Rocks described in our original paper (Cann & Funnell 1967) as amphibolites were recovered in two dredge hauls, 5610 and 5985. They are not in appearance very like the amphibolites of continental regions, with their jet black, well-cleaved parallel hornblende crystals; these rocks are dull, dark green and massive without any trace of foliation or lineation. But they are composed essentially of hornblende and plagioclase, and they are metamorphic rocks, so, failing a suitable alternative term, I shall continue to call them amphibolites here, though drawing attention to their unusual nature.

Amphibolites from both dredge hauls show up to three superimposed mineral assemblages, representing different stages in their development. There is the primary igneous assemblage of calcic plagioclase, augite and iron ore, developed with a characteristic dolerite igneous texture.

Then there is the primary metamorphic assemblage superimposed on this, and finally retrograde secondary metamorphic assemblages superimposed in turn on the primary one.

Some of the rocks are completely unaffected by retrograde metamorphism, and of these 5985.10 was selected as the best example. This rock has a well-preserved igneous texture of grain size intermediate between basaltic and doleritic. It contains some megacrysts of plagioclase zoned from cores about An_{80} to margins about An_{65}. The groundmass is composed of brownish green to bluish-green hornblende pseudomorphing augite and enclosing occasionally some relicts of primary augite, associated with calcic plagioclase laths, and iron ore grains.

Table 5. Chemical analyses of amphibolites

number ...	5985.10	5985.22	5985.25	5985.28	5610.2	5610.3
analyst ...	AAM	AAM	AAM	AAM	JRC	JRC
SiO_2	50.2	49.6	48.4	40.3	51.20	52.80
Al_2O_3	14.7	15.2	16.9	17.8	14.55	14.16
Fe_2O_3	2.9	3.0	3.2	2.3	1.83	1.84
FeO	6.6	6.9	6.2	8.6	5.79	5.71
MnO	0.19	0.37	0.24	0.51	0.10	0.17
MgO	8.3	8.5	8.5	12.3	9.12	8.41
CaO	11.9	10.1	8.7	8.6	11.86	10.09
Na_2O	2.4	2.7	2.1	0.9	2.46	3.67
K_2O	0.18	0.31	1.73	1.20	0.50	0.80
TiO_2	0.97	1.4	1.07	1.19	1.09	1.02
P_2O_5	0.13	0.26	0.15	0.13	0.08	0.11
H_2O^+	1.0	1.7	2.2	5.8	1.56	1.37
H_2O^-	0.3	0.2	0.5	0.6	0.23	0.25
Cr_2O_3	0.03	<0.01	0.06	0.06	—	—
	99.8	100.2	100.0	100.3	100.37	100.40
parts/10^6						
Rb	—	—	—	—	6	3
Sr	—	—	—	—	105	140
Y	—	—	—	—	30	25
Zr	—	—	—	—	60	55
Ni	75	100	85	—	110	80
Cu	65	100	5	—	15	5
Zn	65	250	70	—	40	50
Ga	15	15	15	—	13	12

Analysts: AAM, A. A. Moss; JRC, J. R. Cann. Trace elements by X-ray fluorescence analysis.

A chemical analysis of this rock is given in table 5, and electron probe analyses of the hornblende in table 6. Rocks of this kind have undoubtedly reached their present condition by metamorphism of dolerites (perhaps dolerite dykes) within the ocean crust in the absence of shearing stress. The presence of green hornblende indicates a different metamorphic facies from the greenschist facies more commonly developed within the ocean crust (Cann 1969; Melson, Thompson & van Andel 1968), and probably a higher grade one. The presence of calcic plagioclase + hornblende and the lack of clinozoisite or epidote suggests either moderate grade amphibolite facies conditions, or, more plausibly here, water deficient metamorphism just above the upper limit of the greenschist facies (Cann 1970).

