A GEOLOGICAL RECONNAISSANCE OF BOWIE SEAMOUNT

BY

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Frontispiece - Photograph taken on the eastern flank of Bowie Seamount at a depth of 3,000 ft.

ABSTRACT

Bowie Seamount, a submerged volcano situated off the west coast of Canada at 53° 18' N, 135° 39' W, has a relief of 10,000 ft. and comes to within 100 ft. of the ocean surface. It is made up of a series of intersecting ridges which together give the mountain an overall northeast - southwest elongation. It appears to be a combination central and fissure type volcano which has been built up over a system of intersecting fractures in the oceanic crust. Two terraces form the flattened summit of the volcano at approximate depths of 45 and 130 fathoms. These are thought to be the remains of platforms produced by combined wave erosion and shallow-water vulçanism during late Quaternary time when sea level was lower than it is today. The last phase of volcanic activity on the summit occurred after the formation of the upper terrace no more than 18,000 years ago. Samples dredged from the upper half of the volcano include: pillow fragments, fragments of non-pillowed flows, pillow breccias, bombs, tuffs, ash, and unsorted tephra. The rocks are mainly alkali olivine basalts, accompanied by rare andesites which, presumably, were derived by differentiation of the basaltic magma. Feldspathic and gabbroic inclusions, many of which

appear to be cumulates, are common in the basalt. Ice-rafted rocks are rare on the summit of Bowie Seamount but are common on its nearest neighbour - Hodgkins Seamount. A ferro-manganese deposit, apparently over 1 million years old, that exists on the summit of Hodgkins Seamount, suggests that this peak is relatively much older than the summit area of Bowie Seamount. Palagonite appears to form as the initial phase of weathering of glassy basalts in the area of study but the products of more advanced weathering are montmorillonite and zeolites. Rock fragments that have been rounded by chemical weathering are common.

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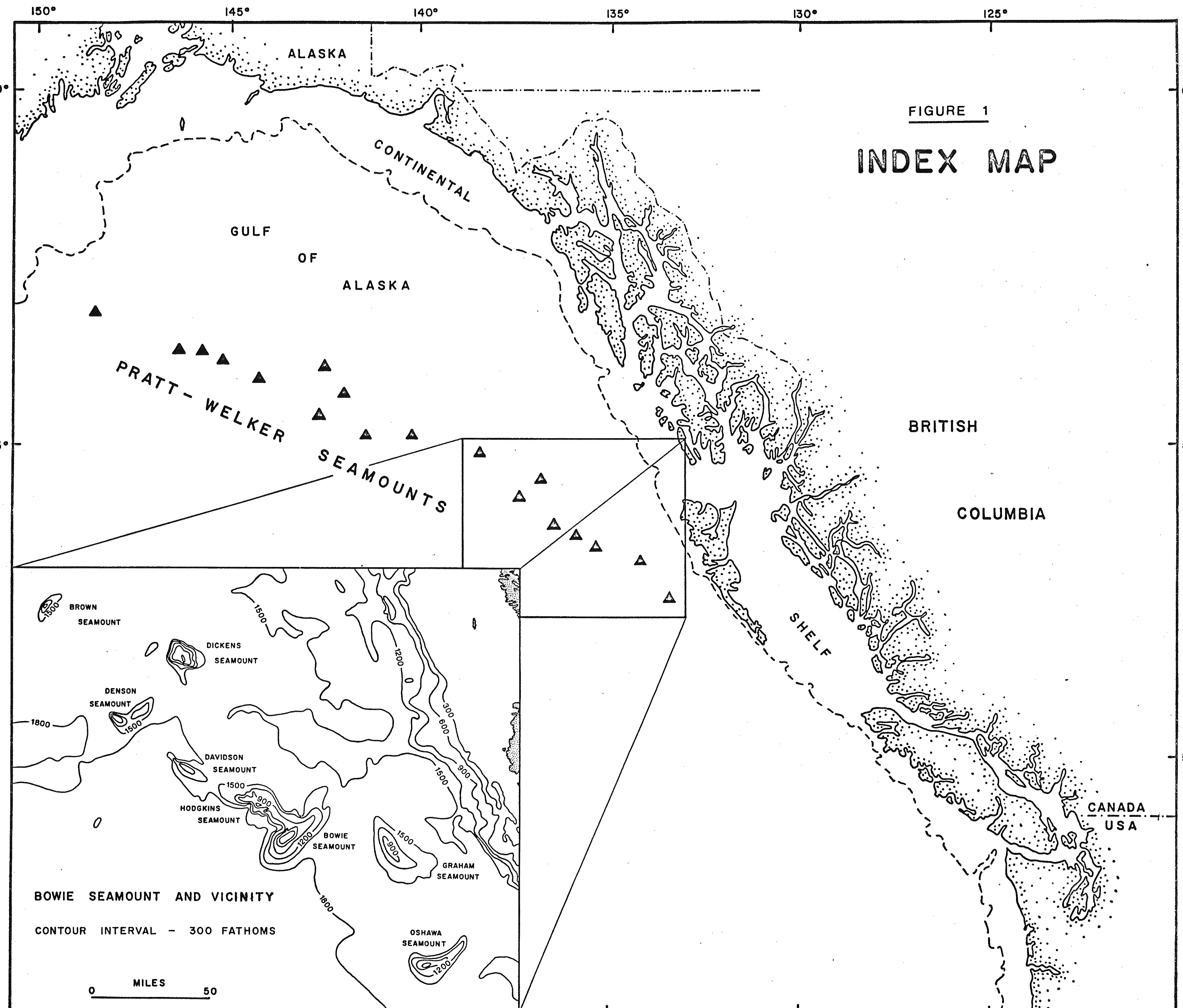
INTRODUCTION

A. Purpose and Scope of the Study

The area of study encompasses Bowie Seamount, a submarine volcano in the northeast Pacific Ocean 100 miles west of the Queen Charlotte Islands, British Columbia. The purpose of the present investigation was to determine the form of the seamount, the geologic processes that have contributed to its development, and the age of its formation. Its proximity to the coast and the nearness of its summit to the surface (15 fathoms) make it well suited for geologic investigation.

B. Geologic Setting

The seamount, ($53^{o}18'$N, $135^{o}39'$W) (Scrimger 1969) is situated on the continental rise on the southern part of the Pratt-Welker chain (Figure I) in the Gulf of Alaska Seamount Province (Menard, 1964). The Pratt-Welker group is a line of seamounts and guyots which strikes southeast from Kodiak Seamount in the Aleutian Trench towards the Queen Charlotte Islands off the west coast of Canada. East of Bowie Seamount, along the continental margin, lies the Queen Charlotte Fault (St. Amand, 1957 and Sutherland Brown, 1968) which may be a major structural element of the East Pacific Rise. The relationships of the Pratt-Welker chain and Bowie Seamount to the East Pacific Rise, to the continental



INSET MAP BASED ON U.S. NAVAL OCEANOGRAPHIC CONTOUR SHEETS: 410 AND 411.

margin and to the recently delineated magnetic anomaly bands in the region are still not clear.

C. Previous Work on the Seamount

Only one previous geologic expedition has been made to Bowie Seamount, the results of which were published in abstract form (Hurley and Nayudu, 1961). These authors found an extensive terrace near the summit between 120 and 140 fathoms, above which, small pinnacles rise an additional 100 fathoms. They recovered palagonitic material from the terrace and fresh basalt from the peaks and concluded that the peaks were formed by post-glacial vulcanism. In 1962, Nayudu proposed that the terrace was not erosional but a product of primary vulcanism. Engel and Engel (1963) included an alkali basalt from Bowie Seamount in their analyses of northeast Pacific basalts. Other work on the seamount has been limited to infrequent crossings during general bathymetric surveys carried out by the U.S. Navy and the U.S. Coast and Geodetic Survey around the time of the Second World War.

D. Scope of the Field Work

The field work was carried out over a total of about two weeks during two short visits to Bowie Seamount in the summers of 1967 and 1968. The vessel used for both cruises was the Canadian Naval Auxillary

Vessel ENDEAVOUR, furnished by Defence Research Establishment Pacific in Esquimalt, British Columbia. Just over 600 miles of echo sounding lines were run in a pattern over the seamount and bottom samples were obtained from seventeen localities and underwater photographs from four.

II. FIELD WORK

A. 1967 Cruise

The first phase of the field work on Bowie Seamount was completed during three days of a two-week cruise in 1967 devoted primarily to a continuous seismic profiling survey of the continental shelf off Canada's west coast. At that time, a preliminary survey was made by echo sounder followed by dredge and grab sampling stations in the shallow waters of the summit.

Since sufficiently accurate fixing of positions by LORAN or by celestial navigation was impossible, navigation was to have been effected by frequent radar fixes on an aluminum reflector mounted on a tall spar buoy which was moored on the summit of the seamount. Unfortunately, loss of the reflector in rough weather shortly after the buoy was set out, necessitated resorting to navigation by dead reckoning with occasional LORAN fixes and sightings of the crippled buoy.

The proposed ship's track was in the form of an elongate Maltese cross with two superimposed concentric circles. This pattern was retained during the sonar survey using the ship's log to estimate the distance covered and the headings on the Gyro compass to approximate the actual course. Visual contacts with the the buoy were recorded. A further close pattern of four mutually adjacent one-mile squares was run in the vicinity of the buoy in order to obtain detailed topographic control in the area to be sampled.

The compilation of the continuous sounding lines, obtained after corrections were made for closure on the basis of five visual fixes on the buoy, revealed that the ship had been set so far to the southeast by wind and ocean currents during the survey that only half of the seamount was actually mapped.

Six dredge hauls and seven grab samples were taken on the central peaks and the terraces (Figure 2).

B. <u>1968 Cruise</u>

During the 1968 cruise, the entire seamount was resurveyed. More accurate and detailed topographic coverage was obtained and sample control was extended out onto the flanks (Figure 2). A magnetic survey was run in conjunction with the sounding survey by the

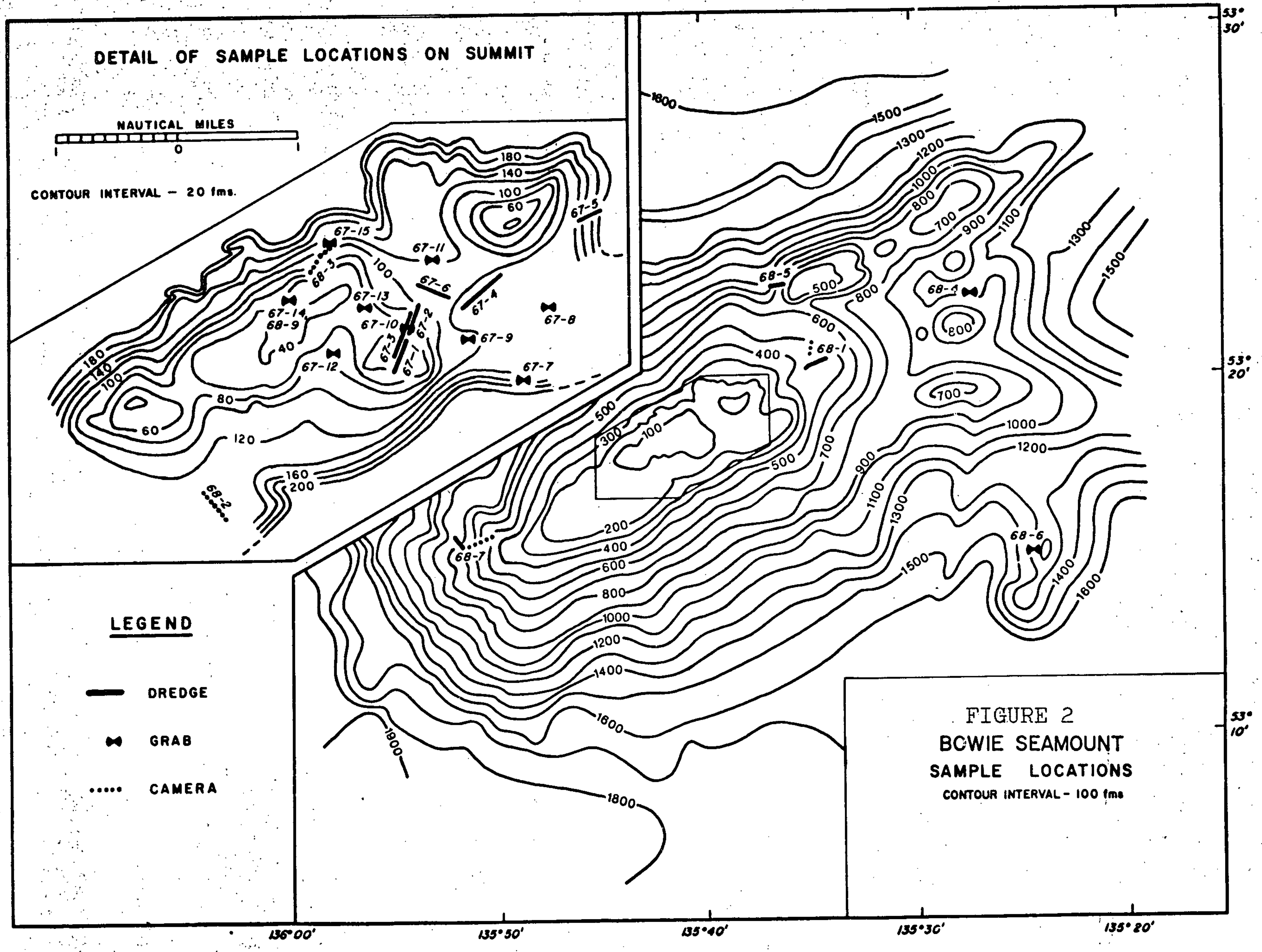


FIGURE 2
BOWIE SEAMOUNT
SAMPLE LOCATIONS
CONTOUR INTERVAL – 100 fms

Department of Geophysics at this University (Michkofsky, 1969). The magnetic survey required very close spacing of lines and consequently a total of 475 miles of simultaneous magnetic and sounding lines were obtained.

Employing the same basic navigation technique as that of the previous summer, that is, radar fixes on a single stationary target, the ship's track was planned in the form of an expanding rectangle superimposed on a series of sixteen radiating lines, the whole resembling a rectangular spider web (Figure 3). The radar target, anchored on the summit of the seamount, naturally formed the centre of the pattern.

Since the success of the entire venture depended on accurate and reliable navigation a more elaborate navigation system than that employed in 1967 was used. A radar transponder (Appendix A) was mounted on top of a 20 ft. long steel spar buoy, 8 ft of which projected above the water. The unit, triggered by the beam from the interrogating radar aboard the ship, replied automatically with a strong signal which produced a distinctive double blip on the ship's radar screen.

This navigation system, which proved to be highly reliable, furnished a range and bearing to the buoy at any time which were accurate to within 0.2 miles and 0.5 degrees respectively at distances up to 14 miles.

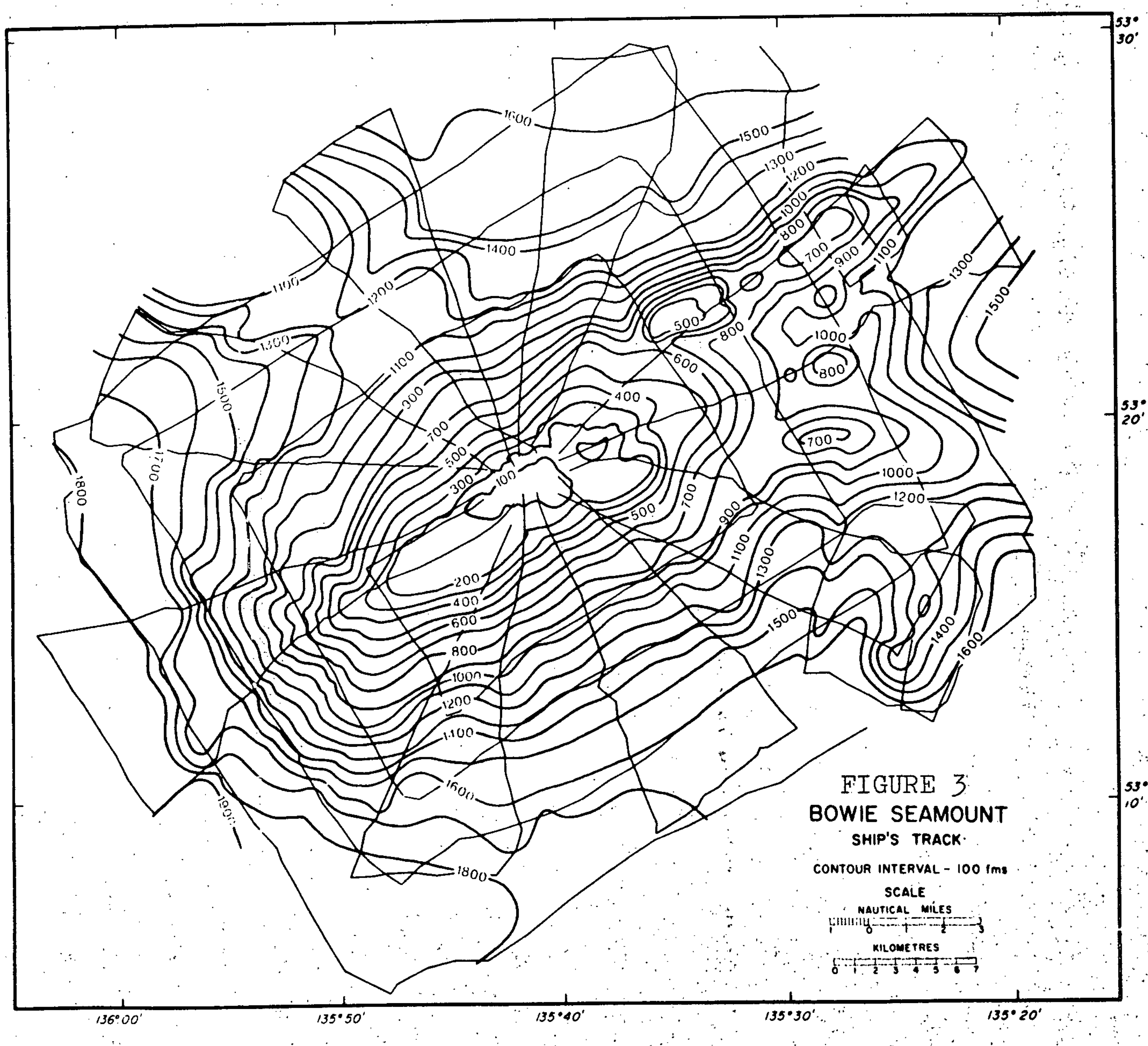


FIGURE 3
BOWIE SEAMOUNT
SHIP'S TRACK
CONTOUR INTERVAL - 100 fms
SCALE

Intermittent weak signals were picked up when the ship was once 16miles from the buoy. During the survey, fixes were taken every half mile or at even closer intervals, the position was plotted and corrections were made in the ship's heading to counteract the varying set. By this method, the ship was able to follow closely the planned ship's track, with the result that the entire survey area was uniformly covered with accurate continuous sounding profiles (Figure 3).

