

Geology Of The Bermuda Seamount

FABRIZIO AUMENTO¹ AND BERNARD M. GUNN²

¹ DALHOUSIE UNIVERSITY, HALIFAX. (NOW AT ELC-ELECTRONCONSULT MILANO – ITALIA 1982)

² UNIVERSITIE DE MONTREAL (NOW AT VOLCANIC DATA RESEARCH, WANAKA, NEW ZEALAND INFO@GEOKEM.COM)

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ABSTRACT

Contrary to common belief, the Bermuda Islands are not made up totally of limestones and eolian sands, but in fact some 99% of its structure is in the form of a truncated cone built up of interlayered igneous rocks. The latter are totally capped by a very thin layer of the sedimentary rocks of coralline origin that the visitors to Bermuda are so enchanted with during their stay. Bermuda is a typical Pacific type atoll, the only one found in the Atlantic region.

To date, four holes have been drilled through the limestone capping into the basement igneous rocks. Two of the holes were shallow perforations in the search for potable water; another shallow hole was drilled during the construction of the International Airport, and a fourth, deep hole was sunk for scientific purposes by Dalhousie University in co-operation with Dr Maurice Ewing of the Lamont-Doherty Geological Observatory.

The basement, at least for the top 800m, consists of over 1000 thin, inter-layered flows and sheets. The flows, many of them pillow lavas, are similar to mid-ocean tholeiites which extruded at the axis of the Mid-Atlantic Ridge some 90-110 m.a., ago. These flows suffered both halmyrolysis and spilitization to some degree. Contact with seawater has altered the olivine, pyroxene, plagioclase and glass to carbonates, albite, chlorite and smectites, resulting in the chemical reconstitution of these lavas, especially along margins, where considerable absorption of K, Rb, Ba, and U, has taken place.

A second igneous event occurred 34 m.a. ago, when basic sheeted dykes intruded the tholeiites. These dykes are of an extremely basic, alkaline character with up to 7% TiO₂, 4% K₂O and only 38% SiO₂. The name "Bermudite" has been re-instated for these rocks. Chemical variations within the Bermudites are dominated by variations in titanaugite content.

It is this last igneous event, with its intrusives and now lost extrusive counterparts, which was responsible for the local thickening of the oceanic crust and the building of a huge volcano, the remnants of which we now call Bermuda.

INTRODUCTION

Seamounts occur in great numbers in all major ocean basins. Although by definition they are isolated features rising at least 1000 meters from the ocean floor, some, like the New England Seamounts, occur in chains or provinces. Some of these chains include emergent islands. Despite the great numbers of seamounts of probable volcanic origin known to exist, very little is known of their lithology or structure. The few seamounts which have been sampled by dredging (primarily in the Pacific) yielded highly-altered and weathered extrusive rocks, mainly of the pillow-basalt type (Barr 1972).

Recent investigations of submerged seamounts by the DSDP drillship Glomar Challenger have revealed the often complex history of these underwater volcanoes (see for example Leg 32, Geotimes, December, 1973), suggesting periods of emergence and submergence. Multiple holes and especially the continuous drill core through the Bermuda Seamount reported here provides a unique insight into the lithology, structure and origin of one of the large seamounts in the Atlantic Ocean.

The Bermuda Islands lie approximately 1100 km east of Cape Hatteras, a third of the way to the axis of the Mid-Atlantic Ridge. The islands have a maximum elevation of only 30m above sea level and occupy the southeastern 7% of the 116km² platform forming the top of the Bermuda pedestal. This pedestal is the northernmost and largest of three seamounts on the Bermuda Rise. Only limestones are exposed subaerially on the islands.

Seismic reflection profiles (Gees and Medioli, 1970) suggest that volcanic rocks first occur at an average elevation of 76m below sea level, with their greatest elevation being in the region of Ferry Reach. In nearby Whalebone Bay dark, heavy beach sands give the only external indication of a volcanic edifice beneath the limestones.

Two holes had been drilled into Bermuda prior to the Dalhousie/LDGO effort. The first, in 1912, was sited on the slope of a hill nearly half a mile west of the Lighthouse on Gibb's Hill. It was sunk to 430m with a churn drill (Pirsson and Vaughan, 1913), without core recovery, for the purposes of locating (unsuccessfully) artesian fresh water. The material recovered was in the form of a coarse powder with the occasional rock chip; the latter were used by Pirsson (1914) for making thin sections, who described them as mafic basalt. The second borehole, made by percussion drilling, was sunk near Ferry Reach during investigations of the sub-soil prior to building the International Airport and the causeway between St George's Island and the main Bermuda Island. This hole also provided chips only. These were investigated by Gees (1969) who reported a radiometric age of 52.4 (± 2.5) m.a. on a sample from 43m down.

The Bermuda Biological Station for Research has grounds close to Whalebone Bay, and its Director, Dr. W. Sterrer, gave permission for Dalhousie University to site a drill hole on their property. Deep Drill – 1972, an 800m deep hole was drilled for Dalhousie University by Inspiration Drilling Limited of North Bay, Ontario, on the Biological Station site at 32° 22' N, 64° W (Figure 1). Almost total core recovery was obtained over the complete vertical (± 1° maximum deviation) section penetrated).