The initial stages of the retrograde metamorphic effects are marked by the beginning of replacement of the plagioclase laths, while the igneous texture remains well preserved. 5985.22 is a good example of this kind of rock. Here the plagioclase is partly replaced by flakes of highly birefringent muscovite and by chlorite, and the grains of iron ore are mantled with rims of sphene. A chemical analysis of this rock is given in table 5. This is the most common kind of alteration, but in some rocks in both hauls the onset of retrograde metamorphism is marked by replacement of plagioclase, particularly in the cores of crystals, by single crystals of a so-far unidentified mineral of low birefringence, a refractive index about 1.52 and small negative $2V$. Unfortunately, it has not yet proved possible to separate any grains of this mineral for further study. 5610.2, 5610.3 and 5985.25 have suffered this replacement to a greater or lesser extent. Chemical analyses of 5610.2 and 5610.3 are given in table 5, and electron probe analyses of some of their minerals in table 6.

Table 6. Partial electron probe analyses of hornblendes from the amphibolites

	5985.10		5610.3		
	1	2	1	2	3
SiO_2	51.37	51.06	47.79	48.35	48.03
Al_2O_3	2.34	4.46	4.75	7.62	4.02
FeO	14.17	14.31	13.01	13.40	13.98
MgO	15.66	14.94	15.92	15.26	16.24
CaO	10.90	11.47	11.43	11.99	10.94

	5985.25	5610.2			
	1	1	2	3	4
SiO_2	44.89	50.38	45.91	50.10	50.52
Al_2O_3	8.83	6.67	6.58	4.41	8.78
FeO	12.91	12.47	14.15	12.68	12.57
MgO	13.31	14.94	13.47	15.38	13.99
CaO	11.29	12.57	12.49	11.71	12.91

Partial electron probe analyses of plagioclases from the amphibolites

	5985.10	5610.2	
	1	1	2
SiO_2	51.39	50.01	52.40
Al_2O_3	31.73	31.79	31.74
CaO	13.13	14.26	13.32
An %	66	71	65

At late stages in this retrograde metamorphism, the plagioclase grains become represented by areas thickly strewn with flakes of muscovite, apparently set in albite, and the igneous texture is quite lost. Instead hornblende occurs as ovoid clusters between areas of muscovite impregnated feldspar. Iron ore grains are mantled and almost entirely replaced by sphene. The best example of this is 5985.25, of which a chemical analysis appears in table 5 and an electron probe analysis of a hornblende in table 6. Note in table 5 how K_2O increases as the degree of retrograde metamorphism increases from 5985.10 to 5985.25, and how Al_2O_3 increases too, while SiO_2 and CaO decrease. The identification of the highly birefringent flakes as muscovite depends on an X-ray powder photograph of a concentrate (intergrown with feldspar), chemical evidence from the bulk chemical analyses, and electron probe identification of the areas highly charged with birefringent flakes as K_2O rich areas relative to the rest of the rock.

5985.28 (see table 5 for analysis) is another rock showing an advanced stage of retrograde metamorphism, but is rather more difficult to interpret. It has a poorly preserved fine-grained basaltic igneous texture rather than a dolerite one. The plagioclase here has been extensively replaced by both chlorite and muscovite, relict augite crystals are common, hornblende partly replaces them and sphene mantles iron ore grains. The presence of extensive areas of chlorite and muscovite gives the chemical analysis its character (high in MgO and K_2O and low in CaO and Na_2O), and in some respects this rock resembles the chlorite-rich rocks dredged from $5\frac{1}{2}°$ N on the Carlsberg Ridge (Cann 1969). It is notable that this specimen gives a discordant potassium–argon age (see later).

The development of chlorite and the breakdown of plagioclase suggests that the retrograde metamorphism took place at a lower grade than the primary one, probably within the green-schist facies. The influx of K_2O in such large quantities, when K_2O is very depleted generally in the ocean crust, suggests sea water as a source, and invites comparison with the enrichment of K_2O observed in basalts weathered on the ocean floor (see above, section on basalts and dolerites). Certainly the system must have been open to K_2O and it must have travelled over rather large distances.

The amphibolites are commonly cut by veins. The following assemblages have been observed in them: epidote, epidote–actinolite, chlorite, epidote–chlorite, quartz–albite, quartz–chlorite, chlorite–sphene.

Breccias

As in the greenschist facies dredge hauls from the Carlsberg Ridge (Cann 1969), the metamorphic rocks in this series of dredge hauls were accompanied by numerous specimens of breccias, though here the breccias seem to be of a somewhat different character. The Palmer Ridge breccias are nearly all polymict, with up to five different rock types found as fragments in the same breccia sample.