A detailed survey of the summit above the 200 fathom level was made at the end of the 1968 cruise (Figure 4), and in March of 1969, the summit was resurveyed by Defence Research Establishment Pacific using CSS PARIZEAU (Figure 5). The maps resulting from these two independent surveys agree to within 0.2 nautical miles (Scrimger, 1969), a figure which does not exceed the intrinsic error of the radar navigation system used on the survey. The U.B.C. survey employed a series of parallel tracks spaced a quarter of a mile apart with navigation fixes taken every quarter mile. To this was added data from the sounding lines which crossed the summit during the large scale survey of the seamount (Figure 6). The D.R.E.P. survey used similar parallel lines spaced onequarter of a mile apart with navigational fixes taken at the beginning and end of each

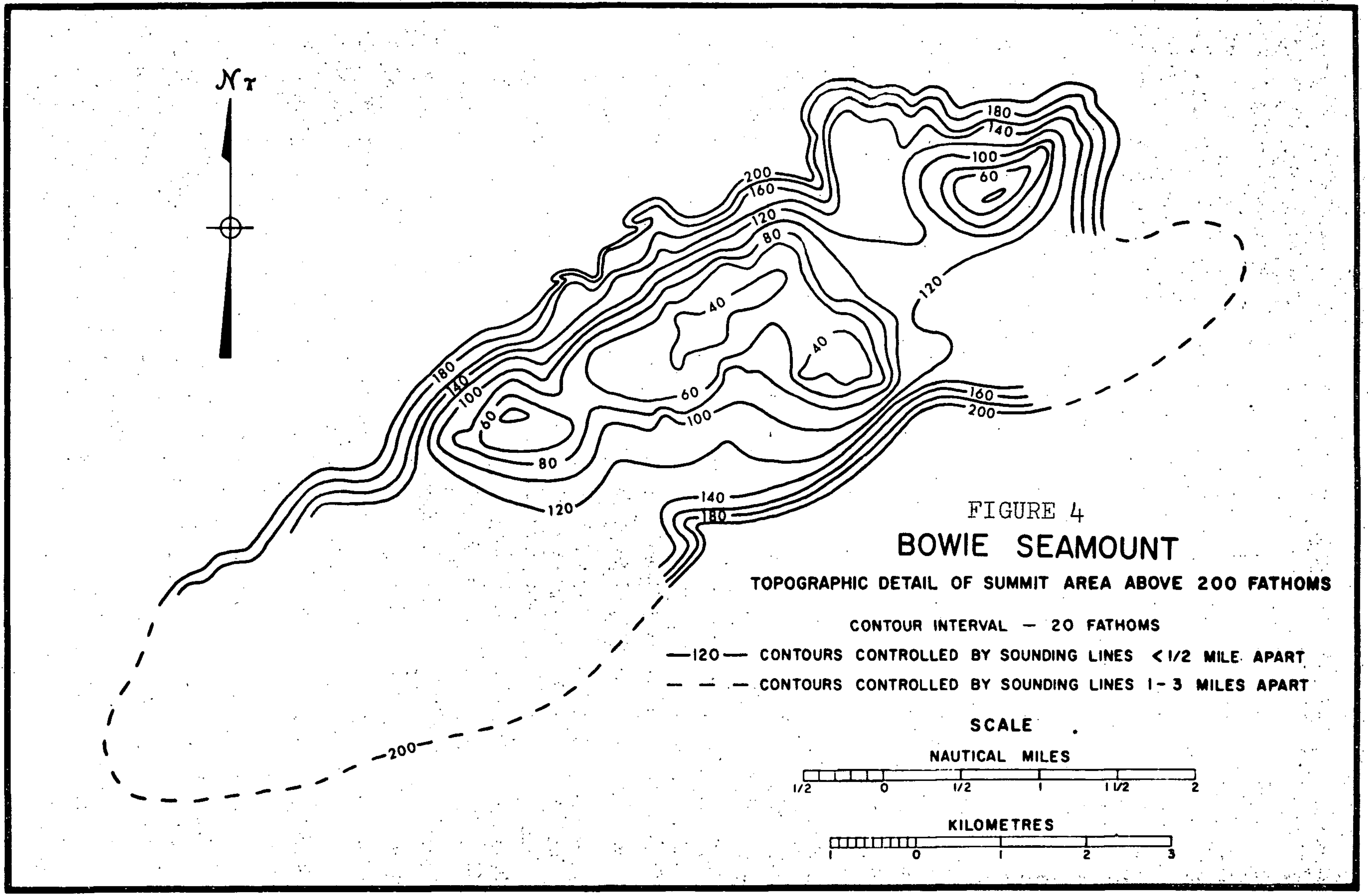


FIGURE 4

BOWIE SEAMOUNT

TOPOGRAPHIC DETAIL OF SUMMIT AREA ABOVE 200 FATHOMS

CONTOUR INTERVAL — 20 FATHOMS

—120— CONTOURS CONTROLLED BY SOUNDING LINES < 1/2 MILE APART

— — — CONTOURS CONTROLLED BY SOUNDING LINES 1 - 3 MILES APART

SCALE

NAUTICAL MILES

1/2 0 1/2 1 1 1/2 2

KILOMETRES

1 0 1 2 3

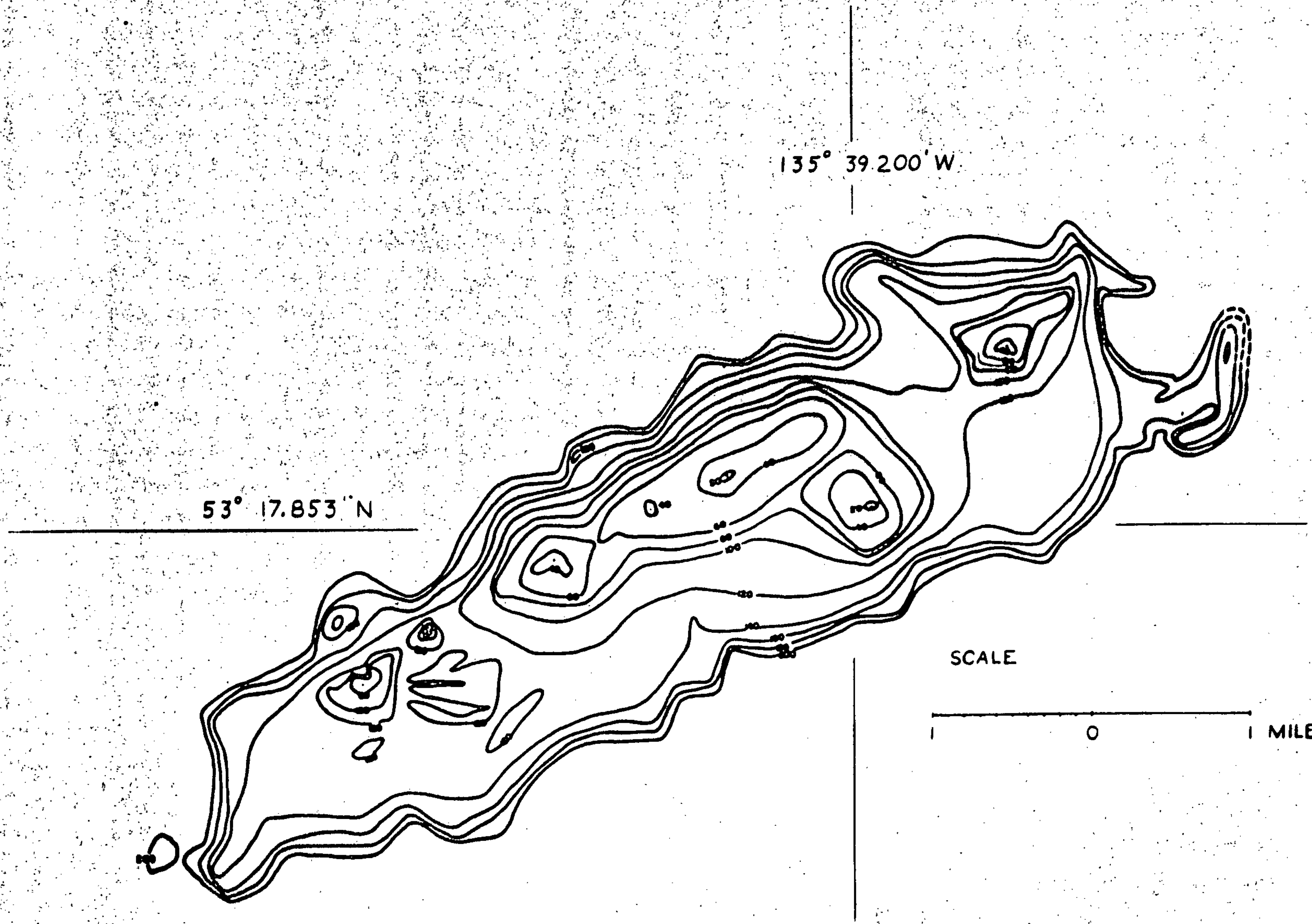
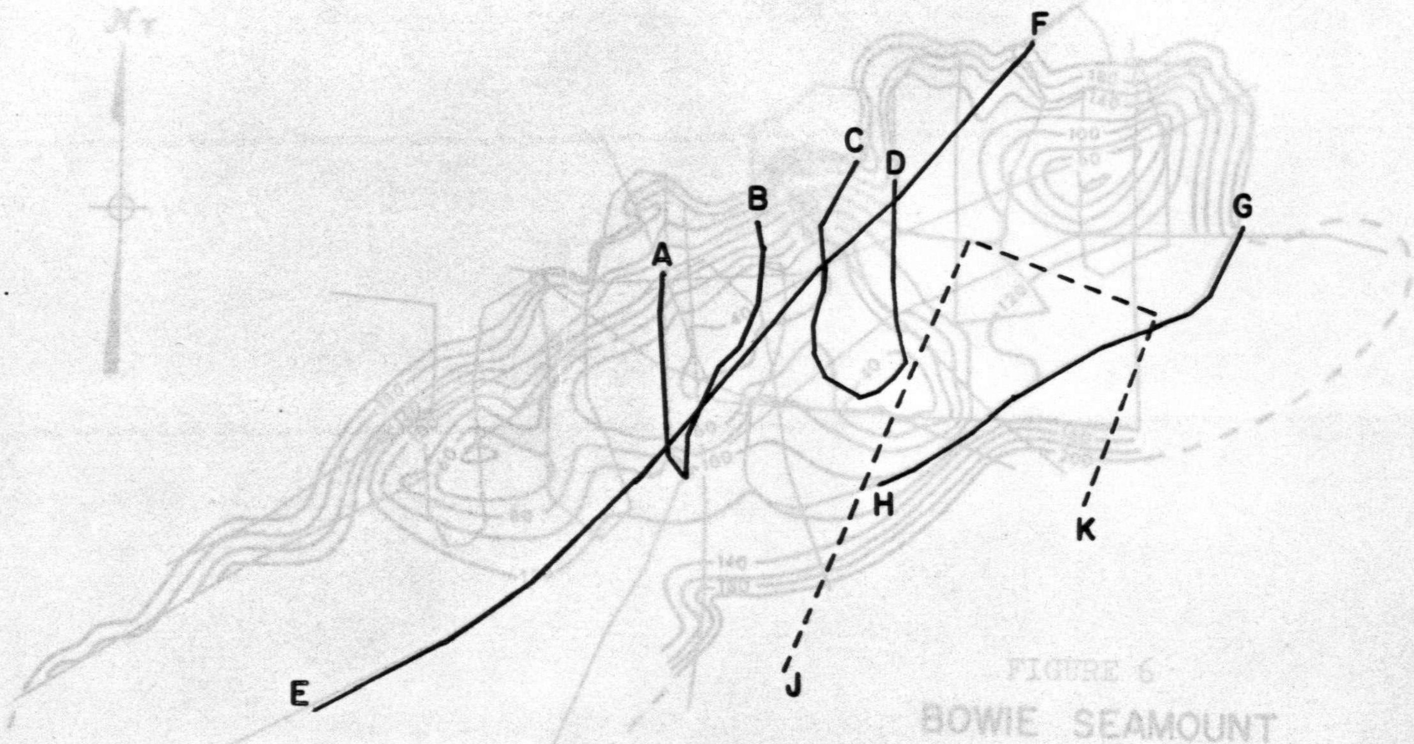


FIGURE 5 - Topographic map of the summit of Bowie Seamount (after Scrimger, 1969).



LOCATIONS OF PROFILES APPEARING IN PLATE 1.

—— Lines run in 1968.

- - - - Line run in 1967. (location approximate) line.

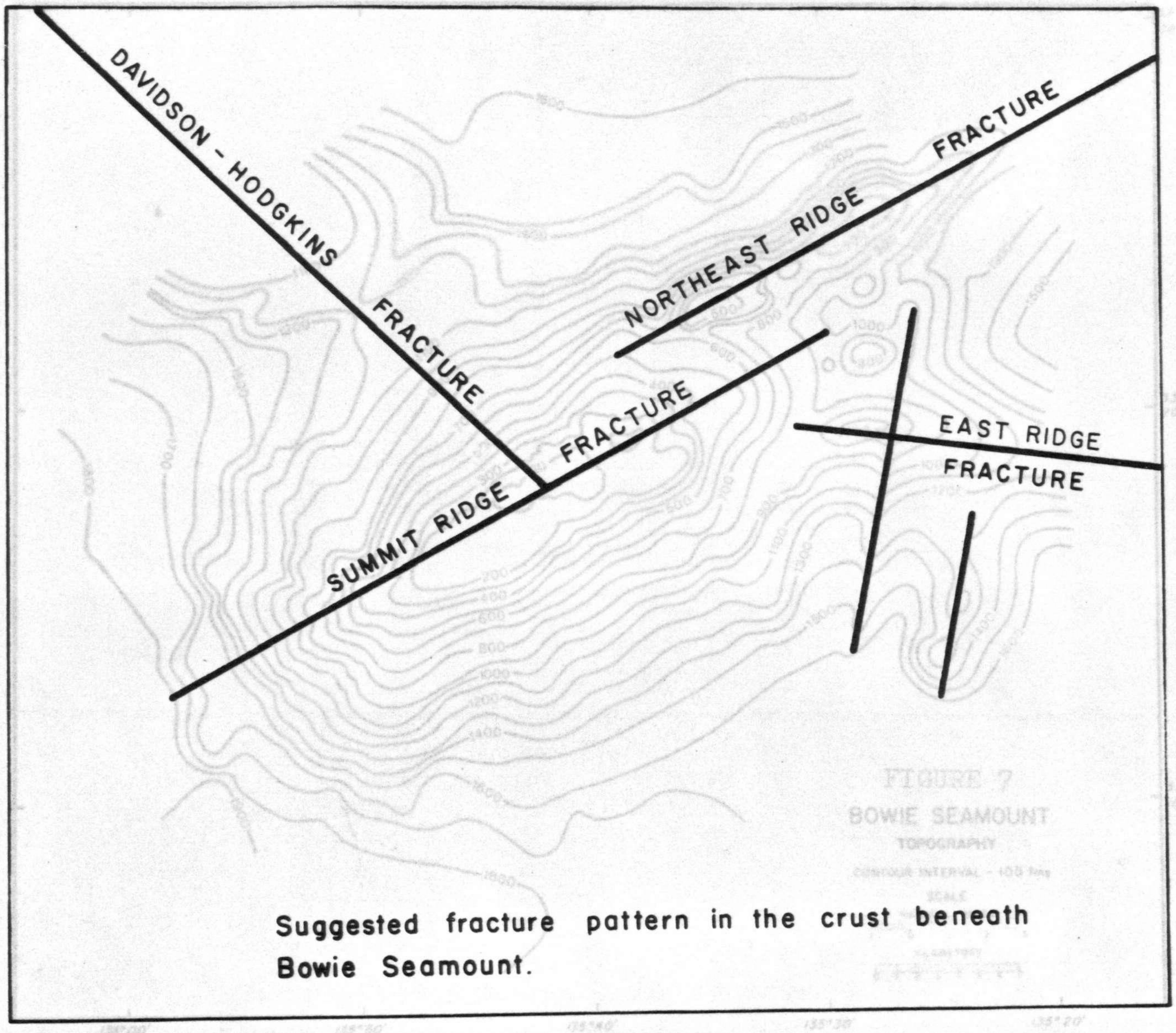
Dredging at four stations and underwater photography at four other stations were successfully undertaken during the 1968 cruise but attempts at sampling in deep water with grab, snapper, dredge and corer met with little success.

III. GEOMORPHOLOGY

A. Topography

Compilation of the sounding records revealed a close agreement in depths at sounding line intersections, usually to within 10 fathoms. Only at 7 out of a total of 67 intersections did depths disagree by 50 fathoms or more. The occasional discrepancy of this magnitude is to be expected in view of the potential sources of error. The maximum slope measured on the seamount is 30° but most slopes range between 10° and 20°. The water depths range from 15 to 1,800 fathoms. It is estimated that the steep slopes, the great depths, the navigation error of 0.2 miles, and the 30° spread of the sonar beam could easily combine to produce an error of 100 fathoms or more. All the major discrepancies did, in fact, occur in deep water or where steep slopes and rapidly changing bottom topography prevailed.

The map (Figure 7) was contoured by hand. Where the discrepancy in depths at a profile intersection was



Suggested fracture pattern in the crust beneath Bowie Seamount.

large enough to produce a significant shift in the contour lines, the line with the least reliable bathymetric record was discarded. During parts of the survey, malfunctions in the sonar equipment resulted in discontinuous records, hence the less reliable bathymetry referred to above. If a major discrepancy occurred where reliable lines crossed each other, the conflicting soundings were discarded and the contours were drawn to satisfy surrounding points which were in agreement.

Although the survey area did not extend far enough eastward to include all of Bowie Seamount, the resulting map shows that the seamount generally has the form of a northeast-striking mountain 13 miles wide on the average and at least 30 miles long (Figure 7) which rises abruptly from the gently sloping ocean floor (Figure 8). The regional survey by the U.S. Navy (Figure 1, inset) indicates that the northeast trend of Bowie Seamount meets the northwest trend of Hodgkins, Davidson and Denson Seamounts approximately at right angles on its northwest side, and that several other seamounts on this part of the Pratt-Welker chain are similarly elongate in these two directions.