Subsequently, in 1973, a fourth hole was sunk down to 55m by rotary drilling by Island Engineering Assoc. Ltd, of Hamilton, Bermuda, at the intersection of Rosemont Avenue and Serpentine

Road, again in the search for water. Cuttings from this hole were kindly made available to the authors.

The descriptions which follows are based primarily on investigations of cores from the Dalhousie drill hole; findings are comparable to those from the 1973 Island Eng. Assoc. hole.

STRATIGRAPHY OF THE DALHOUSIE DRILL CORE

The drill hole, which was placed 10m above sea level, first encountered 94m of Walsingham Limestone, a marine calcarenite extensively altered to calcitic limestone with later solution channels. Beneath there are 3m of redbeds, marking the Sub-Walsingham soil, an interglacial subaerial deposit, followed by 16.4m of extensively recrystallized carbonate, which may record the initial Pleistocene glacial epoch – the Nebraskan (Schenk, 1973).

At 28.9m the Nebraskan carbonate is underlain by 6.4m of volcanic soil with lava cobbles, overlying weathered lava at 35.4m. Artesian fresh water, previously unknown in Bermuda, was found in this soil. The 767.5m of core drilled beneath the volcanic soil penetrated over 1000 different igneous units.

PHYSICAL PROPERTIES

Some of the basic investigations made on the igneous sections of the Dalhousie and the Island Eng. Holes include petrography and geochemistry, heat flow and heat production, paleomagnetism, age determinations and seismic velocities. Hyndman, Muecke, and Aumento (1974) measured the geothermal heat flux down the Dalhousie hole to be $1.36\mu \text{ cal/cm}^2 \text{ sec}$ (57mW/m^2). If the heat production attributable to the seamount is subtracted from the measured heat flux, then a value of $1.26\mu \text{ cal/cm}^2 \text{ sec}$ (53mW/m^2) is obtained. This value is in good agreement with the mean of surrounding sea-floor measurements and with the mean for a Cretaceous ocean floor.

Reynolds and Aumento (1974) reported K/Ar age determinations on the igneous rocks. Two events are apparent; the first, some 91 m.a. ago (minimum age) formed the seamount through massive outpouring of lava, and the second at 34 m.a. B.P. marked the intrusion of new magmas into the then already old seamount. Therefore, Bermuda formed soon after or contemporaneously with the creation of new ocean floor on the axis of the Mid-Atlantic Ridge (100-110 m.a., according to the magnetic anomaly studies of Larson and Pitman, 1972). Only much later, and at a great distance from the axis of the Ridge, did a new phase of igneous activity subject the seamount to massive intrusions.

The measurements of sound velocities in the intrusive sheets are of considerable interest; compressional wave velocities (V_p) range from 5.70 to 7.01 km/sec (mean at 6.20km/sec), with bulk densities as high as 3.2 gm. Cm^{-3} . With confining pressures increased to 2.5kb, V_p exceeds 6.9 km/sec (Barrett, et al., 1973). These velocities are equivalent to, or higher than, those expected of oceanic layer 3. Such an extensive occurrence on the first seamount sampled to any depth has caused speculation as to the real nature of the lower oceanic layers. This will not be resolved until more deep holes are drilled, both on seamounts and in the deep ocean.

MACROSCOPIC OBSERVATIONS

It is immediately apparent in hand specimen that the core recovered has suffered extensive hydrothermal alteration. All through the core, in addition to the filling of vesicles by carbonates and zeolites, many primary minerals have been replaced by calcite, and inter-unit sections of breccia are held together by a mixed chloritic-carbonaceous cement. The top-most 300m of core is stained red, possibly due to oxidation by percolating ground waters.

The drilled section comprises two distinct igneous units: lava flows and intrusive units: these we will call sheets. Fig. 4 shows the distribution of these two units down the hole. There is no preferred

depth distribution for the intrusions, but they do tend to group together and even intrude into one another, as lit-par-lit intrusions.

The igneous section of the core consist of 65% of altered lavas, and of 36% of intrusive sheets. Both the lavas and sheets are generally very thin. The maximum thickness for a lava flow is some 4m, the average being only 0.9m, whereas the maximum for intrusion is 7m with an average of less than 0.6m.

At depths below 150m many of the lavas exhibit apparent pillow structures with highly altered palagonitic margins and chloritic breccias separating individual pillows. One can distinguish 600-odd lava units, but these represent pillow units rather than flows. Due to the similarity in lithology and chemistry of these pillows, it is not possible to group them into distinct eruptive events. However, the distribution of distinctive pillow structures may be significant: they are extremely abundant below 500m, common in the 150m – 600m range, and totally absent in the 30 – 150m range. This distribution might be interpreted as representing a gradual emergence of the seamount during its construction. Inter-flow (inter-pillow) chloritic or carbonate breccia is rare in the top 150m of the core but becomes progressively more common below 150m, paralleling distribution of the pillows.

Thus it appears that the Bermuda Seamount may have emerged as an active volcanic island in its later stages of eruption at the time of its original formation on the axis of the Mid-Atlantic Ridge. Pirsson (1914) has calculated, from the underwater profile of Bermuda, that the summit of the original volcano may have been 3500m above sea level, almost twice the height of the present-day island of Pico, in the Azores Archipelago, on the Mid-Atlantic Ridge. Of course Pirsson had not known of the two stages of activity in Bermuda: eliminating the effects of the subsequent reactivation, the original activity on the axis of the Mid-Atlantic Ridge probably did produce a volcano of the dimensions of Pico, over 2000m in elevation.