Twelve breccia samples were sectioned. Eight of them contained fragments of amphibolite usually with a fine-grained basaltic texture and affected moderately to very severely by the retrograde metamorphism described above. Seven contained fragments of serpentinite together with its talc- or carbonate-rich alteration products (see below), and fragments of indurated and very often recrystallized pelagic ooze were found in eight specimens. Five specimens contained fragments of chlorite-rich rock, either composed almost entirely of pure chlorite, or of chlorite in association with actinolite, sphene or iron ore. These fragments seem often to pseudomorph fine-grained or glassy basalt, and perhaps have a similar origin to chlorite-rich rocks from the Carlsberg Ridge (Cann 1969). Other varieties of fragments somewhat less abundant are quartz, as large single crystals (two samples), epidotite (two samples), and material consisting entirely of tremolite, perhaps formed in association with the serpentinites (one sample). There appear to be no consistent associations of rock types, any variety being likely to occur in association with any other.

The matrices in which the fragments lie are of three main types. The commonest (eight samples) is of the materials composing the fragments ground up smaller, so that there is a complete gradation from the fragments through to the smallest grains of matrix. Sometimes in this type quartz grains appear in the matrix when they are not observed in the fragments. Three of the breccias have their fragments set in a matrix of coarsely crystalline calcium carbonate, which must have been introduced in solution. The one other breccia sample is remarkable in its resemblance to some of the Carlsberg Ridge breccias in that here fragments of serpentinite and recrystallized limestone are set in a matrix of euhedral quartz crystals clearly growing *in situ* (see Cann & Vine 1966, figure 14).

Because of their polymict character these breccias are almost certainly tectonic rather than volcanic, and this view is supported by the presence of abundant fragments of indurated pelagic ooze. The presence of the indurated ooze, retrograded amphibolite and abundant serpentinite together in the breccias also indicates strongly that they formed at the same time as, or later than, the intrusion of the serpentinite diapir into Palmer Ridge, and the evidence of active solution and redeposition in the carbonate and quartz matrices would indicate an origin contemporaneous with the retrograde metamorphic effects, and thus with the serpentinite intrusion. The breccias here, then, can be interpreted as tectonic breccias formed from pre-existing rocks during the intrusion of the serpentinite body.

Serpentinites

Serpentinite is the most abundant rock type encountered in this series of dredge hauls, occurring in seven out of the fourteen successful hauls. All four dredge hauls that cut the crest of the ridge brought up serpentinite, and this, coupled with other evidence, led us (Cann & Funnell 1967) to postulate the intrusion of a serpentinite diapir along the axis of Palmer Ridge which was perhaps responsible for its uplift. Further evidence from the breccias in haul 5985 (see above) also suggests a tectonic event that could well be interpreted as the intrusion of a serpentinite diapir.

The serpentinites resemble strongly other serpentinites from the oceans, and also from the land. They are dark brick red to dark green veined rocks, often well jointed. At least four different factors affect the development of the final mineralogy and texture of the rocks. First is the degree of serpentinization, how much of the primary peridotite mineralogy remains, and then there is the degree and kind of metasomatic reactions, such as carbonation, replacement by talc, etc. At a later stage the original texture may be more or less obliterated by crushing, and finally exposure on the ocean floor appears to lead to the development of clay mineral serpentine minerals from the normal high-temperature ones (though the evidence for this is more circumstantial than concrete) and to the weathering of other silicates.

To take the first factor first, almost all of the serpentinites from Palmer Ridge are completely serpentinized, that is, none of the silicate minerals present are high temperature anhydrous phases such as olivine or pyroxene. Three specimens were found with unserpentinized fragments of orthopyroxene containing clinopyroxene exsolution lamellae, but unfortunately these three are among those most affected by weathering, and their value for, say, electron probe studies is uncertain. The rocks affected solely by this process contain large bastite pseudomorphs after orthopyroxene set in a matrix of flaky serpentine and iron ore grains pseudomorphing olivine. Large spinel crystals are quite common, and, though their margins are usually opaque, their cores are often translucent and deep brown in colour, indicating a chromium-rich composition. This chrome spinel is presumably an original component of the unserpentinized peridotites. The rocks are cut by veins filled with fibrous serpentine minerals. X-ray powder photographs of material picked from bastite pseudomorphs, matrix and veins give reflexions corresponding to serpentine minerals and magnetite. No brucite was seen. Chemical analyses of two of these serpentinites are given in table 2.