The highest peak, which stands 10,000 ft. above the ocean floor, dominates the southwestern half of the seamount and is elongated in a northeast-southwest

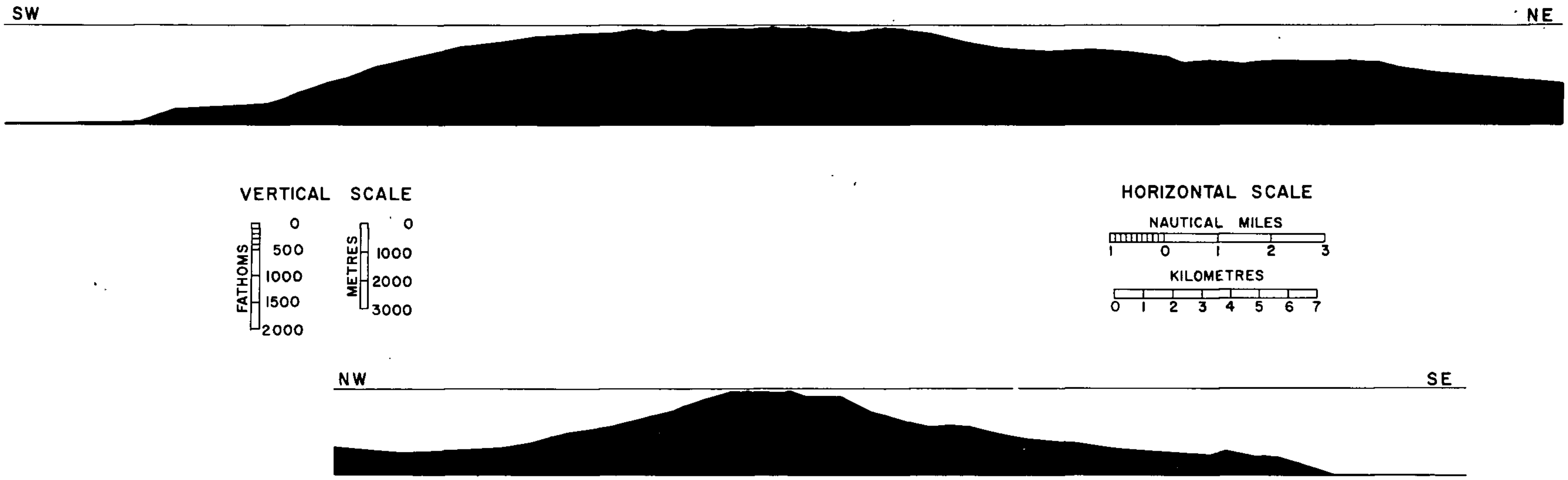


FIGURE 8

SILHOUETTES OF BOWIE SEAMOUNT

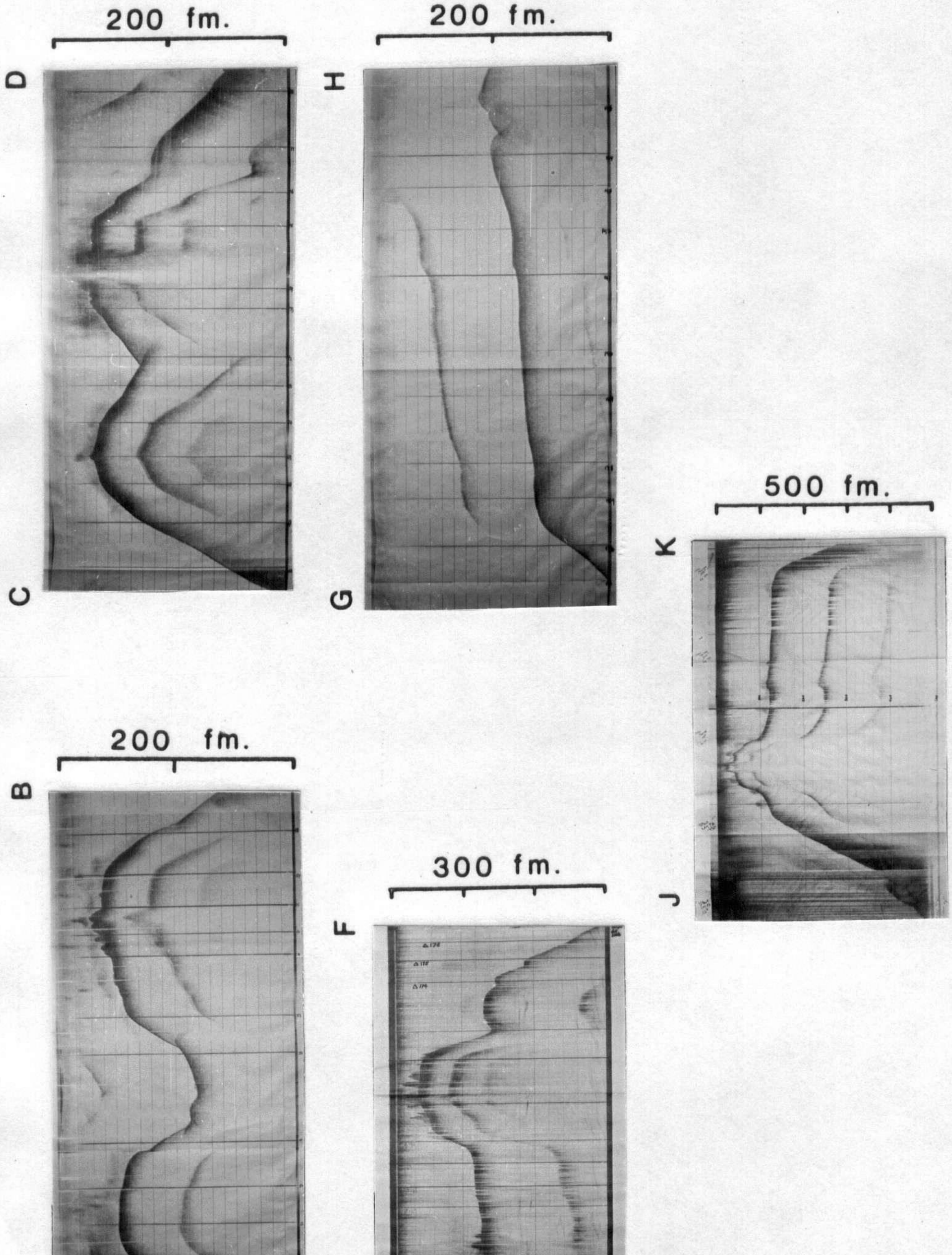
direction. To the northeast, a lower ridge continues along the same trend but at a slight northerly offset, and comprises most of the remaining half of the mountain. Together, these two features control the overall northeast-southwest elongation of Bowie Seamount. A similar ridge strikes eastward from the main mass or summit ridge, forming a major spur which, like the northeast ridge, extends beyond the eastern limit of the map area. To the south of this ridge, a small lobe projects beyond the foot of the mountain into the surrounding plain of the ocean floor. The eastern flank of the seamount is further complicated by a series of small peaks and valleys.

The flattened summit is seen in Figures 4 and 5 to be, in effect, a discontinuous terrace at a depth of 130 fathoms which is surmounted by a series of peaks, most of which are aligned along the northeast trend characteristic of the seamount itself. Figures 4 and 8, and Plate 1 reveal that these summit hills are, in turn, cut by a terrace between 35 and 55 fathoms.

B. Theoretical Development of Flat-Topped Seamounts

Traditionally, flat-topped seamounts have been thought of either as the truncated and subsided foundations of ancient volcanic islands, or as atolls that have

PLATE 1 - Sonar profiles of the summit of Bowie Seamount. Clearly visible are: the lower terrace between 120 and 140 fathoms (profiles E-F, G-H and J-K), the summit hills which rise above it (profiles E-F and J-K), the upper terrace between 35 and 55 fathoms which forms the flattened tops of the summit hills (profiles A-B, C-D, E-F and J-K), and the small, rugged pinnacles which project, in turn, above the latter terrace (profiles A-B, C-D and J-K). The location of the profiles is shown in Figure 6 (overlay).


200 fm.
D
C
200 fm.
H
G
500 fm.
K
J
200 fm.
B
A
300 fm.
F
E

submerged due to a too rapid relative rise of sea level.

Nayudu (1962) proposed that the larger seamounts become more or less flat-topped due to the growth of a large dome of magma within the volcano beneath a pyroclastic mantle (Figure 9). His argument is based on the following evidence: 1. Guyots have generally steep slopes, in the order of 18° to 25° which would indicate that they were composed of fragmental material rather than lava flows. He cites the occurrence of palagonite tuffs on the terraces of Bowie and Cobb Seamounts as supporting evidence. 2. Seismic refraction work on Bikini Atoll (Raitt, 1954) has shown the existence of a high velocity, probably basaltic core, capped by a lower velocity, possibly pyroclastic layer, upon which the reef limestone is built.

Jones (1966) and Kjartansson (1966) proposed that flat-topped seamounts are submarine analogues of the Pleistocene intraglacial volcanoes of Iceland and British Columbia (Figure 10). These flat-topped volcanoes are thought to have grown within lakes melted through an ice cap by volcanic heat (Kjartansson, 1943 and Mathews, 1947). The base of such a volcano is usually composed of pillow lavas, pillow breccias and hyaloclastites which formed by quiet effusion of

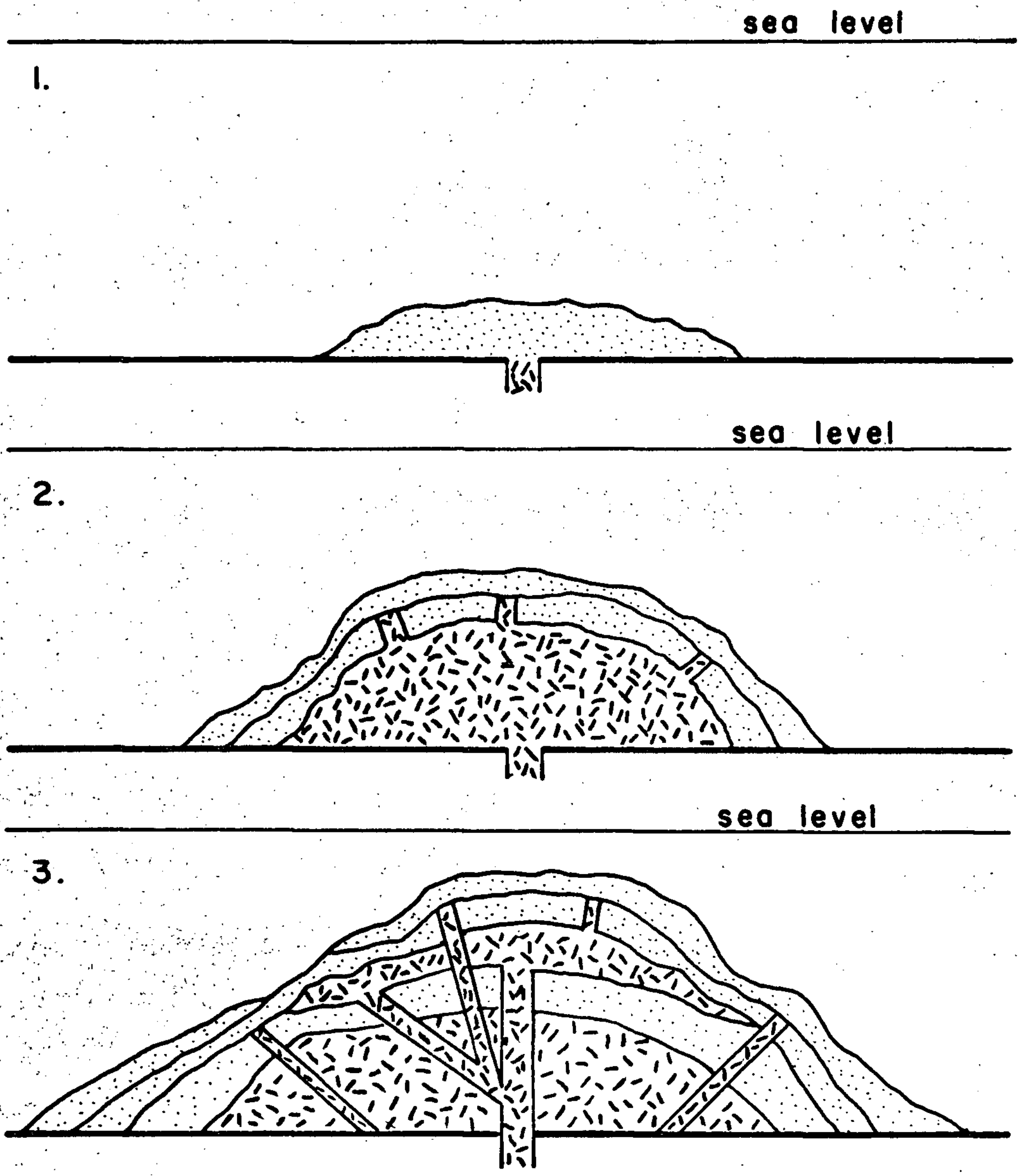


Figure 9 — Method of formation of flat-topped seamounts suggested by Nayudu (1962).

Stage I: Eruption on sea floor produces a mound of clastic debris derived from the aqueous brecciation of lava flows.
Stage 2: Growth of a dome beneath the clastic mound. The clastic mantle continues to grow, fed by lava reaching the surface.
Stage 3: Continued growth as in stage 2 with the development of more complex structure.

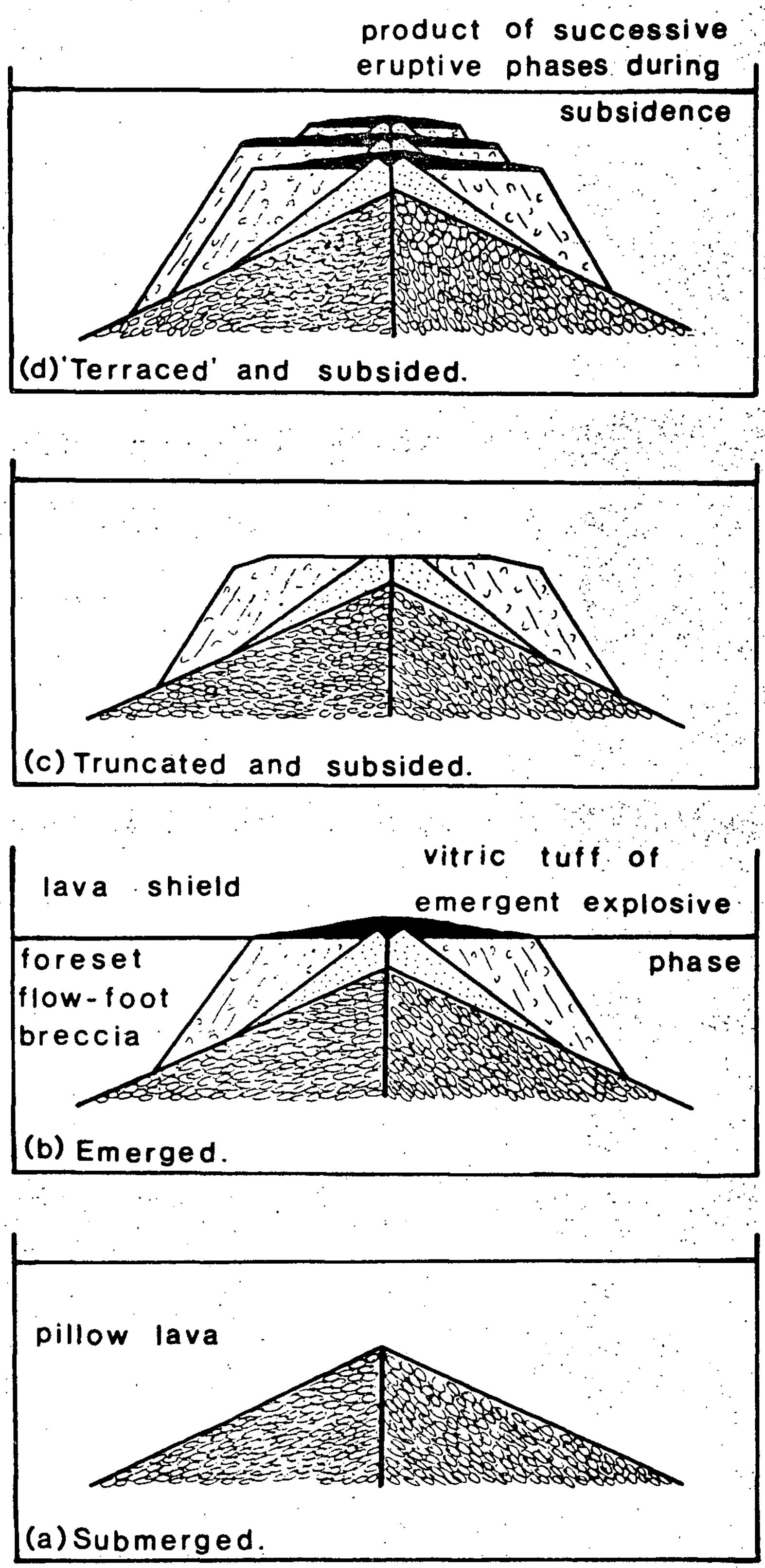


FIGURE 10 - Method of formation of flat-topped seamounts suggested by Jones (1966).

basaltic lava in deep water where perhaps the confining pressure was great enough to prevent phreatic and volcanic explosions (McBirney, 1963; Kjartansson, 1966; and Jones, 1967 in Moore and Fiske, 1967). The upper reaches of the volcano are dominated by clastic volcanic debris which commonly occurs in steep, outward-dipping beds, and above this, the flat mountain top is formed by a shield of subaerial basalt flows. The clastic material is apparently the product partly of phreatic explosions, which characteristically accompany basaltic eruptions in shallow water, and partly of brecciation of subaerial flows where they entered the waters of the lake (Fuller, 1931). If the lava shield is absent, it is presumed either that it was removed by prolonged wave erosion, exposing the clastic platform, or that it never existed and that the volcano succeeded only in building a broad, wave-washed platform of tephra. Kjartansson's (1966) work on Surtsey suggests that this young volcano may be a recent marine analogue of the Icelandic table-mountains. Moore and Fiske (1969) observed that the substructure of Kilauea Volcano, Hawaii, may similarly fit this model. Raitt's seismic data on Bikini Atoll apparently supports this model as well as it does Nayudu's.

C. Geomorphic Development of Bowie Seamount

Because rocks dredged from the seamount are almost exclusively basalt vitrophyres with a wide variety of volcanic textures and structures, the seamount is presumed to be of volcanic origin. In the author's opinion, submarine erosion on a scale large enough to affect the gross volcanic morphology of the seamount has not occurred.

Little is known of the volcanic substructure of Bowie Seamount but the prominent ridges that make up the volcano suggest that it grew from eruptions along a system of fissures (Figure 7, overlay). Extrusions along a main northeast-striking set of fissures probably formed the long summit and northeast ridges. Subordinate feeders probably underlie the spurs on the volcano's southeastern flank. A second major fracture is assumed to underlie Hodgkins and Davidson Seamounts, which extend northwestwards in a line from Bowie Seamount (Figures 1 and 7). The intersection of the northeast-trending fracture beneath Bowie with the northwest-trending fracture of the Hodgkins - Davidson system may have afforded the magma relatively easy access to the surface and thus have accounted for the huge volcanic pile of the summit ridge. Bowie Seamount, therefore, appears to be a combination central and fissure type volcano. The network of internal conduits in a volcano of this size and shape must be far from simple and many of the smaller peaks on the seamount's flanks may be parasite cones.