Although the azimuth of the drill core is not known, the inclination of the hole is known to be within $\pm 1^\circ$ from the vertical, so the attitude of the various contacts could be studied. Fig. 5 shows the attitudes of the 210 flow contacts and 571 intrusive contacts measured: the flow contacts are randomly oriented from horizontal to almost vertical; many of the steeper contacts are probably the sides of pillows intersected by the drill.

The intrusive contacts, on the other hand, lie predominately in the 40-70° range. Fig. 6 attempts to separate the contact relationships as a function of both depth and rock type: there is a slight indication that intrusions closer to the surface have shallower inclinations than those deeper down the hole; perhaps they form a cone sheet system.

PETROGRAPHY

Pirsson (1914) described the petrology of the igneous chips recovered from the Gibb's Hill Lighthouse core. He and H.H. Thomas summed up the petrographic character of the chips as being:

“mostly, if not entirely, lavas of the alkali group, and they fall under two main heads:

- a) Feldspar free basalts, including melilite basalt
- b) Lavas of monchiquitic and lamprophyric affinities”

Pirsson stressed that the largest of the few chips they were able to examine, was only less than half a pea in size.

THE LAVAS

Although representing some 64% by volume of the core, the two hundred thin sections made of the lava flows show only textural variations from totally aphanitic to porphyritic. The majority are very fine grained, typical of submarine pillow lavas or thin, rapidly cooled flows (Fig.7). A small proportion of them are vesicular; with vesicles commonly containing calcite, phillipsite, analcite and a potassic kalsilite. The chemical analysis of a water-clear analcite from the 788.8m level compares closely with analcite from vesicles in the Triassic basalts of Nova Scotia (Aumento 1965).

In most cases the original groundmass must have been vitreous or very fine grained. Now it consists of a dark felted mass of chlorite, calcite, analcite, clay minerals, and disseminated magnetite. The magnetite is always fine grained, and sometimes clearly exhibits two generations. The microlites present, in the form of partially albitised acicular plagioclases and less common clinopyroxenes, or the secondary biotite (rare) and calcite replacing olivine, often show original flow texture. In a very few cases the lavas are porphyritic, with pseudomorphs after euhedral olivine phenocrysts. The pseudomorphs are made up primarily of calcite and a pleochroic (bright green to yellow) micaceous mineral (Fig. 8). Though plagioclase microlites may make up 50% of a sample, the grain size is very small (0.2 mm to submicroscopic).

THE SHEETS

The sheets include aphanitic, fine-grained, porphyritic and amygdaloidal textures and are mineralogically more variable than the flows (Fig. 9, 10 and 11). Almost all the sheets have chilled margins, some of which trap oriented phenocrysts in a glassy matrix (Fig. 12); some of the sheets also exhibit double or triple chilled margins formed by multiple intrusion along the same boundary plane. Certain samples show a cumulate texture with close packed olivine and titanite phenocrysts and, in the thicker sheets the crystal size increases sharply with distance from the chilled margins. Clinopyroxene phenocrysts 1 cm or more in size may be concentrated at the centre of sheets (Fig. 13), a flow phenomenon which has been reproduced experimentally by Bhattacharji (1967). Phenocrysts include clinopyroxene, plagioclase, olivine, melilite, mica and magnetite. Many of the sheets are amygdaloidal, especially in tabular layers equidistant from the margins; the cavities are filled, as in the lavas, by calcite, analcite and tridymite.

Olivine phenocrysts have been pseudomorphed by calcite (Fig. 14). Only one relict olivine crystal was found in 200 thin sections (#1875.6): electron probe analyses reveal a normally zoned composition range between Fo84 and Fo87. The pseudomorphs range from small skeletal crystals to large, euhedral crystals. They are found in 70% of the sheets in concentrations ranging from 2% to a maximum of 35% (13% average). The calcite pseudomorphs are themselves replaced in part by chlorite. Calcite also makes up most of the vein material, which is abundant through the core.

Plagioclase occurs both as laths (showing pilotaxitic arrangement) and as scarcer larger phenocrysts. Their severe alteration makes original composition determinations difficult, but most of those whose composition could be estimated optically fall into the andesine-labradorite range. Some oligoclase and albite were also detected, often coexisting with the calcic plagioclase within a single slide. Maximum concentration in the porphyritic sheets never exceeded 10%, in contrast to the more abundant olivine and clinopyroxene.

Clinopyroxene is the most abundant and least altered mineral, both as phenocrysts and groundmass. Some of the euhedral crystals are up to 2cm in size, and locally can make up to 70% of a sheet. Modal concentrations of 30% are common. The phenocrysts, both subhedral and euhedral, are normally zoned with Mg rich cores and Fe rich rims; they show good hourglass structures, showing pleochroism from colourless to pinkish brown, especially in the Fe and Ti rich rims. The composition of a number of phenocrysts, determined by electron micro-probe, show that all have a diopside-salite composition, (Wo 48.93, En 42.48, Fs 7.47, Jd 1.14) with

little variation except for Ti enrichment on the rims of grains (Wo 49.46, En 40.12, Fs 9.22, Jd 1.21).