The serpentinites often show signs of replacement by carbonate minerals, which develop first as small scattered crystals in the matrix, and later invade and replace a large part of the rock. A similar partial to complete replacement by talc is common, and again the talc replaces the serpentine of the matrix first, only later being found in the bastite pseudomorphs. The talc is sometimes associated with tremolite, as bladed crystals, and chlorite. Talc, tremolite and chlorite have all been identified optically and by X-ray powder photographs.

The crushing that affects the serpentinites is seen first by the deformation of the bastite pseudomorphs, sometimes accompanied by the formation of kink bands. At a later stage the bastites break up into fragments, and when the crushing is most advanced, all sign of pseudomorphous texture in the rocks is lost, and they are seen to be uniformly composed of flaky serpentine cut by veins. This crushing, and the hydrothermal replacement described above, may well be associated with the intrusion of the serpentinite mass.

The weathering of serpentinites is not a subject that has attracted much attention. The problem was discussed by Hess & Otalora (1964) in connexion with the Mayaguez serpentinite core. At Palmer Ridge, serpentinites were interpreted as weathered if they dried out to give a light porous rock, and if the thin sections showed extensive iron staining and similar phenomena. Essentially it seems possible that expanding clay mineral serpentine minerals may form from normal serpentines during prolonged low-temperature contact with water, but the whole problem is rather poorly defined and would repay more detailed mineralogical work.

Dating

Dating of the sediments recovered has been carried out by micropalaeontological techniques, and the reader is referred to Ramsay (1970) for the results for the Palmer Ridge sediments. These results are, of course, critical for the interpretation of the geological history of the area.

Dr J. A. Miller, Dr R. Grasty and Dr J. Mitchell of the Department of Geodesy and Geophysics in Cambridge kindly carried out potassium–argon determinations on some of the amphibolites. Their results are listed in table 7.

Table 7. Radiometric age measurements on amphibolites

number	K_2O (%)	radiogenic argon/$mm^3\ g^{-1}$ v/m	atmospheric contamination (%)	age/Ma
5985.10	0.179 ± 0.01	3.54×10^{-4}	83.4	59 ± 8.5
		3.64×10^{-4}	85.5	60 ± 6.5
5985.22	0.312 ± 0.02	4.45×10^{-4}	68.0	43 ± 3
		4.07×10^{-4}	69.1	40 ± 3
5985.25	1.73 ± 0.10	1.622×10^{-3}	55.2	29 ± 2
5985.28	1.20 ± 0.10	3.71×10^{-3}	19.5	89
		3.71×10^{-3}	10.5	89
5610.2	0.50 ± 0.05	4.56×10^{-4}	61.8	27 ± 4
5610.3	0.80 ± 0.05	5.58×10^{-4}	78.3	21 ± 5

The content of radiogenic argon is measured at s.t.p. The percentage atmospheric contamination is in the gas released. Calculations were made using values of $\lambda_\beta = 4.72 \times 10^{-10}\ a^{-1}$ and $\lambda_C = 0.584 \times 10^{-10}\ a^{-1}$.

The problems of potassium–argon dating of ocean floor rocks have received a good deal of attention lately. Not only does the low K_2O and young age of most ocean-floor rocks make the problem difficult technically, but other difficulties also intervene. Ocean-floor basalts take up K_2O significantly even after only a very slight degree of weathering (Philpotts, Schnetzler & Hart 1969), thus affecting their measured ages. In addition, the presence in the basalts of excess radiogenic argon derived from the mantle has also been demonstrated (Funkhouser, Fisher & Bonatti 1968; Dalrymple & Moore 1968). Thus potassium–argon ages of ocean-floor rocks should be treated with caution.

However, measurements on metamorphic rocks should avoid both of these problems to some extent. First, the metamorphism leads to the formation of lower temperature mineral assemblages than the original igneous ones, which are thus more stable relative to sea water, and likely to be less affected by weathering. Secondly, the metamorphic process should lead to outgassing of any excess radiogenic argon incorporated during the original crystallization of the igneous rocks. Potassium–argon ages on ocean floor metamorphic rocks should thus be much more reliable than ages measured on igneous rocks, and they are treated as such here.