The natural 10° to 20° slopes of the summit ridge are truncated around 140 fathoms, from which depth a broad terrace slopes gently up to a depth of 120 fathoms (Figure 8 and Plate 1). Above this platform rise hills 300 to 700 ft. high which barely alter the flat-topped silhouette of the 10,000 ft. high volcano. The four highest of these summit hills are, in turn, terraced between 35 and 55 fathoms (Figure 4 and Plate 1). Small, rugged peaks project an additional 100 to 200 ft. above this upper terrace level, the tallest coming to within 100 ft. of the ocean surface (Scrimger, 1969).

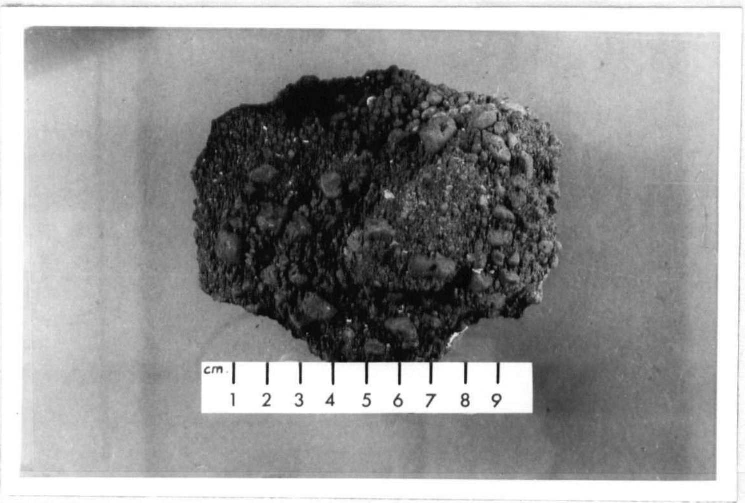
The surface material on the terraces and summit hills is made up mainly of tephra and broken flow-rock. The freshness of the volcanic ejecta and the nearness of the terraces to sea level suggest that the terraces were produced by combined wave erosion and shallow water vulcanism during late Quaternary sea level lows, and that the summit hills mark the centres of eruption. Additional evidence supporting wave erosion is seen in the distinctly abraded and winnowed nature of some of the lapilli deposits. Two such deposits were discovered: one on or just below the 45 fathom terrace (sample 67 - 2, Appendix B) and the other just off the 130 fathom terrace (sample 67 - 7, Appendix B). These are both composed of well rounded lapilli and contain abraded phenocrysts and shell fragments; such shell fragments being very conspicuous in sample 67 - 2 (Plate 2). Although the sorting of the grains cannot be said to be good in either deposit, it is much better in sample 67 - 7 than in any other lapilli deposit found on the seamount.

The present depth of the terraces suggests that they must have been formed at some time in the past when either the seamount stood higher above the geoid or sea level stood lower. An estimated maximum sea level lowering of 540 ft. is given by Shepard (1963). A low Pleistocene stand, therefore, could conceivably have accounted for the upper terrace, whose depth varies from 210 to 330 ft. but apparently not for the lower terrace, which has a depth of 720 to 840 ft. It is reasonable to suppose, however, that the seamount itself may have subsided since the formation of the lower terrace. Subsidence of oceanic volcanoes is commonplace and guyots are common on the Pratt - Welker chain.

PLATE 2 - Reworked Lapilli Deposits

(a) Weakly cemented volcanic conglomerate found in the vicinity of the 45 fathom terrace. The rock is composed of well-rounded lapilli, frosted phenocrysts, and abraded shell fragments (white in the photograph) (Station 67 - 2).

(b) Loose deposit of well-rounded lapilli and frosted phenocrysts, found near the edge of the 130 fathom terrace. The sorting of this deposit is better than that of any other on the seamount. The thumb-tack in the lower right hand corner provides the scale (Station 67 - 7)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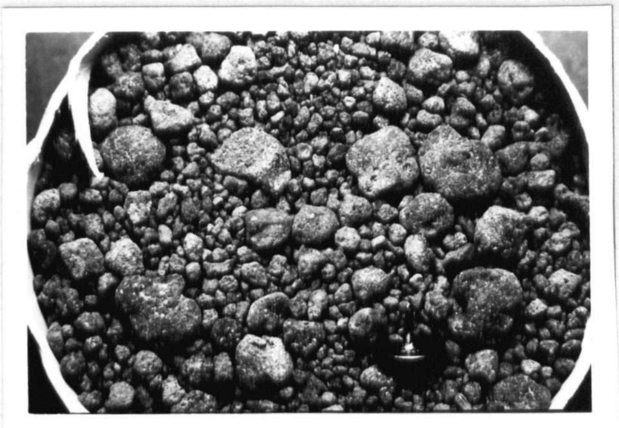


Ignoring subsidence, one can estimate a maximum age for the upper terrace from published Quaternary sea level curves (Figure 11) (Kenney, 1964, Curray, 1965, and Hopkins, 1967). The upper terrace is composed of unstable, loose or weakly cemented material and it seems certain that the terrace, which has a depth of 210 to 330 ft., would not survive if sea level were to drop for long to the level of its late Wisconsin low of 400 ft. This terrace then could not have been in existence prior to the low stand of 18,000 to 22,000 years B.P. and must, therefore, have formed during the Holocene transgression. According to the sea level curves, Holocene sea level was at the present upper terrace level between 13,000 and 18,000 years ago. If the volcano has, in fact, subsided since that time, the terrace must be even younger. The proposed maximum age of the upper terrace is, therefore, 18,000 years.

No satisfactory age could be established for the lower terrace but there is a high probability that it too was formed during the Pleistocene. Ice-rafted material is virtually absent on both terraces, but occurs in abundance on the north flank and on the summit of nearby Hodgkins Seamount (Appendix B). The summit of Bowie Seamount may, therefore, have stood high enough

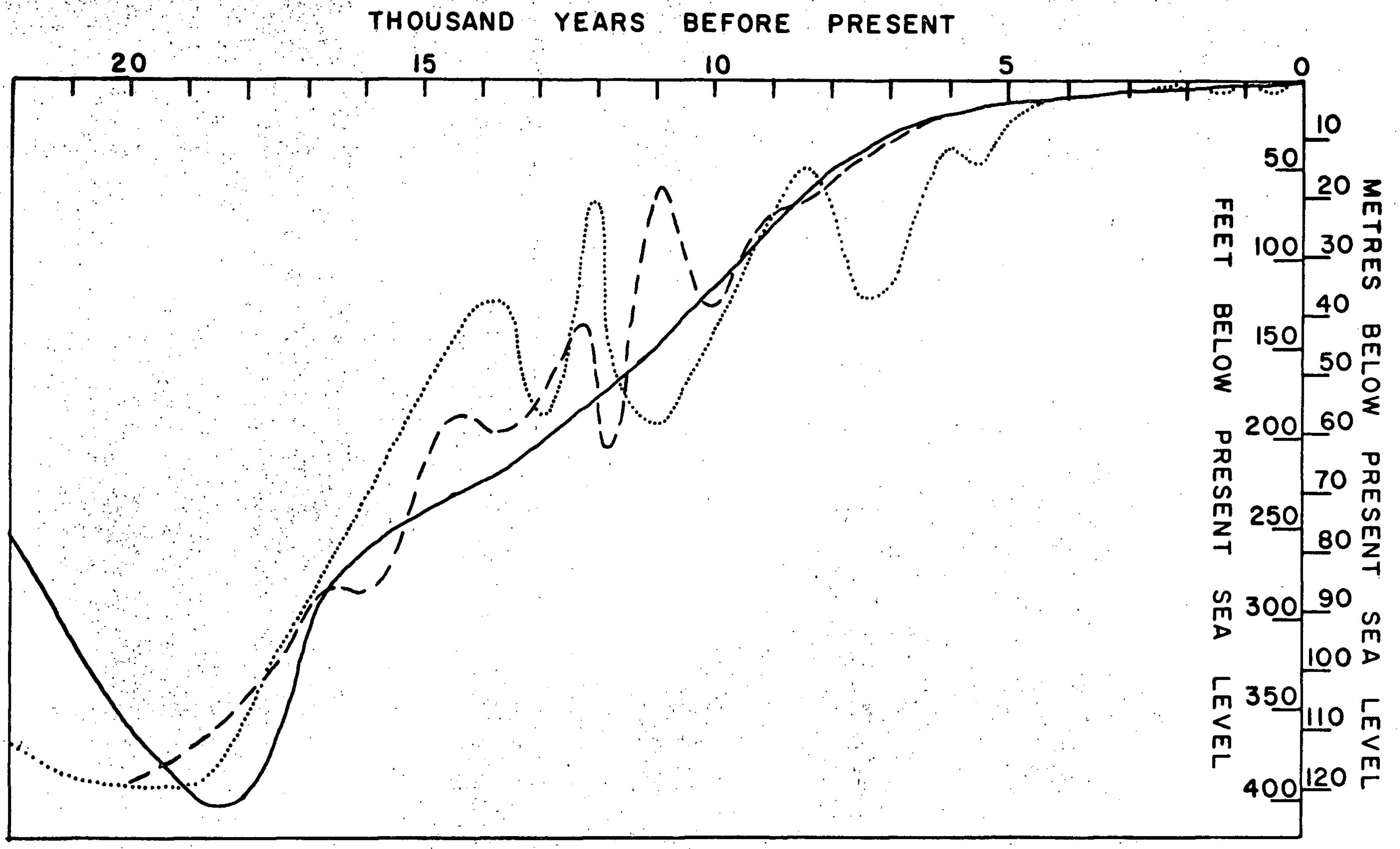


FIGURE 11 – Sea level changes during the last ice retreat.

Dotted line: Bering Sea area (Hopkins, 1967).

Dashed line: Eastern North America and Northern Europe (Kenney, 1964).

Solid line: Mean of compiled estimates of sea level fluctuations (Curray, 1965).

during low Pleistocene stands to prevent the passage of debris-laden icebergs which, during such periods, must have calved in great numbers from glaciers reaching the sea. If the lower terrace were a pre-Pleistocene feature, it would nevertheless have had ample opportunity to accumulate a considerable quantity of ice-rafted debris. Furthermore the tephra deposits and tuffs of both terraces contain only recent and Pleistocene micro-faunas (Cameron, 1969 personal communication). Post-terrace vulcanism might have obscured a pre-Pleistocene fauna, if such existed on the lower terrace, and might also have buried any accumulated glacial material. However, it would also tend to obscure the terrace itself. Vulcanism has, in fact, continued until so recently on the summit that the survival of a pre-Pleistocene terrace would seem highly unlikely. In view of the excellent preservation of the 130 fathom terrace, it is probable that this feature was also formed during late Pleistocene time.

Wave erosion during periods of low Pleistocene sea levels was evidently instrumental in the formation of these terraces. However, evidence of post-glacial volcanic activity indicates that the summit morphology is not due to wave erosion alone.

The summit peaks are striking in their alignment parallel to the long axis of the seamount (Figure 5), an alignment which was probably controlled by the structure of the volcano. If these are erosional remnants of a once greater peak that has been deeply dissected, they would have to be made of relatively more resistant rock to preserve their structural alignment, in which case, they might be a line of volcanic plugs or dykes. Work on part of the central L-shaped system of peaks (Figure 2) has indicated that the bulk of the surface cover is composed of loose or weakly cemented tephra and lesser amounts of fragmental flow rock. The shallowest pinnacle was found by dredging and diving to be composed of strongly cemented ferruginous tuffs. Some peaks, then, are not simply volcanic plugs.

The incoherence of the material making up the central summit peaks precludes the possibility of their survival for long as an island during the low sea level stand which formed the lower terrace. Richards (1965) reported that a tephra sea cliff with an average height of 200 ft., formed by the 1952 eruption of Barcena on Isla San Benedicto, west of Mexico, was cut back by wave erosion at an average rate of 5.5 ft. per day. An associated aa lava flow was similarly eroded at an average daily rate of 0.4 ft. per day. At such rates, the summit peaks, if they were islands, would have been destroyed within a year! It is probable, therefore, that the summit hills were formed by volcanic eruptions after the formation and submergence of a summit plateau, which now exists in relic form as the 130 fathom terrace. By the same token, the 45 fathom terrace level may be a later planation surface capped by late tuff cones. The tephra on the summit of the seamount are, for the most part, extremely fresh (Chapter IV), as would be expected from such recent vulcanism. The evidence on the summit implies, therefore, that eruptive activity continued after the formation and submergence of the upper terrace less than 18,000 years ago. This confirms the conclusion reached by Hurley and Nayudu (1961) that post-glacial vulcanism formed the summit peaks on the 130 fathom terrace.

This apparent close association in time between the latest episodes of vulcanism and the formation of the summit terraces at sea level suggests that Bowie Seamount is not simply the truncated foundation of an old volcanic island that was finally washed away after a long period of wave erosion. Instead, it appears more likely that the volcano reached sea level during the last stages of its activity and struggled for a while to build itself up above the sea surface. Any volcanic islands which may have thus been formed were probably repeatedly planed off by wave action over the course of months or perhaps years, giving rise, in the end, to flat platforms composed of pyroclastic and erosional debris, which now remain as terraces. If ephemeral islands did, in fact, exist the brecciation of subaerial lava flows entering the sea (Fuller, 1931) may also have contributed substantially to the growth of these platforms by building out forset beds of flow-foot breccias. The behaviour of Bowie Seamount during late Pleistocene and Holocene time may, therefore, have been similar to that of modern submarine volcanoes such as Capelinhos (Zbyszewski, 1960) and Surtsey (Thorarinsson, 1964 and 1965) which have been observed erupting at sea level. The post-Pleistocene rise in sea level, the subsidence of the volcano and the tapering off of volcanic activity apparently brought an end to its brief subaerial history and it has probably remained inactive ever since.

The origin of the terraces appears to fit the model suggested by Jones (1966) and Kjartansson (1966) rather than that proposed by Nayudu (1962). The terraces are known to be presently covered largely by clastic debris and the summit peaks are apparently composed of tuffs but whether a lava shield ever existed on the summit of the seamount is not known. Pillow lavas and pillow breccias are apparently more common on the slopes of the seamount than on the summit (Chapter IV). A modified version of Jones's diagram depicting the suggested present structure of the summit of Bowie Seamount appears in Figure 12.

Late flank eruptions appear to have occurred, possibly at the time of the final summit eruptions, for deposits of broken pillows of very fresh, black, glassy basalt, virtually free of organic growth or alteration, are found 800 fathoms down the west flank near a small cone on the same linear trend as the summit peaks (station 68 - 7) (Plates 3 and 4, and Figure 2).

A boulder of vesicular basalt, fished from the upper terrace at station 68 - 9 was dated by the whole-rock potassium - argon method and found to be 75,000 $\pm$ 100,000 years old. The use of the potassium - argon method for dating young, glassy, submarine lavas has come under fire recently. Potassium makes up less than 2% of most basalts and K^{40}, the radioactive isotope, constitutes about 1/8400 of the total potassium. The half life of K^{40} is 1,310 million years and therefore the amount of radiogenic argon in a basalt less than

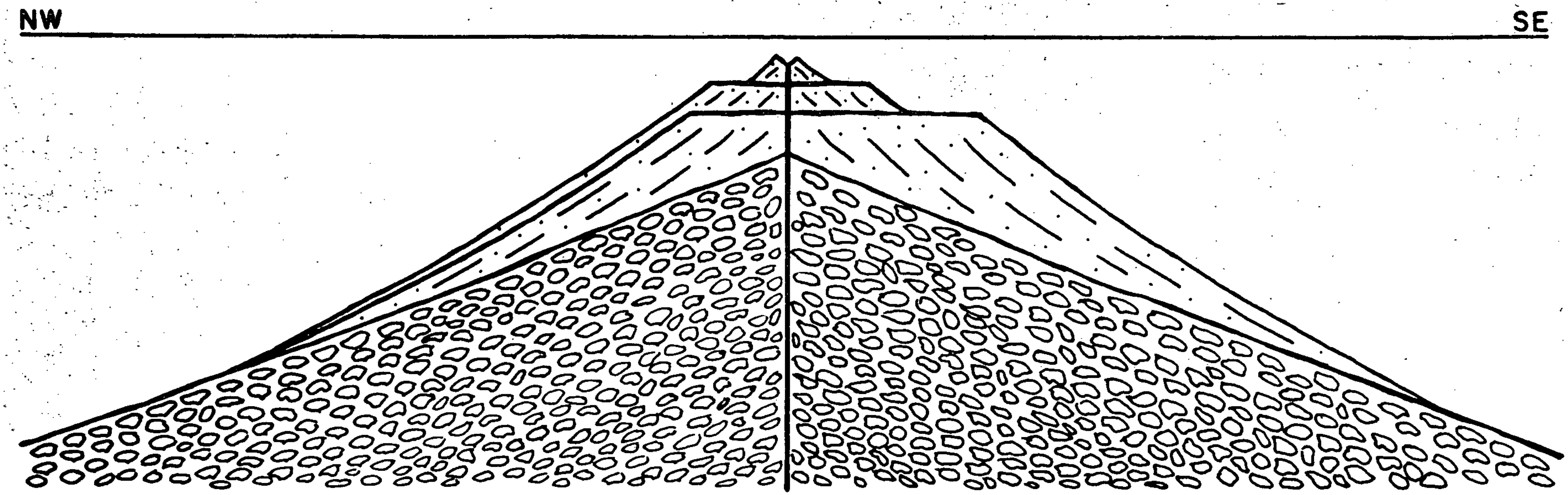


FIGURE 12 — Suggested structure of Bowie Seamount according to the Jones hypothesis. The diagram represents a hypothetical northwest-southeast cross-section through the main body of the seamount.

 Tuff, ash, and possible flow-foot breccia.

 Pillow lava, pillow breccia and hyaloclastites.

PLATE 3 - Pillow fragments on the west flank of Bowie Seamount at Station 68 - 7. The diameter of the compass is 3 inches and the length of the vane is 10 inches.