Mica phenocrysts are conspicuous in 10% of the sheets, where they range from 4% to 25% modal concentration (average 8%). They are of a deep reddish-brown pleochroic variety and electron microprobe analyses indicate a phlogopitic composition (Phlo 79.11, Ann 20.89 average). A number of the thin sections suggest that there are two generations of phlogopite, possibly one due to a primary igneous crystallization forming large phenocrysts poikilically enclosed by olivine and pyroxenes, and a second generation of smaller flakes associated with calcite pseudomorphs. The larger, primary flakes gave K/Ar ages of 34 m.a., whereas a concentrate containing both types of phlogopite gave a much younger age of 16 m.a. (Reynolds and Aumento, 1974), Fig. 15.

The remaining conspicuous phenocryst mineral is a titaniferous magnetite which can make up to 10% of a sheet. Commonly, however, it occurs in concentrations of 3-5% or less. The magnetite usually occurs as tiny crystals in the groundmass, but sometimes forms euhedral phenocrysts. Other opaque patches with translucent red borders are common in the upper 300 m, these are probably massive patches of hematite. Both magnetite and hematite have the characteristics of secondary minerals. Microprobe analyses have revealed that sub-microscopic exsolution lamellae of a chrome-spinel may exist in the magnetite: local concentrations of Cr increased up to 3.18% Cr₂O₃ within some magnetite grains.

On the basis of the relative concentrations of a phenocrysts and of the groundmass texture, the sheets have been subdivided into a non-porphyritic, a porphyritic, and a diabasic type; the latter is quite unlike the others, with broad plagioclase laths and interstitial pyroxenes producing a characteristic diabasic texture. The diabasic types occur in three horizons only, namely at 269m, 338m and 385m.

GEOCHEMISTRY

In view of the altered nature of the core, geochemical analyses could only be performed on those units which in hand specimen and thin section appeared to be least altered; however, some of these were later shown to be soda or potash metasomatised.

Composite samples for each unit to be analysed were made by homogenizing powders taken at intervals along the length of the unit. All primary analyses were performed, therefore, on whole rock composites attempting to characterize an average composition for each unit; the variations within individual units were investigated separately.

Sixty-seven composite sheet units and 59 composites of lava flows were analysed for 14 major elements and 8 trace elements each, using a combination X-ray fluorescence, atomic absorption, neutron activation, wet chemical and fission track techniques.

In addition to the 126 total analyses* mentioned above, a further 40 lavas and 10 sheets were analysed for Fe₂O₃, TiO₂, U, CO₂ and H₂O+ and H₂O- primarily to establish the existence of any depth variation for these elemental concentrations and, using the H₂O and CO₂ content as an indicator, to detect relatively unaltered specimens for other investigations.

The chemistry of the whole core is strongly bimodal, the flows being highly sodic and tholeiitic in type, and the sheets highly potassic and alkaline. The mean compositions of the two groups is given in Table I together with their standard deviation from the mean. The flows show little variation, apart from that due to secondary alteration. The mean compositions (and standard deviations) are also given for the nonporphyritic, the porphyritic and the diabasic subgroups of the sheets. The aphanitic, variolitic and porphyritic lavas were not geochemically distinguishable, so that their individual means are not tabulated.

CHEMISTRY OF THE LAVAS

The lavas, which are mostly thin flows and pillows, show remarkable homogeneity, apart from the variations in the Na as K elements described below.

(*) Detailed analyses are on file in the Library of the Bermuda Biological Station.

They are just quartz normative and their low average TiO₂, Sr, K, Rb, and Ba places them in the field of sea-floor basalts (Table I, and Fig. 16). However, they have an extremely variable soda content, ranging between 2.6 and 5.5% Na₂O. The low soda rocks are typical ocean floor basalts of the low alumina variety, and though the mean K₂O (0.6%) is somewhat higher than that of some ocean floor basalt, many have 0.1% K₂O or less. The high soda rocks do not differ in Al, Ca or Sr from those of low soda. Electron probe analysis shows the high soda units to contain albite or plagioclase of highly variable composition, with individual microlites varying from albite to labradorite or even bytownite. On grouping the lavas according to their normative plagioclase content An₂₀-30, An₃₀-40 (A₄₀+) it can be shown that no other significant change occurs in any other component as the feldspar composition changes.

HOMOGENEITY AND ALTERATION OF THE BERMUDA LAVAS

Multiple analyses at 0.3m intervals were made of three flows to test the distribution of the alkali elements. This proved to be extremely variable. A 3.4m thick unit between 416.0m and 419.4m had over 2% K₂O, 0.2 ppm U, 32 ppm Rb and 200 ppm Ba at the upper and lower contacts. The central 2m of this unit had almost constant composition of 0.6% K₂O, 8 ppm Rb and 70 ppm Ba, indicating a marginal enrichment of the alkali elements of factors of 3 to 4, (Fig. 17). This enrichment was especially marked at the lower contact; the upper contact showed renewed depletion in the case of U and possibly Ba. Soda values are high and variable but higher at the centre of the flow (4.07%) than at the margins (3.04%). Sr averaged 230 ppm but values of 300 and 400 ppm were also found; especially near the lower contact. The CO₂ values parallel the distribution of the K group elements with a minimum of 3% at the centre and 6.5% at the margins; as for U, however, there is a marked depletion at the extreme upper contact.