Of the rocks on which measurements were carried out, only one was unaffected by the retrograde metamorphic effects described above. This was 5985.10, and the date of about 60 Ma recorded for this specimen can be considered to give a good estimate of the date of the primary metamorphism. 5610.2, 5610.3 and 5985.25 have all been well retrograded, the first two with the formation of muscovite, and all three give ages consistent with an age for the retrograde metamorphism of about 27 Ma. 5985.22 is a partly retrograded example, with feldspar only partly replaced by muscovite, and, as would be expected, it gives an age intermediate between the dates of the primary metamorphism and of the retrograde metamorphism. 5985.28 gives an anomalous age. It is highly retrograded, but has a measured age quite discordant with that of other retrograded examples. This specimen is, in fact, petrographically rather anomalous, as was noted above, and it is possible that it has accumulated radiogenic argon released from other nearby rocks during the retrograde metamorphism.

All of these rocks were described petrographically in the section on amphibolites, and their chemical analyses may be found in table 5.

Conclusions

The detailed petrographic and chemical study of the basement rocks from Palmer Ridge broadly substantiates the preliminary conclusion (Cann & Funnell 1967) about the geological history of this small area of ocean floor. Detailed palaeontology (Ramsay 1970) has also led to similar conclusions. The basement rocks found here were originally formed at the crest of the M.A.R. about 60 Ma ago when the Atlantic was some 1200 km narrower than it is at the present day. Interpreted after a scheme for ocean-crust formation presented elsewhere (Cann 1970), the basalts and dolerites represent the uppermost part of the ocean crust, now weathered by prolonged contact with sea water. The amphibolites represent the upper part of layer 3, the dense dyke swarm almost lacking in pillow lavas, metamorphosed at moderate temperatures in the presence of only a small amount of water. The gabbros represent the upper part of the now solid magma chamber that supplied the lava for volcanic activity at the ridge crest, and the serpentinites were formed from the upper mantle, or from slices of the upper mantle tectonically included in the ocean crust. Thus, of the rock types believed to make up the ocean crust, the greenschist facies meta-basalts of the lower part of layer 2, and the layered gabbros of the lower part of layer 3 are missing from the collection of samples.

From the occurrence of deep-seated material from within the ocean crust directly underlying the oldest pelagic sediments (as in haul 5981), it is clear that considerable tectonic activity took place between the time the crust was formed and the time that sediments began to accumulate. This process, involving intense faulting, is seen at the crest of the M.A.R. at the present day (van Andel & Bowin 1968), and the M.A.R. must thus have been a rifted ridge then as now.

A period of calm followed the formation of the crust while pelagic sediment accumulated on top of it from about 60 to about 27 Ma, and Palmer Ridge moved about 350 km away from the crest of the M.A.R. Then the tectonic activity leading to the formation of Palmer Ridge, the intrusion of a serpentinite diapir along its crest, the retrograde metamorphism of the rocks, and, by extension, the formation of the rest of the King's Trough feature, took place. A broader geophysical setting for these events has been provided by Matthews *et al.* (1969). Perhaps one could postulate that at this time a readjustment of the velocities of nearby plates, possibly resulting from the collision of two continental plates in the Alpine region, led to the formation of a temporary plate boundary in this position while the readjustment was taking place. The King's Trough feature might then be a fossil plate boundary, activated for a short while and now quiescent.

Following the formation of Palmer Ridge, sedimentation took place on terraces near its summit, leading to the formation of the Upper Tertiary limestones collected from near the crest at the present day.

Of the petrological problems raised in this research, the most interesting is the question of the metamorphic facies of the amphibolites. The occurrence of hornblende suggests relatively high temperatures, perhaps 400 °C, and geological considerations suggest a pressure of not more than 1000 bar (0.1 GN m^{-2}). The lack of any replacement of plagioclase by clinozoisite or epidote is puzzling, though, as was suggested above, this may have been caused by a low ambient water-vapour pressure such as one would expect in the dyke swarm segment of the crust. It is interesting that almost identical rocks were described by Reinhardt (1969) from the dyke swarm section of the South Oman ophiolite complex.