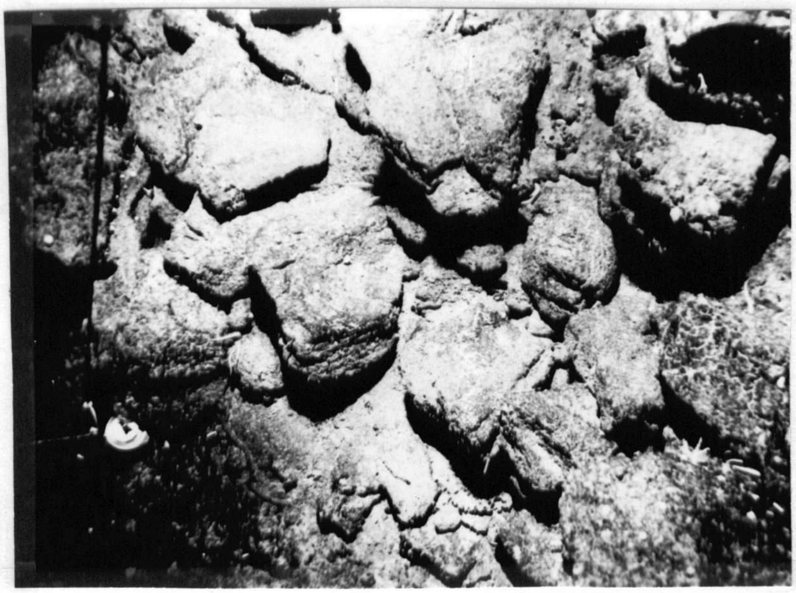
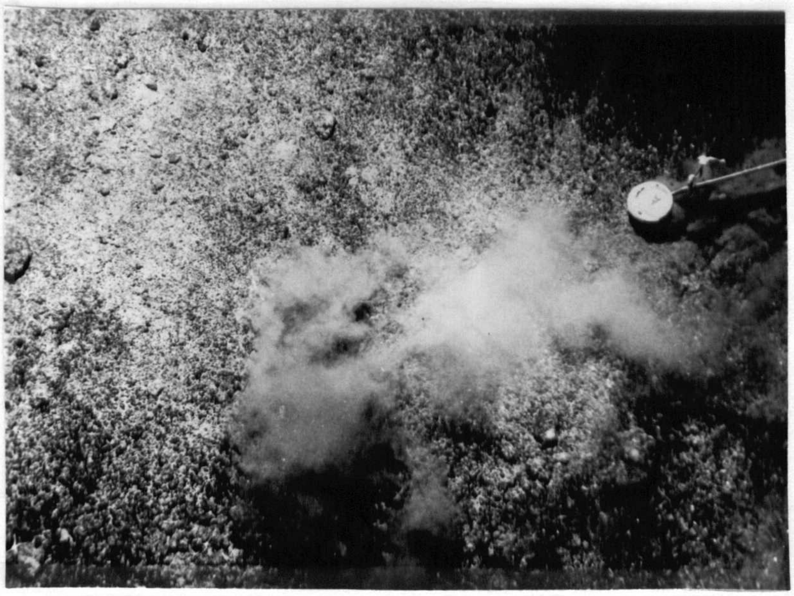


PLATE 4 - Loose deposit of small pillow crust fragments and larger pillow fragments on the west flank (Station 68 - 7). In the lower photograph, the thin cover of fine volcanic and pelagic sediment has been disturbed by the camera frame and the compass. The diameter of the compass is 3 inches and the length of the vane is 10 inches.



1 million years old is exceedingly small. Furthermore volcanic glass will lose argon with the passage of time, resulting in a younger than actual date (Hills and Baadsgaard, 1967). Fluid inclusions, common in phenocrysts, may contain argon, which will give an anomalously old age (as much as +880 M.Y.) (Funkhauser et al, 1966). Glass produced by rapid quenching of submarine lavas may contain trapped argon - 40 which did not have a chance to escape by vesiculation, or, if the hydrostatic pressure is great enough, argon will be similarly retained due to lack of vesiculation, both situations yielding older than actual ages (Dalrymple and Moore, 1968). To avoid as much error as possible, a vesicular rock, free of chilled surface phenomena and fluid inclusions, which was found in shallow water (60 fathoms) was selected for the age dating.

Since Bowie Seamount was apparently still active towards the end of the Pleistocene it is of great interest to know when it first appeared on the sea floor. On the basis of magnetic data, Michkofsky (1969) believes that the main body of the seamount was formed during a period of geomagnetic reversal, putting its age back at least 0.69 million years (Cox, 1969). Its age beyond this can only be guessed at.

IV. PETROLOGY

A. Lava Flows

1. Types and distribution of flow rock

Rocks which appear to have originated by quiet flow were recovered from nine stations scattered over the seamount (Appendix B). On the basis of their physical appearance, these rocks fall into three categories: pillow fragments, tops of non-pillowed lava flows, and highly jointed non-vesicular rock. Most of these rocks occurred as surface rubble in the areas sampled. In only one case (station 67 - 4) were samples taken from what appeared to be a coherent lava flow.

(i) Pillow Fragments

About half of the samples of flow rock are fragments of pillows. Most of these have the characteristic pyramidal shape (Plate 5a) and a quenched outer surface marked by a transition from a microlite-rich, tachylyte vitrophyre in the interior to a clear sideromelane vitrophyre at the surface (Plate 6). Palagonite rims are uncommon, but may be locally well developed (Plate 32).

Sideromelane is thought to form at the surface of a subaqueous flow where basaltic lava is chilled so quickly that iron is retained in solution, imparting an amber colour to the translucent glass, whereas tachylyte forms

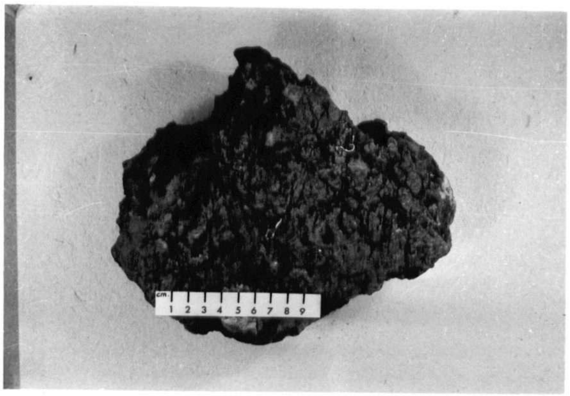
PLATE 5 - Types of flow-rock found on Bowie Seamount

(a) Pillow fragments. The locations of the samples are, from left to right: Station 68 - 7, Station 68 - 1, and Station 67 - 2. Intact pillows were found at Station 68 - 1.

(b) Fragment from the surface of a flat, non-pillowed lava flow. (Station 68 - 1)

(c) Block lava or talus material eroded from an outcropping dyke or dissected flow. (Station 67 - 7)


1 2 3 4 5 6 7 8 9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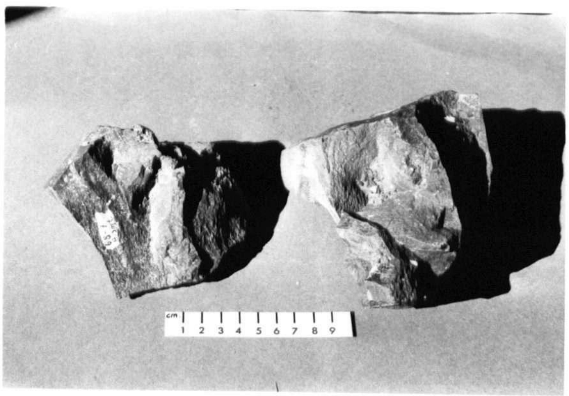
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PLATE 6 - The textural change from tachylyte to sideromelane in the chilled surface of a vesicular basaltic lava. The surface of the rock is out of view, just beyond the top of the photograph. (Plane light) (Thin section 68 - 7 - B). (x27)

just below the surface where the lava cools less rapidly, allowing the precipitation of fine magnetite which renders the glass black and opaque (Peacock, 1928)

It is difficult to tell whether these pillow fragments represent the products of pillows which have broken up immediately after formation, or of pillows which have disintegrated during post-volcanic erosion. Pillow fragments formed 100% of the loose cover at Station 68 - 7 on the steeply sloping west flank of the seamount (Plates 3 and 4) and were also found in abundance at Station 68 - 1 on the east flank (Plates 25 and 26).

(ii) Tops of non-pillowed flows

Fragments of lava flows without pillow structure were retrieved at several locations (Appendix B). The tops of these flows exhibit the tachylyte-to-sideromelane chill texture described above and may have a thin skin of palagonite. Bread crust fracturing is common on the upper surface (Plate 5b).

(iii) Angular, non-vesicular rock

Whether this type of rock represents a flow of "Block Lava", as described by Washington (1926) and Finch (1933), or talus material from an exposed dyke or plug cannot be ascertained. The only two specimens are highly but irregularly jointed, angular, non-vesicular blocks (Plate 5c), the only massive volcanic rock obtained from the seamount.

2. Petrography of the Lavas

Basalt

The rocks of Bowie Seamount are mainly basaltic, although andesitic varieties do occur rarely. The basalts are of the alkali olivine type (Yoder and Tilley, 1962) (Tables 1 and 2) and are apparently similar in composition to other oceanic basalts from similar environments (cf. Engel and Engel, 1963, 1964, 1966 and Engel et al., 1965). Their occurrence on a high volcanic structure is compatible with the hypothesis of Engel and Engel (1964), which limits such rocks to the larger oceanic volcanoes. Their results, and the results of previous workers, suggest that alkali olivine basalts represent late phases of vulcanism which crown volcanoes formed primarily of tholeiitic basalt. The basalts listed in the tables were dredged from the summit ridge of Bowie Seamount in depths shallower than 500 fathoms. It is possible that the rocks on the lower reaches of the seamount are tholeiitic.

The alkali olivine basalt, which is the most wide-spread rock type, is a dark grey, vesicular, porphyritic

Oxide	67 - 7	67 - 6 - 12	68 - 1 - 8	68 - 9	PV 50
SiO_2	53.5	45.4	48;0	45.2	45.33
TiO_2	1.07	2.60	2.43	3.10	3.53
Al_2O_3	19.8	18.5	18.5	16.4	15.50
Fe_2O_3	1.7	1.0	1.5	0.6	1.81
FeO	6.7	9.7	7.5	10.3	10.64
MnO	0.25	0.19	0.15	0.18	0.23
MgO	1.4	5.9	5.0	6.9	6.77
CaO	3.6	8.5	8.5	8.1	8.50
Na_2O	5.1	3.8	4.0	3.8	4.30
K_2O	3.1	1.9	1.6	2.4	2.36
H_2O	1.1	0.3	0.6	0.6	0.21
P_2O_5	0.43	0.70	0.07	0.71	0.73
CO_2	<0.1	<0.1	<0.1	<0.1	

TABLE I - Chemical compositions of rock samples from Bowie Seamount
The first two parts of a sample number indicate the station at which the sample was found (Figure 2). Sample 67 - 7 is an andesite. The others are alkali olivine basalts. 67 - 6 - 12 is a xenocryst-rich basalt, from which the xenocrysts were removed prior to analysis. PV 50 is a basalt from Bowie Seamount, analyzed by Engel and Engel (1963). The other analyses were made by the Laboratories of the Geological Survey of Canada, Ottawa.

Mineral	67 - 7	67 - 6 - 12	68 - 1 - 8	68 - 9	PV 50
Albite	44.01	18.86	25.15	15.20	13.62
Anorthite	13.62	28.08	28.36	21.13	16.12
Orthoclase	18.90	11.12	9.45	14.46	13.90
Nepheline	-	7.38	5.11	9.37	12.21
Diopside	-	8.26	12.12	12.30	17.53
Hypersthene	11.15	-	-	-	-
Olivine	2.87	17.59	12.70	18.16	15.41
Magnetite	2.55	1.62	2.09	0.93	2.55
Ilmenite	2.13	5.02	2.89	6.04	6.69
Apatite	1.01	1.68	-	1.68	1.68
Corundum	3.16	-	-	-	

TABLE 2 - Normative compositions of rock samples from Bowie Seamount. The first two parts of a sample number indicate the station at which the sample was found (Figure 2). Sample 67 - 7 is an andesite. The others are alkali olivine basalts. 67 - 6 - 12 is a xenocryst-rich basalt from which the xenocrysts were removed prior to analysis. PV 50 is a basalt from Bowie Seamount analyzed by Engle and Engel (1963).

Component	67 - 7	67 - 6 - 12	68 - 1 - 8	68 - 9	PV 50
Plagioclase	19	20	8	10	10.0
Pyroxene	1	3	1	3	3.0
Olivine	1	2	1	4	4.1
Opaque	1	<1	<1	3	2.1
Groundmass (glass)	78	47	42	52	52.6
Vesicles	-	28	48	28	28.0

TABLE 3 - Modal compositions of rock samples from Bowie Seamount PV 50 is reproduced from published results of Engel and Engel (1963). The others are visual estimates made by the author.

rock with conspicuous phenocrysts of olivine and plagioclase. Black clinopyroxene phenocrysts are also present but are not conspicuous because of their dark colour. The phenocrysts are generally no larger than 5mm. in diameter.

In thin section, these basalts exhibit some mineralogical variations and a great range of textural types, probably reflecting many different environments. All have a matrix of either pure glass or microlites with interstitial glass. The minerals are olivine, labradorite (An 62 - 70), clinopyroxene, and magnetite. These may occur individually as phenocrysts, together as glomerophenocrysts, or swarming in the matrix as microlites and crystallites. In general, the micro-phenocrysts were in apparent equilibrium with the magma and are well formed and unzoned but the larger phenocrysts (visible in hand specimen) show stages in their history when there was a growth hiatus or partial resorption by the magma (Plate 7).

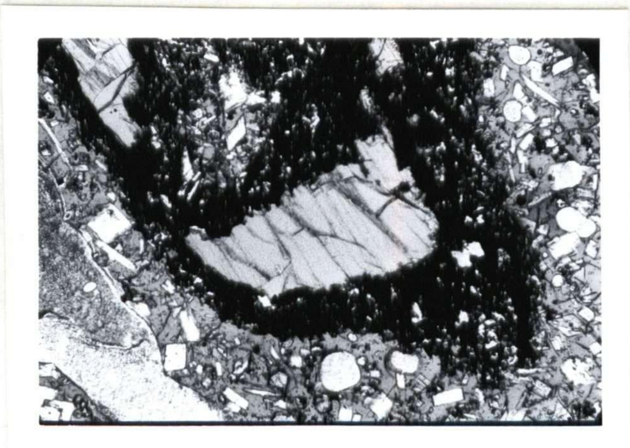
A unique alkali olivine basalt of apparently restricted areal extent dominates the eastern half of the survey area on the summit. This rock is distinguished by an abundance of large xenocrysts of plagioclase (An 54 - 64) and hornblende, 1 to 2 cm. across, and

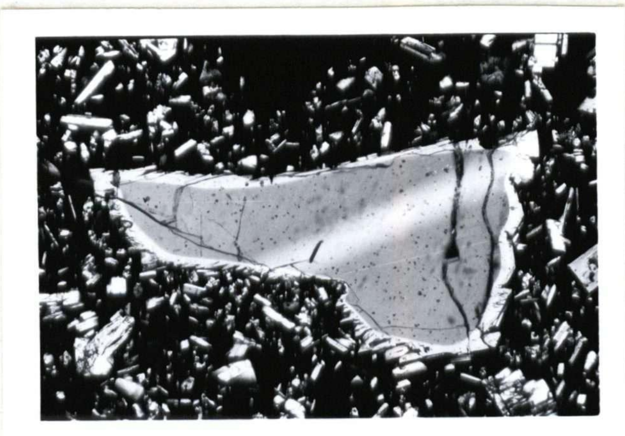
PLATE 7 - Some microscopic textures of the alkali olivine basalts.

(a) Zoned, altered phenocrysts and euhedral, unaltered microphenocrysts in a matrix of isotropic glass. (Crossed nicols). (Thin section 67 - 5 - C). (x27)

(b) Xenocryst of basaltic hornblende with a reaction rim of magnetite and orthopyroxene. (Plane light). (Thin section 67 - 4). (x27)

(c) Rounded xenocryst of plagioclase, rimmed by a fresh outer zone of more calcic composition. (Crossed nicols). (Thin section 67 - 4). (x27)





coarse-grained, wholly or partly crystalline inclusions, 2 to 5 cm. in diameter. Phenocrysts of olivine, clinopyroxene, and plagioclase (An 62 - 66), under 5mm. in diameter, are more common in the rock but are not conspicuous. The host rock, in which the xenocrysts and inclusions are found, is an alkali olivine basalt similar to the others on the seamount (Table 1, 67 - 6 - 12). In it, the great hornblende xenocrysts, many of which are fragmented, have reacted strongly, producing thick rims of magnetite and orthopyroxene, and the large plagioclase xenocrysts bear evidence of similar instability in the magma (Plate 7b and c). The inclusions, most of which are feldspathic or gabbroic with a large amount of hornblende, were similarly in disequilibrium with the magma at the time of eruption. The occurrence of abundant inclusions in an alkali olivine basalt is normal, but the great predominance of feldspathic and gabbroic types over ultramafic types is unusual. These inclusions will be discussed in a later section.

Andesites

Andesitic rocks were found at only two locations on Bowie Seamount: Stations 67 - 7 and 68 - 5.

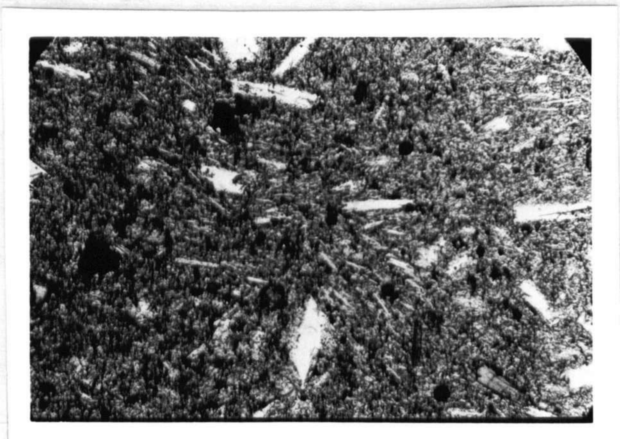
Sample 67 - 7 is distinguished in hand specimen by its total lack of vesicles and high degree of jointing. On a fresh, broken surface, fine needles of plagioclase are conspicuous in a grey groundmass. In thin section, it is seen to be made up dominantly of more or less flow-oriented plagioclase laths (An 45 - 50) with relatively few crystals of olivine, pyroxene, magnetite, and apatite (Plate 8a). None of the minerals shows any indication of instability in the magma. The groundmass is glassy but contains such an abundance of microlites that it is almost masked. The composition of this rock is seen in Tables 1 and 2 to lie between mugearite (cf. Muir and Tilley, 1961) and trachyte. The normative plagioclase was calculated to be An 22.6.

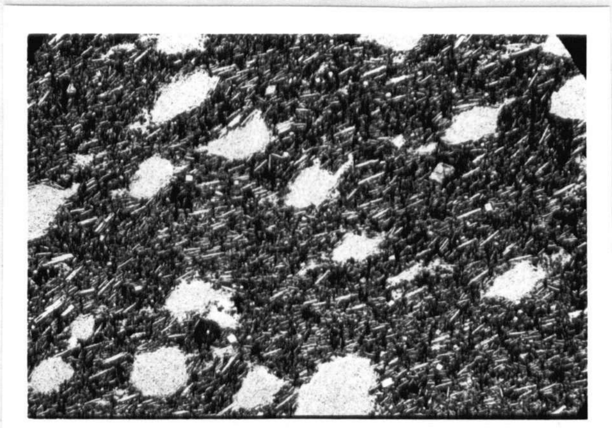
The rock has apparently been chilled as quickly as any of the surface lavas for a zone of sideromelane exists in the ground mass along one margin of a block while tachylyte forms most of the interior. It is possible, therefore, that this rock may have originated in a block lava flow (Washington, 1926 and Finch, 1933). Its highly differentiated composition would certainly favour the formation of such a highly viscous flow (Macdonald, 1967). Without further evidence, however, the possibility still remains that these angular rock samples may have formed part of a talus near an eroded dyke.