A series of interflow breccias containing some sedimentary material gave extremely erratic values of 5-88 ppm Rb, 100-470 ppm Sr, and 0.2 - 2.5% K₂O. Mineralogically these breccias are dominated by chlorite, though illite, calcite and analcite are also present.

CORRELATION BETWEEN MINERALOGY AND CHEMISTRY OF THE LAVAS

Twenty six lava specimens, chosen to represent the widest range of K₂O and Na₂O values were examined by X-ray diffraction. Illite, smectite and chlorite peaks were qualitatively labeled "weak", "medium" or "strong". Weak illite peaks occurred in lavas with between 0.07 and 0.35% K₂O. Lavas with 0.6 to 1.1% K₂O gave medium sized peaks and a single lava with 2.2% K₂O gave the strongest peak. Traces of phillipsite were also found at random in most of the lavas.

Sodian montmorillonites (smectites) (12.A°) occur in abundance in the centres of some flow units (Nos. 761.2, 706, 1370) and with glycerol treatment these gave spacings of 17.8 Å. Montmorillonite-chlorite interlayer structures were found in samples 743, 2178 and the thick flow between 418.6 and 422m of Fig. 13). In a similar study, Hekinian (1974) reported chlorite, vermiculite-chlorite interlayered structures and smectites as alteration products of sea-floor basalts from the Indian Ocean.

Cann (1969) described spilitized sea-floor basalts with marginal palagonite altered to chlorite with loss of silica, soda and potash and altered internally to albite plus chlorite with enhancement of soda. In Bermuda, there has been an internal alteration to calcite + albite + chlorite + smectites, the latter often being in the form of interlayer structures with chlorite. Marginally, the flows appear to

be altered to chlorite + calcite + illite, the latter probably having been formed by halmyrolysis or exchange of water dipoles for large positive cations (including K, Rb, Ba, and U) between groundmass and sea water. The 60 m.y. old Sylvania Guyot, near Bikini Atoll has basaltic glass altered to montmorillonite-chlorite mixed layers, phillipsite and opal (Rex, 1967). Most extreme of all, DePaeppe et al., (1974) found tholeiitic pre-Cretaceous pillow basalts in the Cape Verde Island to have cores with 0.48% K₂O and rims of 6.49%.

The alteration and metasomatism of the Bermuda lavas, which ranges from minimal to extreme, was probably controlled by the length of time each flow was exposed to sea water and by the temperature within the lava pile while the volcano was active. However, the interflow breccias and flow margins are so enriched in the alkali elements that these may have acted as secondary sources in the later alteration of the more massive units. Aumento et al, (1976) published data showing the direction and magnitude of alteration due to sea water contact of ocean ridge basalts with time and depth. These results parallel the direction and magnitude of the alterations described here, suggesting that a similar process may well have occurred on Bermuda. Enhanced alteration along flow margin and adjacent to internal fractures is also in keeping with findings from the deep hole 332 B of DSDP Leg 37 (Aumento et al, 1976).

The side-by-side occurrence of basalt, spilites and greenstone in dredge hauls from the Mid-Atlantic Ridge (Aumento and Loncarevic, 1969) suggests that albitization and chloritization may take place at shallow depths of burial under submarine conditions. A study of the ⁸⁷Rb / ⁸⁶Rb ratios of both fresh and altered basalts from the mid-oceanic ridges tends to confirm this hypothesis (Muehlenbachs and Clayton, 1972).

The means by which the large amounts of soda were introduced is not clear; possibly percolating brines may have been the source of soda during albitization. Multiple electron probe analyses of plagioclase microlites from several samples revealed, as did the optical determinations, that albitization is incomplete; compositions of pure albite and andesine, andesine and labradorite and andesine and bytownite could be found within single thin sections, the soda values for the feldspars ranging from a low of 0.36% to a maximum of 11.9%. The high soda rocks would generally be termed spilites. Albitization may well be a long term process which was unable to reach completion in these lavas. Had the original Bermuda seamount not formed exactly on the axis of the Mid-Atlantic Ridge, i.e., some tens of kilometers to the west, the lava piles might not have been subjected to the high axial temperature gradients which are thought to assist spilitization.

CHEMISTRY OF THE SHEETS

The Bermuda sheets are highly alkaline basic rocks with lamprophyric/limburgitic/melanephelinite affinities, with less than 45% SiO₂. All are nepheline normative and many are leucite normative. The TiO₂ content is unusually high with a mode at about 4.6%, with a maximum near 7%. Ti and Sr, which are neither strongly fractionated in many basalt series, nor subject to severe secondary effects, may be used as a measure of the "alkalinity" of a series (Gunn and Watkins, 1975). A mean TiO₂ of 4.6% and Sr of 900 ppm show the Bermuda sheets to be rather more alkaline than the limburgite series of even such highly alkaline islands as the Cape Verdes (Fig. 6).