The question posed by the title of our preliminary paper seems now to be answered. At Palmer Ridge we have sampled a section through the upper part of the ocean crust, and from this we have been able to come to definite conclusions about the geological history of the area.

I would like to acknowledge the help of the late Dr M. N. Hill, Dr A. S. Laughton and Dr D. H. Matthews and the scientists and crew of R.R.S. *Discovery* during the dredging operations, Dr J. A. Miller, Dr R. Grasty and Dr J. Mitchell for radiometric dates, Dr S. J. B. Reed and Mr R. F. Symes for electron probe analyses, Dr A. A. Moss and Mr A. J. Easton for some of the wet chemical analyses, and the Department of Mineralogy and Petrology, Cambridge, and the Department of Mineralogy, British Museum (Natural History) for reseach facilities.

References (Cann)

Cann, J. R. & Vine, F. J. 1966 An area on the crest of the Carlsberg Ridge; petrology and magnetic survey. *Phil. Trans. Roy. Soc. Lond.* A **259**, 198–217.

Cann, J. R. & Funnell, B. M. 1967 Palmer Ridge: a section through the upper part of the ocean crust? *Nature, Lond.* **213**, 661–664.

Cann, J. R. 1969 Spilites from the Carlsberg Ridge, Indian Ocean. *J. Petrology* **10**, 1–19.

Cann, J. R. 1970 A new model for the structure of the ocean crust. *Nature, Lond.* **226**, 928–930.

Dalrymple, G. B. & Moore, J. G. 1968 Argon-40: excess in submarine pillow basalts from Kilauea volcano, Hawaii. *Science, N.Y.* **161**, 1132–1135.

Funkhouser, J. G., Fisher, D. E. & Bonatti, E. 1968 Excess argon in deep-sea rocks. *Earth Planet. Sci. Lett.* **5**, 95–100.

Hart, S. R. & Nalwalk, A. J. 1970 K, Rb, Cs and Sr relationships in submarine basalts from the Puerto Rico Trench. *Geochim. cosmochim. Acta* **34**, 145–155.

Hess, H. H. & Otalora, G. 1964 Mineralogical and chemical composition of the Mayaguez serpentinite cores. In *A study of serpentinite*, pp. 152–168. Nat. Res. Counc. publ. 1188, Nat. Acad. Sci., Washington, D.C.

Matthews, D. H., Laughton, A. S., Pugh, D. T., Jones, E. J. W., Sunderland, J., Takin, M. & Bacon, M. 1969 Crustal structure and origin of Peake and Freen Deeps, N.E. Atlantic. *Geophys. J. R. astr. Soc.* **18**, 517–542.

Matthews, D. H. 1970 Weathered basalts from Swallow Bank, an abyssal hill in the N. E. Atlantic. *Phil. Trans. Roy. Soc. Lond* A (this volume).

Melson, W. G., Thompson, G. & van Andel, Tj. H. 1968 Volcanism and metamorphism in the Mid-Atlantic Ridge, 22° N latitude. *J. geophys. Res.* **73**, 5925–5941.

Muir, I. D. & Tilley, C. E. 1964 Basalts from the northern part of the rift zone of the Mid-Atlantic Ridge. *J. Petrology* **5**, 409–434.

Philpotts, J. A., Schnetzler, C. C. & Hart. S. R. 1969 Submarine basalts: some K, Rb, Sr, Ba, rare earth, H_2O and CO_2 data bearing on their alteration, modification by plagioclase and possible source materials. *Earth Planet. Sci. Lett.* **7**, 293–299.

Ramsay, A. T. S. 1970 The pre-pleistocene stratigraphy and palaeontology of the Palmer Ridge area, N.E. Atlantic. *Mar. Geol.* (in the Press).

Reinhardt, B. M. 1969 On the genesis and emplacement of ophiolites in the Oman Mountains geosyncline. *Schweiz. Min. Petr. Mitt.* **49**, 1–30.

van Andel, Tj. H. & Bowin, C. O. 1968 Mid-Atlantic Ridge between 22° and 23° north latitude and the tectonics of mid-ocean rises. *J. geophys. Res.* **73**, 1279–1298.

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