PLATE 8 - Photomicrographs of the andesites

(a) Non-vesicular andesitic rock from Station 67 - 7. Phenocrysts of plagioclase, magnetite and clinopyroxene are visible in the matrix of plagioclase microlites and glass. (Plane light) (Thin section 67 - 7 - A) (x27)

(b) Hornblende - bearing andesite from Station 68 - 5. Small diamond-shaped crystals of olivine and a dark crystal of hornblende are surrounded by flow-oriented plagioclase and interstitial glass. The light areas are vesicles (Plane light) (Thin section 68 - 5) (x27)





The single dredge haul on the northeast ridge turned up the only other andesitic rock found on the seamount. It is unimposing in hand specimen, being a pale grey, aphanitic, finely vesicular rock. Under the microscope (Plate 8b), it is seen to be almost wholly composed of flow-oriented plagioclase laths (An 31 - 47) with interstitial glass and rare, euhedral or skeletal crystals of olivine and pyroxene. Brown, basaltic hornblende is present as scattered euhedral phenocrysts, some of which are surrounded by a very thin reaction rim of magnetite and orthopyroxene. The reaction products, apparently formed by the dehydration of hornblende, may have formed as a result of a drop in water pressure when the magma was extruded.

Andesites occur in small proportions on many large oceanic volcanoes and are thought to be highly differentiated derivatives of the alkali olivine basalt which makes up such volcanoes.

B. Inclusions

The inclusions are crystalline, shapeless masses 2 to 5 cm. across. Some of those examined petrographically have textures typical of cumulates (Wager et al. 1960), igneous rocks which apparently have formed by the accumulation of crystals on the floor of a magma chamber.

Others are of less distinctive texture and could be either xenoliths of wall-rock or indistinct cumulates. Only one ultramafic inclusion (a pyroxenite) was found. The rest are feldspathic or gabbroic and many are rich in hornblende. The climopyroxene in these inclusions is pale green in thin section, unlike the buff-coloured clinopyroxenes common to the lavas.

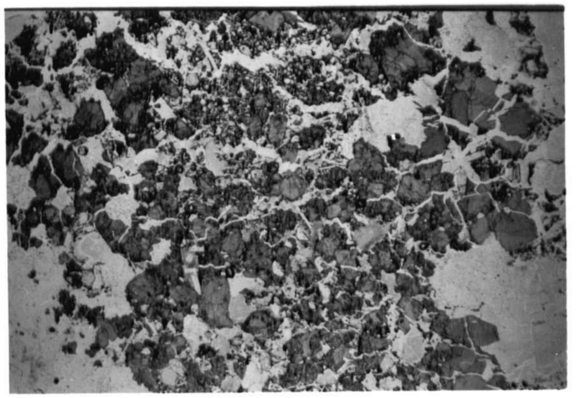
(i) Pyroxene cumulate

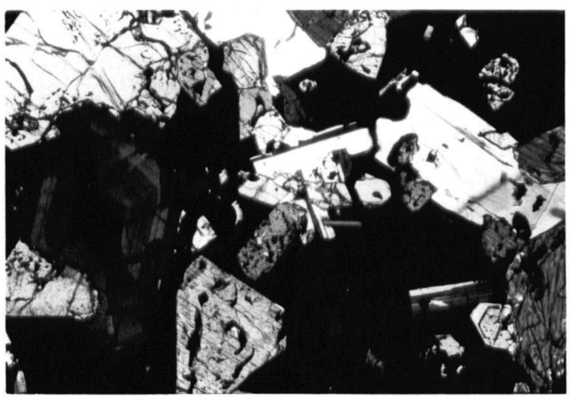
This inclusion (Plate 9) is an aggregate of zoned clinopyroxenes and some olivine with interstitial poikilitic plagioclase and microporphyritic sideromelane. The mafic minerals which, for the most part, are euhedral, are randomly oriented and loosely packed in interstitial vesicular glass. There is no sign of fracturing or resorption on the exposed grain boundaries to indicate the removal of pre-existing minerals from these voids. Apparently then, this ultramafic inclusion was always an aggregate of euhedral crystals with interstitial magma and is not the remnant of a completely crystalline igneous rock. It is probable that it formed as a cumulate on the floor of a magma chamber or perhaps as a nodule of aggregated crystals, suspended freely in the magma. The clinopyroxene and olivine, being the most euhedral phases, were presumably the first to

PLATE 9 - Pyroxene cumulate (Thin section 67 - 3 - C)

(a) Partially intergrown cumulus of clinopyroxene crystals. The speckled material is microlite-rich, vesicular, interstitial glass. The light areas are mainly holes and cracks in the slide but some are plagioclase and olivine crystals. (Plane light)(x2)

(b) Cumulus pyroxenes and a few interstitial plagioclase crystals. Isotropic glass forms the black background. (Crossed nicols) (x27)





crystallize and gravitate to the region of accumulation. Both apparently accumulated as crystals at the same time since neither exerts a dominant crystallographic influence on the other. Growth of the pyroxenes and the few olivines continued after deposition, resulting in the partial coalescence of adjacent crystals. Although some early plagioclase appears to have settled out with the ferromagnesian cumulus minerals, the greater part of it is poikilitic and interstitial, enclosing or partly enclosing pyroxene euhedra. Crystallization had not yet gone to completion when the cumulate was removed from its site of formation, incorporated into the moving magma, and ejected onto the surface of the volcano as a cored bomb (Brady and Webb, 1943), thinly mantled and permeated by quenched sideromelane

(ii) Andesine - olivine cumulate

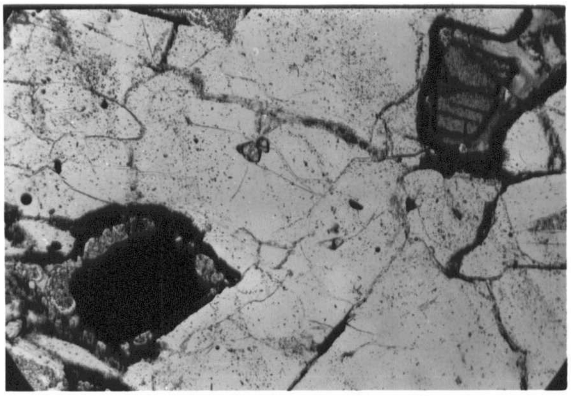
The minerals making up this inclusion are andesine (An 30 - 34), ferro-hortonolite (Fa 80), apatite, and opaque iron oxide (Plate 10). The composition of the olivine was determined by X-ray diffraction using the method of Yoder and Sahama (1957). Such an assemblage of sodic plagioclase and iron-rich olivine probably represents a differentiate of a dry magma somewhere in the system of magma reservoirs below the surface. The

PLATE 10 - Andesine - Olivine cumulate. (Thin section 67 - 6 - E)

(a) Olivine Fa-80 (upper right), apatite (centre), and opaque oxide (lower left), surrounded by plagioclase feldspar An-30-34. Melting of the plagioclase around the olivine and oxide grains is readily apparent. (Plane light) (x27)

(b) Interlocking grains of the plagioclase cumulus. (Crossed nicols) (x27)

(c) Olivine (centre) on the margin of the inclusion, exhibiting a strong reaction with the magma (lower left). The lighter coloured glass, produced by melting of the minerals within the inclusion, is visible in the space between the olivine and the large plagioclase (upper right) (Plane light) (x27)



crystals are large and well formed but have interlocking grain boundaries (Plate 10b), a texture which the author believes to be the result of continued growth and coalescence of aggregated phenocrysts which had settled out of the magma onto a surface of accumulation. A change in the environment, e.g. a pressure decrease during movement of the overlying magma, caused incipient melting of the minerals in the cumulate, especially of the sodic plagioclase around olivine and iron oxide grains, which do not appear themselves to have been so susceptible to remelting (Plate 10a). Pieces of the cumulate, transported to the surface as inclusions during an eruption, reacted with the magma at their margins (Plate 10c) but retained within them the interstitial liquid formed by the melting of the andesine and olivine. Quenching of both the lava and the interstitial liquid on reaching the surface, produced two distinctly different glasses: a dark sideromelane, which surrounds the inclusion and a much lighter glass within the inclusion (Plate 10c).

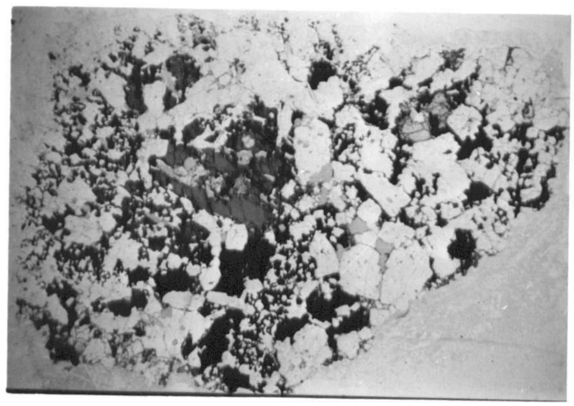
(iii) Plagioclase - hornblende cumulate

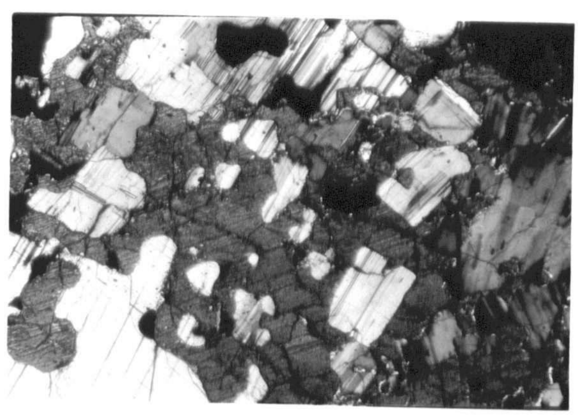
In this cumulate, randomly oriented calcic plagioclase grains are enclosed in large (1 - 2 cm), poikilitic basaltic hornblende crystals (Plate 11a). Very small amounts of olivine, apatite and skeletal,

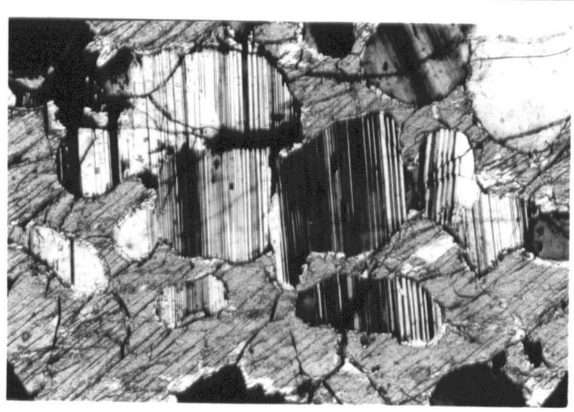
PLATE 11 - Plagioclase - hornblende cumulate (Thin Section 67 - 6 - G)

(a) Plagioclase crystals of cumulus surrounded by poikilitic hornblende (Plane light) (x2)

(b) and (c) Microfractured and rounded skeletal plagioclase showing displacement of adjacent segments of the same crystal. Poikilitic hornblende surrounds the feldspar. (Crossed nicols) ((b) x27, (c) x 80)





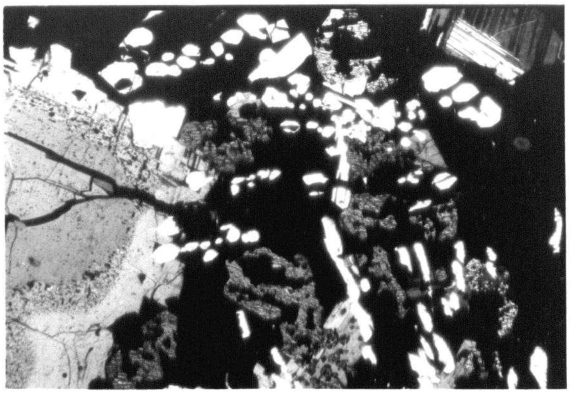


magnetite-rich clinopyroxene are also included by the poikilitic hornblende. The plagioclase is rounded and occurs both as small discrete grains and as large skeletal crystals. The latter show evidence of having once been fragmented and then healed. In places, there is a slight difference in orientation of adjacent units of a single plagioclase crystal in a poikilitic hornblende (Plate 11b and c). Misalignment of twin lamellae and a corresponding disparity in extinction position between different areas within a visibly continuous portion of a plagioclase grain is also apparent. These phenomena can best be explained by microfracturing and healing within the crystal. Each plagioclase unit in the poikilitic hornblende is individually zoned, even if several adjacent units appear to belong to the same large crystal. The hornblende, on the other hand, shows no microfracturing or zoning. The plagioclase is therefore older than the hornblende and appears to be an accumulation of skeletal crystals which, at one point, were broken and then rounded by resorption in an unfavourable magmatic environment. The open spaces and microfractures in the feldspar cumulus were later filled by relatively few, large, poikilitic crystals of basaltic hornblende. The result is similar to the heteradcumulate of Wager et al. (1960). Growth of such large, uniform crystals would necessarily involve the free diffusion of the component ions of hornblende from the magma to relatively rare nucleii in the intercumulus liquid. The apparent age difference between the plagioclase and the hornblende precludes the possibility that this texture represents a eutectic crystallization of the two phases. The possibility remains that hornblende has partly replaced the plagioclase.

(iv) Anorthosite xenolith with harrisitic overgrowth

The core of this type of inclusion consists of coarsely crystalline plagioclase (An 60 - 65), some opaque iron oxide and a relatively small amount of interstitial glass. A change in the magmatic environment at some time caused considerable resorption around the exposed margins of the inclusion and, to a smaller degree along grain boundaries within it (Plate 12). Such a change could be most simply explained by a simple pressure drop or temperature increase in the system. After being partly resorbed and rounded, the plagioclase was finally isolated by a fresh outer zone of more calcic composition. Crystal growth during this second stage was not restricted to plagioclase alone. Skeletal crystals of olivine and of clinopyroxene, shot through with magnetite, apparently nucleated on the surface of the inclusion and grew away from the surface. Adjacent skeletal crystals are

PLATE 12 - Harrisitic overgrowths on anorthosite xenolith. The plagioclase of the inclusion occupies the left corner of the photo. The minerals forming the harrisite are clinopyroxene, which appears grey with a rough surface, and olivine, which appears white in the photograph. Later-fromed poikilitic plagioclase is visible among the skeletal olivine and clinopyroxene crystals, and as a lighter rim on the plagioclase of the inclusion. The black areas within the crystals are composed of glass and magnetite crystals. The black background is isotropic vesicular glass. (Crossed nicols) (Thin section 67 - 1 - C) (x27)



thoroughly intermeshed and in places are rooted to the plagioclase inclusion by poikilitic growth of the outer zone of plagioclase. Small, probably late plagioclase crystals also exhibit a poikilitic texture around parts of the skeletal ferromagnesians. This intricate second stage texture appears to be a variation of the harristic or crescumulate texture of Wager et al. (1960) and Wager (1968)

(v) Plagioclase - magnetite xenolith

This inclusion (Plate 13) consists of intergrown plagioclase (An 70), magnetite and apatite crystals with a good deal of interstitial sideromelane. The plagioclase is highly fractured and sideromelane fills many of the cracks. Resorption of the plagioclase has taken place along exposed grain boundaries, possibly during transport in the magma prior to eruption. The sideromelane in and around the inclusion indicates that rapid quenching took place after its ejection. Local melting of the magnetite may account for a darker stain in the sideromelane adjacent to it.

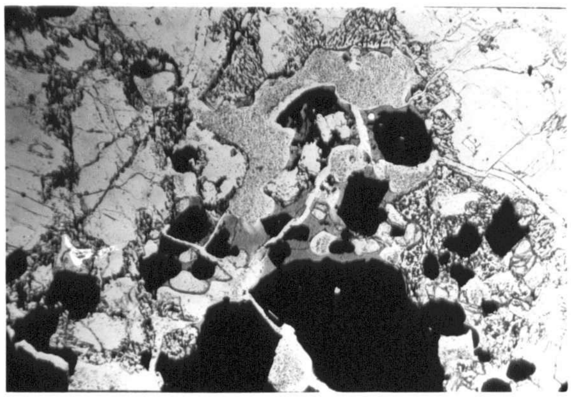
(vi) Hornblende gabbro xenoliths

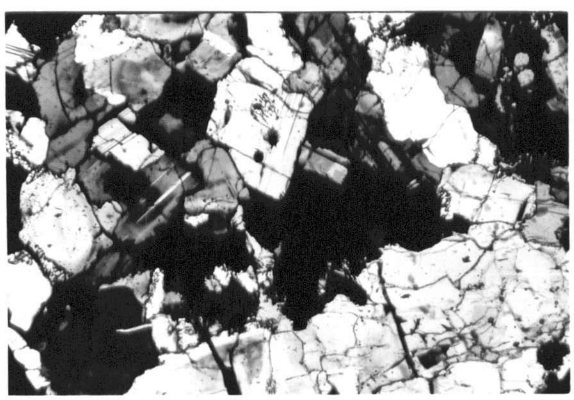
Coarsely crystalline, gabbroic xenoliths composed of plagioclase (An 66 - 76), basaltic hornblende, clinopyroxene, magnetite and minor apatite, are common

PLATE 13 - Plagioclase - magnetite xenolith (Thin section 67 - 6 - H)

(a) Plagioclase (white) surrounding a pocket of magnetite (black), apatite (white grains with high relief and "ground glass" surface), and interstitial sideromelane (dark grey). The plagioclase is strongly resorbed on its margins and sideromelane is visible in fractures within it (upper left). (Plane light). (x27)

(b) A different part of the same section viewed through crossed nicols. Plagioclase appears grey and white. Magnetite and glass appear black. The resorbed margins of the plagioclase appear as dendritic patterns. (x27)





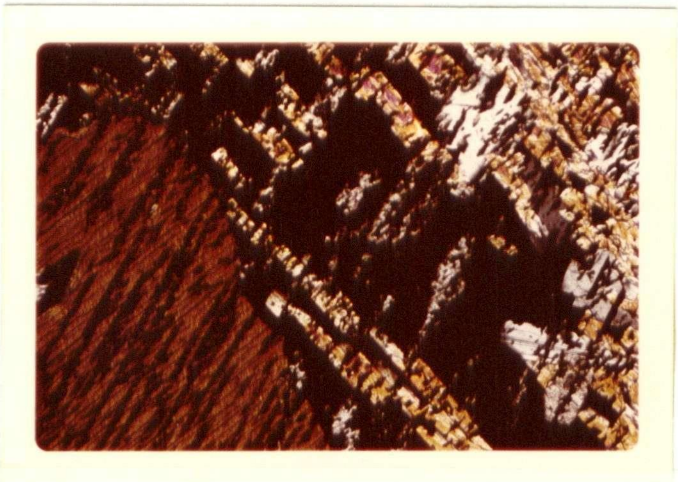
in the inclusion-bearing basalts. The plagioclase has apparently been resorbed by the magma along exposed grain boundaries and the reaction margin is mantled by a thin growth of fresh plagioclase (Plate 14). The hornblende, however, appears to have undergone profound changes where it was exposed to the magma. Those grains which lie on the border of the inclusion are permeated with graphic blebs of magnetite and appear to pass at their outer margin into graphic (or skeletal) clinopyroxene, which retains the orientation and magnetite trains of the hornblende. Acicular, radiating crystals of orthopyroxene occur with this apparent alteration in a few places. In many grains, more conventional reaction rims of fine, unoriented orthopyroxene and magnetite are present instead of this unusual graphic reaction texture but the one type seems to grade into the other. The graphic alteration zones of the hornblende are generally further complicated with what appears to be a harrisitic growth of olivine and augite, similar to that described previously, which probably formed independently on any of the exposed crystal surfaces of the inclusion.