The major chemical characteristics of the Bermuda sheets are as follows:

- a. A range in K₂O from 1 to 4.5% showing a weak negative correlation ($R = -.38$) with silica; the high K rocks having only 35% silica; this trend does not correspond with increase in leucite (55% Si₂O) analcite, alkali feldspar, or even nepheline (44% Si₂O). Though the high K rocks are leucite normative, and one would accept that phlogopite (8% K₂O, 33% Si₂O) should control the K₂O distribution, we have not been able to show a correlation between modal phlogopite and K₂O content. Potassium and rubidium show the usual strong covariance ($R = +.75$) with a constant ratio K/Rb of 303 (Fig. 18) which is normal for alkaline basic lavas. Since Rb is preferentially absorbed on clays, the relative constancy of K and Rb suggest that little ion exchange has taken place. Ba is less regular than ($R = +.5$), but the mean K/Ba of 34 also shows no relative fractionation. The Th content is below 10 ppm but also varies directly with K. Although large amounts of calcite are present in many samples, CaO shows a positive correlation with MgO ($R = +.71$) due to the large variation in the amount of clinopyroxene.
- b. In spite of the high total alkali element content of phlogopite, a negative correlation is found between total ferromagnesian and the alkalis ($R = -0.72$). Fe correlates well with TiO₂ ($R = +.70$). MgO, which varies from 4 to 11%, as already stated, shows a good positive correlation with CaO; were phlogopite the dominant phase, the CaO-MgO correlation should be strongly negative. Obviously olivine and clinopyroxene dominate over any phlogopite effect in the ferro-magnesian minerals.
- c. Ni shows a wider range (10-400 ppm) and has a very close covariance with Mg ($R = +.92$). The low-Mg sheets are thus almost totally depleted in Ni. The Mg/Ni slope is characteristic of olivine fractionation. Cr also shows strong covariance with both Mg and Ni ($R = +.79$). Both Cr and Ni are rather more enriched in relation to Mg than is the case in tholeiitic basalts e.g. in the olivine-picrite series of Hawaii (Gunn, 1971) although the Cr/Ni ratio is similar in both Hawaiian and Bermuda lavas.

Computer averaging of all analyses of the sheets into groups of each whole percent MgO effectively smooths out the scatter caused by late stage alkali localization and minor effects from olivine and mica. The dominant trends are then seen to extrapolate in every case towards the composition of a magnesian titanite. That is, the dominant chemical differences with the intrusive sheets are probably due to mechanical concentration or removal of titanite.

ALKALI VARIATIONS WITHIN THE BERMUDA SHEETS

Both a HIGH-K and a low-K sheet were examined in detail. The high-K sheet (with a mean of 4.0% K₂O) at the 408-411m level has a mean Sr of 900 ppm with extreme values of 765 and 1020 ppm. In the same sheet Rb has a mean of 112 ppm \pm 30 ppm, the distribution of both Sr and Rb through the sheet being erratic but parallel. A low-K sheet (2.65% K₂O) has 600 \pm 10 ppm Sr and 55 \pm 7 ppm Rb. This local variation encompasses much of the K₂O variance seen in the series as a whole.

The alkali elements do not show the steep inward decrease in concentration displayed by the lava flows. Obviously the sheets were never exposed to sea water with its resultant ion absorption process, such that it is probable that they still retain their original bulk chemistry.

CONCLUSIONS

At first sight the existence of two dissimilar igneous events on Bermuda, separated by such a long time span, appears to be quite anomalous, especially in the light of current "hot spot" hypotheses (e.g. Schilling, 1973). If either event were related to the activity of a single hot spot, other seamounts should exist to the east and west. Alternatively a hot spot may have moved with the lithosphere and been reactivated, which is unlikely, or two totally unrelated magma sources may have been tapped beneath Bermuda at different times. It seems even more unlikely that a residual magma chamber beneath the original seamount could have differentiated slowly and have had sufficient heat to survive for 60 m.a. prior to its final massive eruption.

Other evidence is appearing from elsewhere in the oceans for much more complicated magma generation patterns. Leg 17 of D.S.D.P., drilled on Horizon Guyot at site 171 (Winterer and Ewing, 1973) encountered extrusive basalts at the base of the drill section, which was dated at 100 m.a., much like the Bermuda lavas; however, 140m above the base other lava flows were at least 5 m.a., and possibly as much as 30 m.a. younger than the basement flows. More recently, on leg 32 of D.S.D.P. (Geotimes, December 1973) a hole 60 miles from Midway Island (Site 311) showed evidence of volcanic activity which was much older than that found on the island itself (17 m.a.).

Similarly De Paeppe et al., (1974) showed that tholeiitic basalts of pre-Cretaceous age underlie the alkaline limburgite-basanite-phonolite series of the Cape Verde Islands.

The Bermuda Seamount exhibits features not seen elsewhere in other islands, though in the latter the patterns seen are so variable that no general evolutionary trend appears to apply to all islands. Islands and island arcs are consistently more enriched in alkalis than their sea-floor equivalents, and continental andesite series are commonly even more enriched than the islands. Thus, in a very general way, volcanic evolution appears to proceed with time from a relatively depleted tholeiitic sea-floor basalt, through to alkali basalts, basanites and limburgite phonolite suites.

A series of mean Sr and TiO₂ abundances for many basaltic provinces are plotted in Fig 6. The increase in average Ti and Sr that occurs between tholeiitic to alkaline series is paralleled by increase in K, Rb, Ba, Th, U and P. Therefore, to some degree the trend shown reflects the course of evolution followed by many volcanic centres; indeed thick lava piles may show part of this trend from the base to the top (Gunn and Watkins 1972; Schmincke 1973).

Bermuda appears to lack the entire middle part of this evolutionary series, at least within the limitations of the length of the hole. It appears that Bermuda began as a vast seamount, built near the axis of the Mid-Atlantic Ridge and composed of a typical series of tholeiites differing little from those produced on the Mid-Atlantic Ridge of the present day. After a quiescent period lasting 60 m.a., during which the seamount was displaced by some 1000 km to the west into a stable abyssal plain environment, dike injections and possible eruptions of effusive equivalents took place; these were more alkaline and more potassic than any lava previously described from oceanic islands. The lava may still exist on the flanks of the seamount; those from the summit may have been eroded down to sea level during the last 40 m.a. Pirsson, following the initial discovery of alkaline igneous rocks underlying Bermuda, termed them "Bermudites". Sorenson (1974) defines Bermudite as "a biotite nephelinite". The name has not been used due to the rarity of this rock type, but could be reserved for hypabyssal sheets or extrusive lavas of extremely alkaline character, with high TiO₂ (4-7%) and K₂O (2-5%) and normative Ne. Essential minerals are

titanaugite, olivine, phlogopite, calcic plagioclase and titanomagnetite.

PETROGENETIC AFFINITIES OF BERMUDITE

The more alkalic rocks of basaltic type are extremely varied in nature, often occurring as late-stage dikes in alkalic intrusive suites. The most alkaline extrusive suite yet described in detail is the limburgite-basanite-phonolite series of the Cape Verde Islands (Gunn and Watkins, 1975). These islands, incidentally, occur in a position similar to Bermuda across the axis of the Mid-Atlantic Ridge. The limburgites are mafic rocks, with little or no plagioclase and 3-5% TiO₂, 900-100 ppm Sr, similar to the Bermudites but with notably less K₂O (often less than 1%). Such alkaline rocks usually have abundant carbonates, and are often associated with carbonatites; hydrated minerals, especially kaersutite, are common. Late stage dikes in the Mount royal alkaline complex, Quebec, are similar in composition with up to 4% TiO₂ and variable K₂O, but the ferromagnesian phase is predominately kaersutite suggesting high PH₀ during crystallization. The presence of phlogopite and carbonates in the Bermudites is therefore not surprising. The Kaligaites described from Fernando de Noronha and Trinidad (Mitchell-Tome, 1972) are also potassic rocks but with relatively low TiO₂ and high alumina. A search through the 12,000 analyses stored in the GEOKEM data file at the University of Montreal did not reveal any other lavas with closer affinities, there being little similarity to common biotite-bearing lamprophyres. However, a subsequent search through the RKNFYSYS Library File of Chayes (1971) revealed a number of approximate matches with rocks given the names of ankaramite, basanite and limburgite from Madagascar

(Lacroix, 1923). These ankaramites differ in having higher MgO contents (9.32%); similarly the limburgites have higher alumina (12.19%) and soda (3.19%) and lower lime (11.82%). A perfect match was obtained, however, with a basanitoid from the Itasy massif of Madagascar. A single specimen (analyses # 396 from Lacroix, 1923) from Mazy Falls, near Ngilofotsy, has very similar chemistry to the Bermudites, including the high TiO₂ content (5.43%). These basanitoids contain abundant phenocrysts of augite and olivine, 1 cm in size or greater, and titanomagnetite in a fine-grained matrix. Unlike other basanitoids, # 396 contains little or no hornblende. The Bermudites and Madagascar basanitoids may therefore be an extreme form, perhaps end members in the series of possible primary basic magmas.

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LEGEND FOR FIGURES

Figure (1) Map of Bermuda showing the locations of the 1912 and 1958 churn and percussion holes, the 1972 Dalhousie/LDGO Deep Drill – 1972 diamond drill hole, and the 1973 Island Engineering Associates hole.

Figure (2) The drill rig of the 1972 Dalhousie/LDGO diamond drill hole near the entrance to the Bermuda Biological Station. The huge water tanks were later donated to the BioStation for their sea water supply system.

Figure (3) The drill core showing the upper stratigraphy: Walsingham Limestone for the top 9.4m (30.4' as marked on the photo); the 3m of red beds of the Sub-Walsingham soil beneath being clearly visible in the fourth channel of the top box; then the 16.4m (53') of Nebraskan carbonate. Volcanic soil and cobbles at 28.9m (93.6'), and finally the first weathered lava at 35.4m (114.7').

Figure (4) Depth distribution of lavas and sheets, showing their relative abundances, relative thickness (horizontal scale), pillow lava distribution and porphyritic/aphanitic sheet distribution.

Figure (5) Attitude of intrusive and flow contacts.

Figure (6) Attitude variations of the intrusive contacts with depth down the hole, and with porphyritic nature.

Figure (7) Photomicrograph of a typical fine grained tholeiitic Bermuda lava.

Figure (8) Photomicrograph of a porphyritic Bermuda Lava, with skeletal olivine phenocrysts totally replaced by calcite.

Figure (9) Photomicrograph of coarse grained Bermuda lava, with large, interlocking plagioclase laths and interstitial ferromagnesians.

Figure (10) Photomicrograph of a porphyritic Bermudite sheets, with large (1mm), euhedral clinopyroxenes exhibiting the characteristic titanium rich rims.

Figure (11) Photomicrograph of a Bermudite showing different textures formed when a cavity in the more slowly cooling unit was later filled by more rapidly cooling liquid, the latter producing the more fine grained, more ferromagnesian rich bubble visible.