Origin and significance of the inclusions

The great variety of basalts and inclusions suggests that a complex system of magma reservoirs existed

PLATE 14 - Photomicrograph of the graphic hornblende alteration with intermeshed harrisitic olivine. In the photographs, hornblende appears brown, pyroxene appears grey with a rough surface texture, olivine appears yellow, plagioclase appears grey with a smooth surface texture, and magnetite appears as small, black, graphic grains in the other minerals. The extensive dark matrix is isotropic glass. The shape and orientation of the magnetite is evidently controlled by crystallographic directions within the hornblende. The pyroxene, which is similarly oriented, is also thought to have been derived from the hornblende, and small amounts of it can be seen as grey areas within the latter mineral. The skeletal olivine, has apparently grown at right angles to the plagioclase of the inclusion. (Crossed nicols) (Thin section 67 - 6 - F) (Magnification of upper photo x27; lower photo x 80)

L



M

beneath Bowie Seamount both in the crust, and in the mantle, where the magma must originally have been derived. Macdonald (1949) illustrated how lavas of various compositions may originate at different levels within a single magma chamber (Figure 13) and many of the rocks of the seamount are probably related in this way. Several extremes of differentiation however are represented by the inclusions. Xenocrysts of hornblende, xenoliths of hornblende gabbro, and cumulates containing poikilitic hornblende attest to relatively high water pressures that must have prevailed in some parts of the magma chamber system. On the other hand, the ultramafic pyroxenite cumulate and the andesine - olivine cumulate respectively represent early and late stage differentiation of dry basaltic magma. It is therefore probable that several magma chambers existed at a high level in the crust and that differentiation proceeded more or less independently in each.

From the variety of cumulate types, it is apparent that the magma had sufficient time to differentiate to a high degree, and possibly to build up a considerable thickness of accumulated crystals on the magma chamber floors. During eruption there is a decrease in confining pressure in the magma, accompanied by the formation and

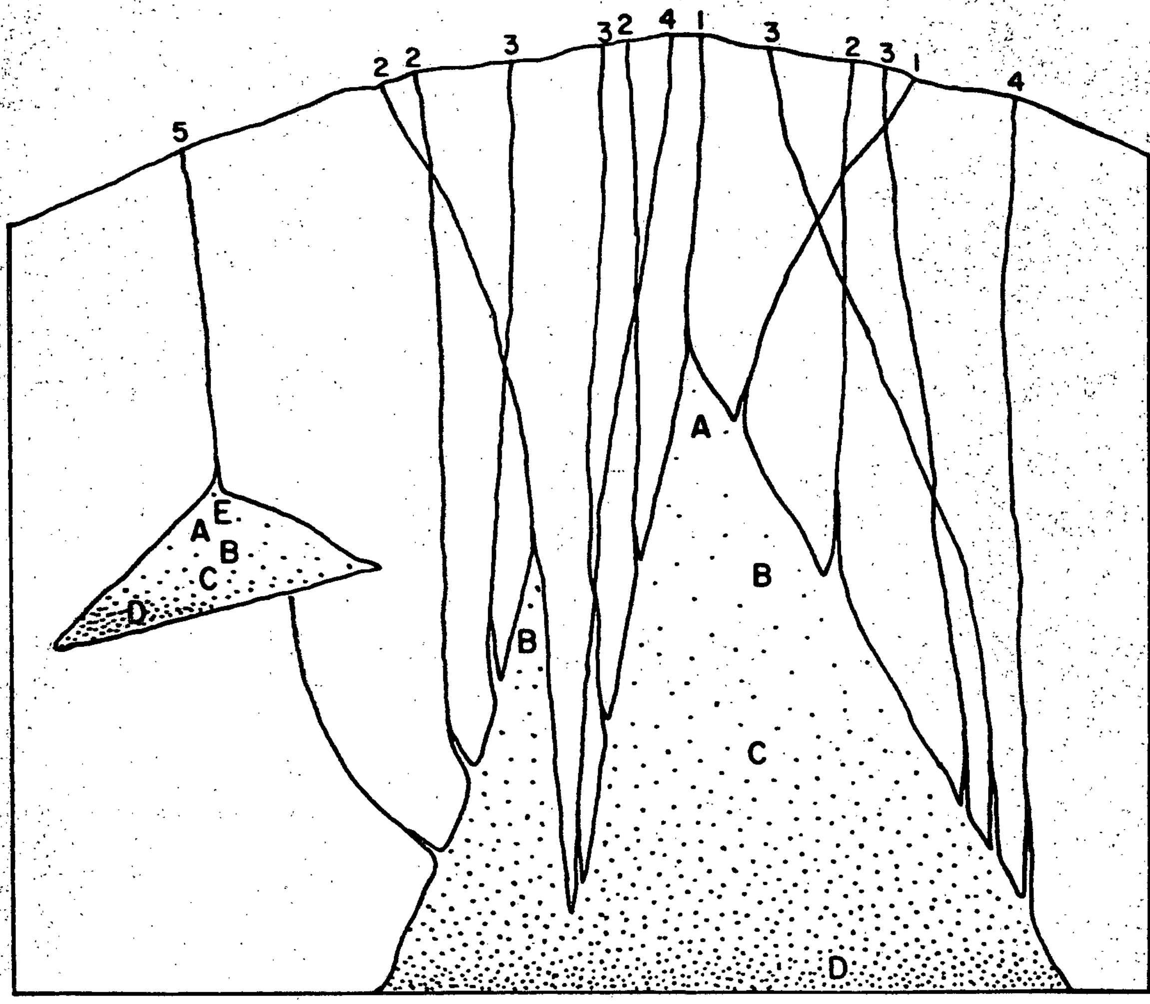


FIGURE 13 - Diagram illustrating a possible manner of eruption of lavas of differing composition from the same magma chamber. A, andesite; B, basalt; C, olivine basalt; D, picrite-basalt; E, trachyte. (After Macdonald, 1949.)

expansion of vesicles. Vesiculation also takes place in the interstitial liquid within the loosely bound crystal mush, and, if the process were violent enough, it could have broken up the cumulate beds and transported fragments of them upwards into the erupting magma as inclusions.

Corroded wall-rocks, perhaps comprising old cumulate beds or conventionally crystallized rock reintruded by a new column of magma, could be broken up and incorporated into the magma in the same way. The drop in pressure in the wall-rock might also be compounded by a Venturi-effect created by rapid upward movement of the magma. The corroded anorthosite and hornblende gabbro inclusions, which are hosts to the unusual harrisitic texture, might be the remains of fractured, magma-permeated wall-rocks or chamber-floor rocks which, for a time, may have supported harrisitic crystal growths before eruption of the magma and their consequent fragmentation and dispersal.

C. Tephra

Pyroclastic material is more easily recovered by dredge and grab sampler than is flow-rock and this is reflected in its occurrence in all but two sample hauls from the seamount (Appendix E). The author estimates that the ratio of tephra to flow-rock on the seamount is probably actually around 1:1.

(i) Volcanic bombs

A collection of volcanic bombs was obtained along a five mile strip of the summit ridge at sites 67 - 1, 67 - 6, 67 - 5 and 68 - 1 (Figure 2). Among the more familiar types are the fusiform bomb (Plate 15a), which is fully formed before landing, and the cow-dung bomb (Plate 15b) which is still partly liquid at the end of its flight and flattens on impact. A few small cow-dung bombs appear to have been flattened and then folded before finally solidifying completely (Plate 15c). The appearance of the great majority of bombs, represented by the suite from station 67 - 5, lies somewhere between the two types. The bombs of this suite range from small flattened forms resembling cow-dung bombs to large, globose, highly deformed individuals with complex involute surfaces but no definable shape (Plate 16). Although the deformation of these bombs was apparently due to impact with a resistant surface, there are no imprints or adhering rock fragments to confirm that the impact was with a solid volcanic substrate, neither is it clear which side of the bomb received the impact. Their mode of origin remains uncertain.

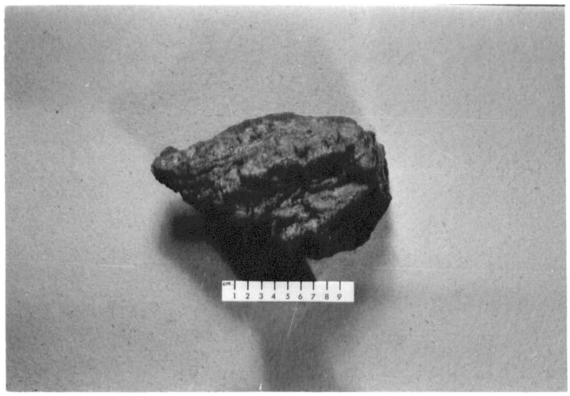
All the bombs have a quenched skin of sideromelane which may show some bread crust fracturing. Normally,

PLATE 15 - Varieties of bombs found on Bowie Seamount

(a) Fusiform bomb (Station 68 - 1)

(b) Cow-dung bombs. The upper bomb was found at Station 67 - 1, the lower left one at Station 67 - 6, and the lower right hand one at Station 67 - 5.

(c) Folded cow-dung bomb (Station 67 - 6).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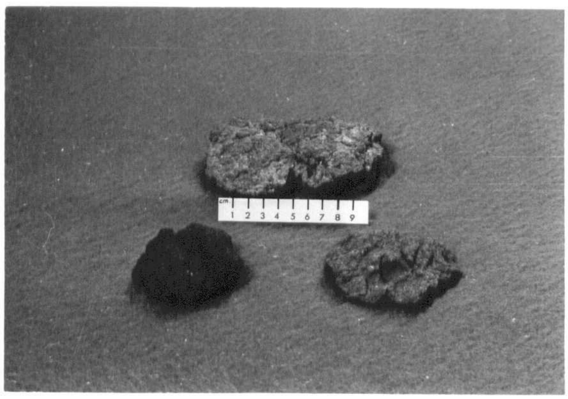
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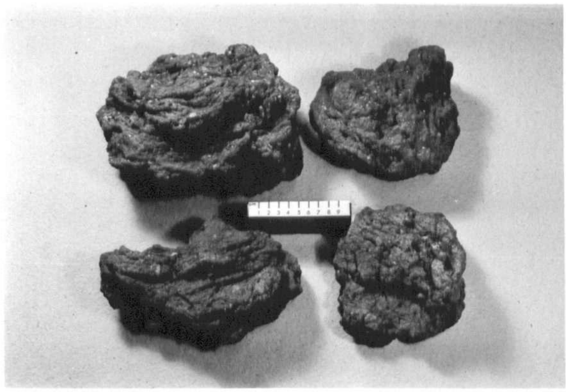
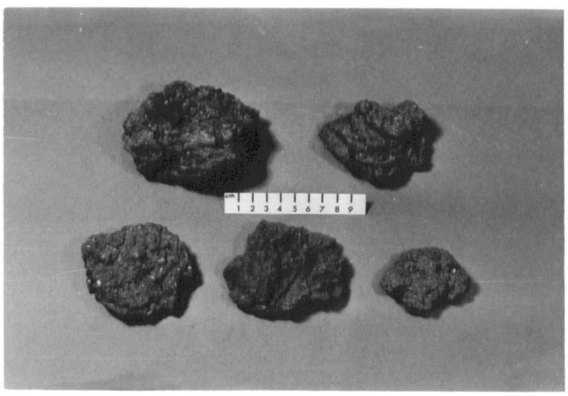
PLATE 16 - Varieties of bombs found on Bowie Seamount (continued)

(a) and (b) Gradation from large bombs with deformed surfaces to the small, flat, cow-dung variety. All the specimens are from Station 67 - 5.




1 2 3 4 5 6 7 8 9

vesicles are deformed near the surface, becoming less so towards the middle. The vesicles of the interior are commonly slightly larger than those of the chilled margin, and, in extreme cases, the interior is virtually hollow (Plate 17a). Those bombs which are not flattened, are concentrically and radially fractured (Plate 17b), and individuals have been found that have completely or partly lost their quenched skin due to spalling along these fractures.

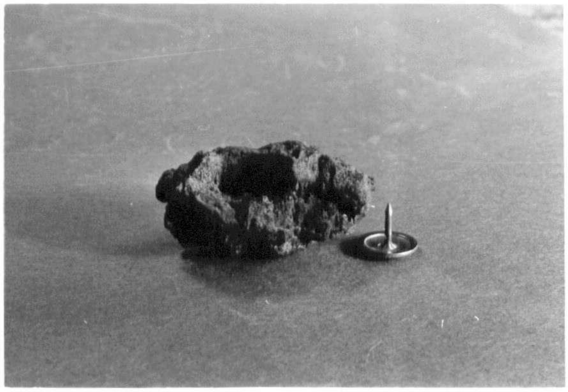
The compositions of the bombs vary from place to place and are similar to that of the rocks in the immediate vicinity. Cored bombs containing inclusions are rare.

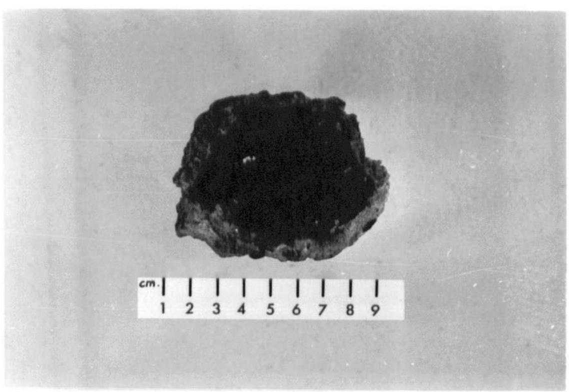
The presence of bombs on the summit implies that lava fountaining and explosive eruptions took place there during the late stages of activity on the summit. In view of the summit's present nearness to sea level and its probable emergence in the past, many, if not all, of the bombs of the summit would have been ejected from either above or just below sea level. Many, therefore, probably travelled through the air along at least part of their trajectories, eventually falling into the sea or onto the surface of young volcanic islands which may have existed there at times during the past.

PLATE 17 - Varieties of bombs found on Bowie Seamount (continued)

(a) Hollow cow-dung bomb (Station 67 - 6)

(b) Concentric and radial fractures in a fusiform bomb. The quenched sideromelane skin appears lighter than the dark core. The specimen is from Station 68 - 1.




cm.
1 2 3 4 5 6 7 8 9

Since these islands are presumed to have been eroded away, the present distribution of the bombs on the seamount may be due not only to primary volcanic dispersal but also to secondary dispersal by wave erosion. It is the author's opinion, however, that few of the subaerially formed bombs could have survived intact the wave action which destroyed the ephemeral islands on which they lay. The majority of the bombs now found on the terraces probably constitute the remainder which either landed in the sea or originated entirely under water. Their present location, if this is the case, should be the result of primary volcanic dispersal. The geographic restriction of large numbers of obviously related bombs, such as the suite from station 67 - 5 (Plate 16), can be explained in this way.

Apparently then, bombs, which are traditionally thought of as being subaerially formed structures, may be capable of forming in shallow water. Perhaps the unusual suite of bombs from station 67 - 5 (Plate 16) is typical only of shallow water eruptions where ejecta may travel through both air and water before finally coming to rest on the surface of the volcano.

(ii) Tuffs and their unconsolidated counterparts

Lapilli and ash, and weakly cemented tuffs derived from them, were found in all but one locality on the summit and at three of the five stations on the flanks (Appendix B). Some of the tuffaceous material may be hyaloclastic rather than pyroclastic, that is, formed by shattering glass during the aqueous chilling of lava (Rittman, 1962), rather than by explosive vulcanism. However, it was difficult in some cases to distinguish between the two of them and the term "pyroclastic", as used in this paper, may therefore cover both true pyroclastic and hyaloclastic products.

Lapilli and Lapilli tuffs

Most of the tephra form massively bedded, unsorted accumulations of lapilli, some of which may be cemented. The particles are generally composed of vesicular hyalocrystalline sideromelane, though tachylyte and holocrystalline fragments may be present in small amounts. Cemented deposits, i.e. tuffs, which are in the process of formation on the surface of the seamount were found only on the summit during the present survey (Plate 18), and there, their occurrence is sporadic.

The cementing agents are manganese oxides (Plate 19), iron oxides (Plate 20), or carbonate of organic origin (Plate 21a). The carbonate cement is restricted to the shallow summit peaks, which are well within the photic zone and are thickly encrusted with sessile marine life,

PLATE 18 - Bottom photographs of a cemented tuff deposit on the 130 fathom terrace (Station 68 - 2)

(a) The cemented surface crust of the tuff, undercut at its margin, stands 6 inches above the deposit of loose tephra in the channel to the right. Sponges grow in abundance on the solid substrate, but not on the loose material in the channel. The diameter of the compass is 3 inches and the length of the vane is 10 inches.

(b) Light cover of sediment, disturbed by the compass as it travels over the bottom. The surface texture of the tuff is revealed quite clearly in this photograph. The diameter of the compass is 3 inches and the length of the vane is 10 inches.