Figure (12) Photomicrograph of a typical lit-par-lit contact, where a more fluid sheet intrudes parallel to an already existing, coarser grained sheet. Note the accumulation of phenocrysts next to the contact.

Figure (13) Photomicrograph of the 2cm size phenocrysts common to the porphyritic Bermudites.

Figure (14) Photomicrograph of euhedral calcite pseudomorphs after olivine in the Bermudites, with smaller unaltered clinopyroxenes adjacent to them.

Figure (15) Photomicrograph of the older, 34 m.a. old biotite phenocrysts in the Bermudites.

Figure (16) TiO₂ versus Sr for suites of oceanic basalts. Black diamond; average of 49 Bermudites; Open diamond average of 31 Bermuda spilitised basalts. Note that the latter plot in the oceanic tholeiites field. Am-Amsterdam Island tholeiites; AT = JOIDES drill cores, legs 2 and 3; AU = average Australian Archaean metabasalts; AZ = Azores; BU = Birch-Uchi Lake; C – East Island (Crozet Group); CH – Archaean metabasalts Chibougamau; CP = ankaramites-basalts of Possession Island, (Crozet Group); CV = Cape Verdes; FD = Ferrar Dolerites, Antarctica; FN = Fernando de Noronha; H = Hawaiian basanites; IC = Iceland tholeiites; K = Kilauea Iki (Hawaii); LW = Lake of the Woods, tholeiites; MC = alkali basalts of Mont du Chateau, Kergulen; OC = Mid-Atlantic tholeiites; PM = Port Mary tholeiites, Kergulen; S = St. Vincent and Soufriere andesites; TA = Tongan Island Arc andesites. MORBS = Mid-Ocean Ridge Basalts. All data from published results stored in the Universite de Montreal computer data file (GEOKEM).

Figure (17) Elemental variation through a thick tholeiitic lava flow between 416 and 419.4 m.

Figure (18) Variations between the elements MgO: Ni, Alkalis: silica, Rb: K₂O: Fe₂O₃ for both lavas and sheets.

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LEGEND FOR TABLES

Table I. Mean major element compositions and the standard deviations for all the Bermuda lavas and sheets.

Mean compositions also given for the sheet subdivided into porphyritic and non-porphyritic types. Norms calculated water free weight percent.

URANIUM IN BERMUDA EXTRA SAMPLES

Sample Number	U.ppm	CO2
145-146	2.20	-
154-156	5.36	9.58
156-159	2.01	6.65
159-162	2.82	7.43
162-164	2.02	5.78
164-166	2.45	6.23
166-169	2.12	6.45
169-171	3.47	3.85
177	3.02	4.78
175-182	2.38	5.43

TABLE 1

	LAVAS		ALL SHEETS		NON-PORPHYRITIC SHEETS		PORPHYRITIC SHEETS		DIABASIC SHEET
	Mean Value	Std Deviation	Mean Value	Std Deviation	Mean Value	Std Deviation	Mean Value	Std Deviation	
SiO2	48.16	2.67	38.32	2.29	39.71	2.29	38.49	1.70	42.22
Al2O3	14.16	0.84	10.94	1.51	11.50	1.34	10.21	1.37	10.02
Fe2O3T	8.61	1.06	12.78	1.10	12.93	0.96	13.02	0.89	11.95
CaO	11.45	1.70	13.93	1.70	13.31	0.90	14.86	1.66	15.60
MgO	5.53	1.31	6.82	1.70	6.13	1.48	7.86	2.12	7.78
Na2O	3.81	0.99	2.23	1.10	2.54	1.26	1.69	0.70	1.84
K2O	0.66	0.95	2.05	0.80	2.23	0.91	2.09	0.99	1.51
TiO2	1.31	0.09	4.63	0.76	4.95	0.77	4.54	0.67	4.09
P2O5	0.16	0.02	0.69	0.19	0.77	0.21	0.69	0.13	0.55
MnO	0.16	0.03	0.20	0.03	0.20	0.03	0.20	0.03	0.16
S	0.07	0.01	0.25	0.14	0.30	0.10	0.23	0.09	nd
CO2	3.21	1.57	4.48	2.99	5.14	2.27	3.72	1.73	4.28
H2OTot	2.72	1.32	2.67	0.84	2.99	0.93	2.43	0.58	nd
Q	0.46	-	-	-	-	-	-	-	-
OR	4.05	-	12.64	-	13.44	-	12.83	-	9.05
AB	33.45	-	15.41	-	21.86	-	8.32	-	15.77
AN	20.33	-	14.37	-	13.67	-	14.68	-	14.81
NE	-	-	2.31	-	-	-	3.54	-	-
DI	13.31	-	18.71	-	12.35	-	26.21	-	25.95
HY	14.47	-	-	-	0.48	-	0.78	-	7.29
OL	-	-	9.74	-	9.84	-	8.84	-	3.71
MT	3.23	-	4.84	-	4.77	-	4.91	-	4.39
IL	2.58	-	9.17	-	9.58	-	8.96	-	7.87
AP	0.38	-	1.67	-	1.80	-	1.67	-	1.29
CC	7.58	-	10.62	-	11.90	-	8.79	-	9.86
TOTAL	99.85		99.46		99.69		99.53		100.00