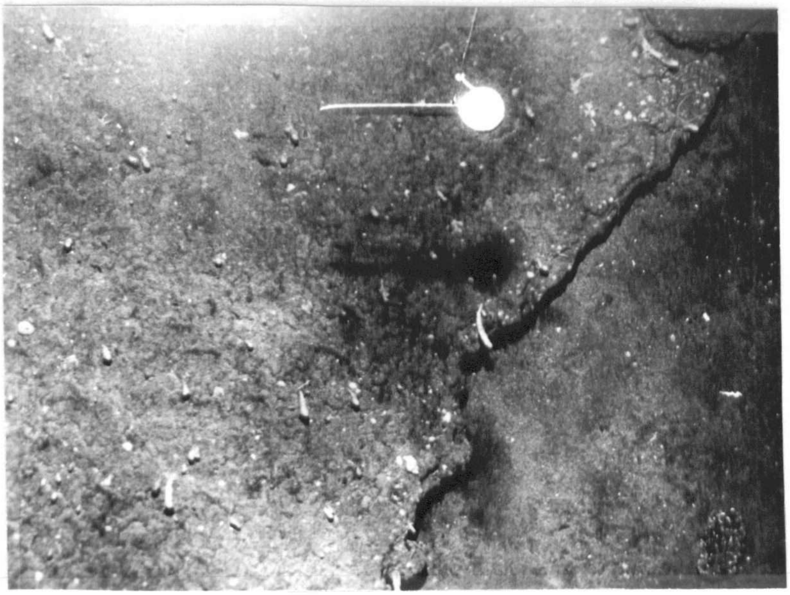


PLATE 19 - The nature of cementation of the tuffs

(a) Hand specimen showing black colour imparted by cementing ferro-manganese oxides (Sample from Station 67 - 5).

(b) Thin section showing the black ferro-manganese cement among the lapilli of vesicular, microporphyrytic sideromelane. (Plane light) (Thin section 67 - 5 - A) (x2)


cm
1 2 3 4 5 6 7 8 9

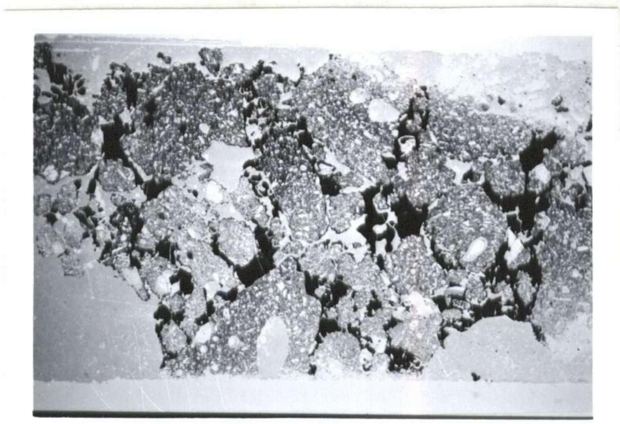


PLATE 20 - The nature of the cementation of the tuffs (continued)

(a) Hand specimen showing red colouration imparted by ferruginous cement. A growth of coraline algae covers the other side of the rock and appears as a white rim in this photograph. (Sample from Station 67 - 3).

(b) Thin section showing lapilli, interstitial ferruginous cement (black) and growth of coraline algae (black strip at top of slide. (Plane light) (Thin section 67 - 3 - B) (x2)


cm
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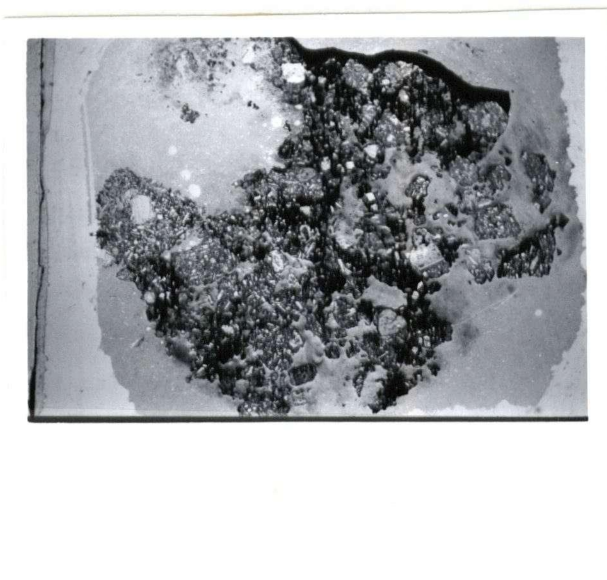
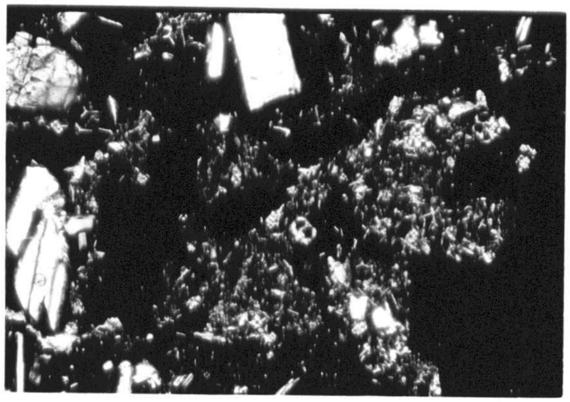


PLATE 21 - The nature of cementation of the tuffs (continued)

(a) Binding matrix of organic carbonate and silica comprising foraminifer tests and sponge spicules. (Crossed nicols) (Thin section 67 - 1 - A). (x27)

(b) Uniformly cemented lapilli tuff (Station 67 - 3)

(c) A strongly indurated surface crust capping an otherwise weakly cemented lapilli tuff (Station 67 - 2)

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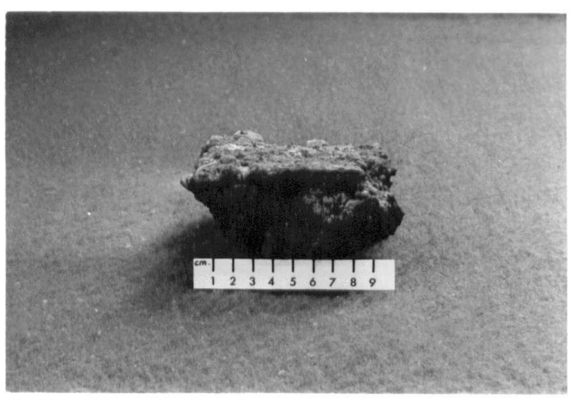
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notably the red coraline alga Lithothamnion, barnacles, and various siliceous sponges. The ferruginous and manganiferous cements do not appear to have any such depth limitation.

Some samples appear to be uniformly cemented throughout (Plate 21b) but others are strongly cemented only in the top few centimetres of the deposit (Plate 21c) and simply form a crust overlying unconsolidated material (Plate 18a).

Loose deposits of lapilli and shell fragments (Plate 22) are very widespread on and just below the upper terrace. The origin of the shell debris is uncertain, but much of it is similar to the fauna presently living on boulders found on the terrace. Much of the shell material may therefore have been recently derived from boulders and rocky outcrops in the vicinity of the upper terrace and its central pinnacles. Currents, have, in places, reworked the loose deposit enough to produce ripple marks in the light shell material (Plate 23).

Sediments, both loose and cemented, of well rounded lapilli are associated with both the 45 fathom and 130 fathom terraces (Plate 2). These are thought to represent fossil wave-washed deposits, (Chapter III-B).

Thin-bedded Tuff

Thin-bedded tuffs composed of volcanic ash are not

PLATE 22 - The loose lapilli deposit of the 45 fathom terrace with its conspicuous shell debris. A thumb-tack at the bottom of the lower photograph provides the scale. (Camera Station 68 - 3 and sample Station 67 - 12)

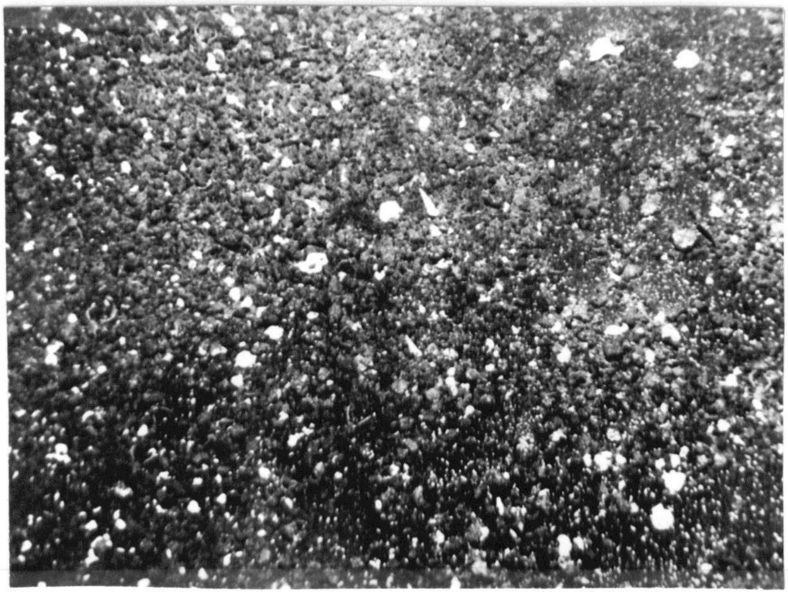
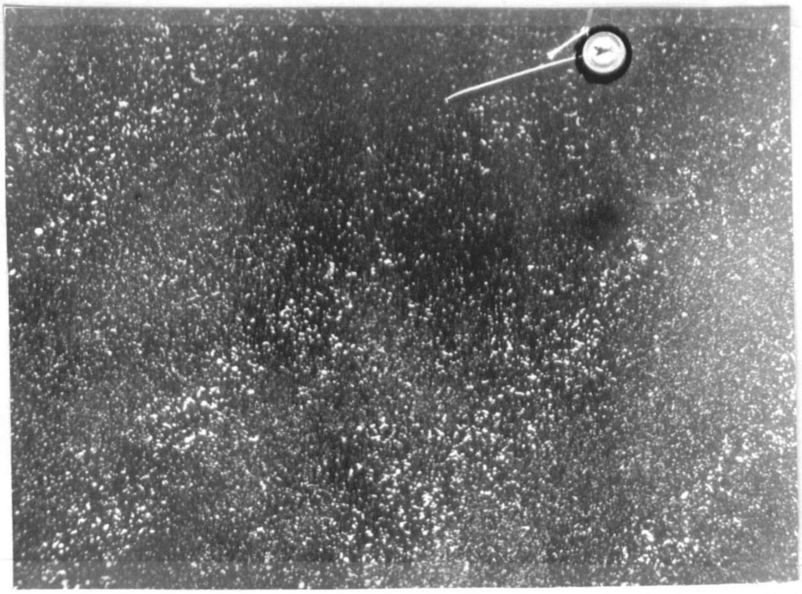


PLATE 23 - Ripple marks visible in the light shell material of the deposits on the 45 fathom terrace. The compass is 3 inches in diameter and the vane is 10 inches long (Station 68 - 3).



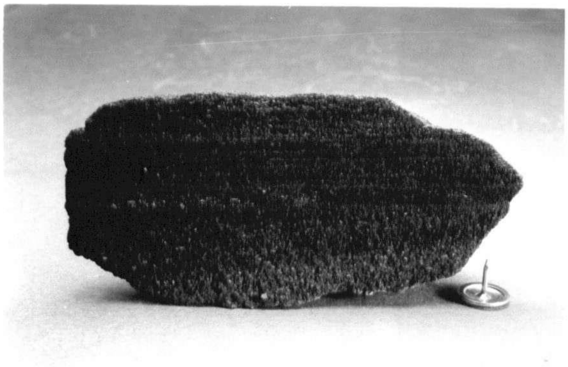
as common as lipilli tuffs. The only deposit found is on the 130 fathom terrace in the area covered by dredge site 67 - 6 and touched by 67 - 2 and 67 - 4. This tuff (Plate 24) is generally dark brown but, in places, may be reddish brown or ochre coloured, depending on the relative amount of ferruginous cement. The samples are friable and slabby and none exceeds 4 cm. in thickness. It characteristically possesses graded bedding with particle sizes ranging mainly from coarse to medium sand but lapilli up to 1 cm. in diameter are frequently embedded in the base of the unit. Whether this grading continues downward below the layer represented by the sample slabs is not known. The visibly graded portion is usually capped by a thinner laminated unit of medium to fine sand. In thin section, the rock is seen to be a vitric-crystal tuff (Pettijohn, 1957), wholly composed of vitrophyric sideromelane shards and crystal fragments.

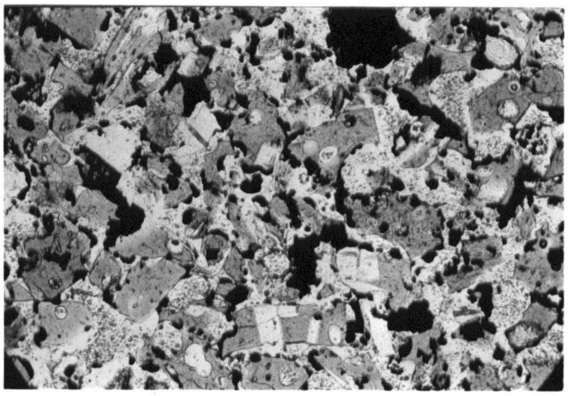
The glass of the grains is exclusively sideromelane with a narrow range of refractive indices. The refractive index was determined using immersion oils and the Becke line method, the index of each oil being checked immediately prior to use with an Abbe refractometer. The shards were cleaned ultrasonically in distilled water, a simple time-saving technique which, for unaltered shards,

PLATE 24 - Thin-bedded vitric-crystal tuff (bedded ash) (Station 67 - 6)

(a) Section through the tuff showing graded bedding

(b) Photomicrograph of the same tuff. The black material between the shards is the ferruginous cement. (Plane light) (Thin section 67 - 6 - D) (x80)





was found to work as well as the chemical method of Kittrick and Hope (1963). Based on observation of 225 grains, the glass has an index between 1.57 and 1.59, with a strong mode between 1.580 and 1.586. The spread of this mode is within the limits one would expect for a single ash fall (Wilcox, 1965). This deposit must, therefore, have originated during a single volcanic event.

The sedimentary structures and petrographic properties of this particular tuff furnish some insight into its origin. The sequence of graded and laminated units resemble the A and B intervals of the turbidites described by Bouma (1962), but this does not necessarily mean that the tuff was deposited by turbidity flow. The finer volcanic ejecta from a single explosive event during a period of explosive eruption may rain vertically from the eruptive ash cloud, or may be carried laterally in the base surge (Moore, 1967) down the flanks of the cone. In the case of a submarine explosion which breaches the surface, a base surge will spread out across the surface of the water. It is easy to imagine an ash deposit with graded bedding originating from any of these processes. Straightforward vertical differential settling of the ash column through air or water will produce a graded sequence, as will the similar foundering of a base surge on the sea surface when its energy is spent. A submarine base surge, spreading down the flanks of the active cone should behave much like a turbidity current and would give rise to a tuff with turbidite features. Such a glassy tuff might also be a hyaloclastite derived from the shattering surface skin of a submarine flow of pillow lava.

Pillow breccia

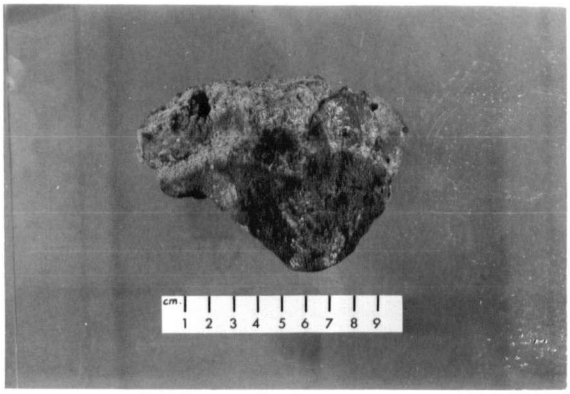
A grain-supported volcanic breccia, composed of large, pyramidal pillow fragments and small, angular pillow-crust fragments, set in an unstratified matrix of vitric tuff (Plate 25), was dredged from the eastern flank of the summit ridge (Station 68 - 1, Appendix B). The black basalt fragments contrast sharply with the grey-green and creamy yellow variegated matrix. The outer surface of the rock is covered with a thin layer (0 - 2mm.) of black and brown ferro-manganese. Recovered with it were various independent pillow fragments and a more or less intact pillow. Bottom photographs in the area (Plate 26) revealed a rubbly substrate with visible pillow fragments and what may be intact pillows.

The matrix of the breccia was examined petrographically and by means of X-ray diffraction. Samples were prepared for X-ray diffraction using the chemical cleaning procedure of Kittrick and Hope (1963).

PLATE 25 - Pillow breccia (Station 68 - 1)

(a) Pillow fragment extracted from the pillow breccia. The lighter coloured material on the upper surface is palagonite. A colour photograph of the upper surface of this specimen appears in Plate 32.

(b) Section through the pillow breccia showing pillow crust fragments in a tuffaceous matrix.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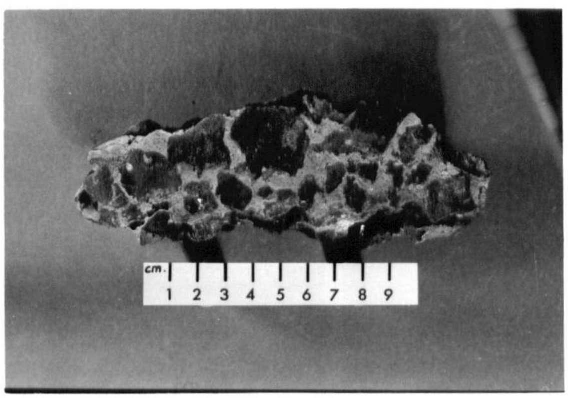
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PLATE 26 - Bottom photographs in the area of outcrop of the pillow breccia (Station 68 - 1). The diameter of the compass is 3 inches and the length of the vane is 10 inches.

(a) A basalt pillow (?). A wedge shaped pillow fragment is also visible to the left of the compass.

(b) Unidentified boulders in the neighbourhood of the pillow breccia occurence.

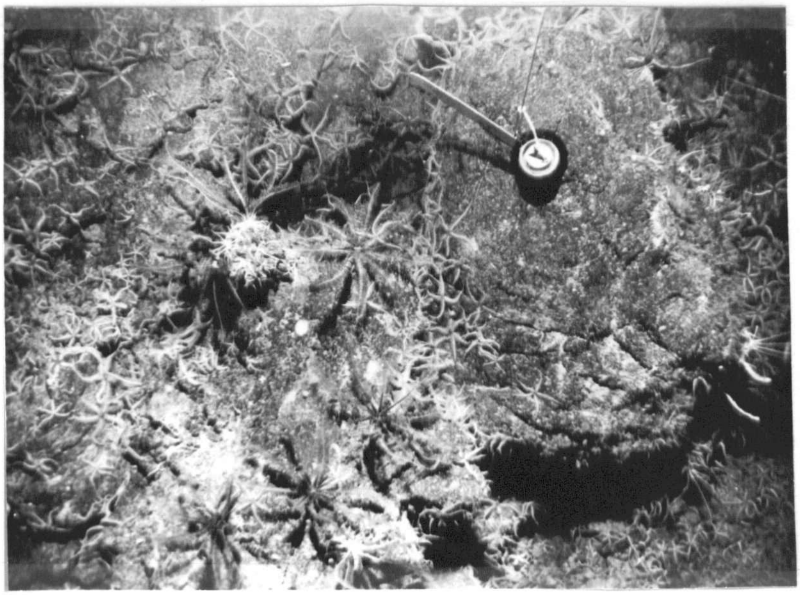
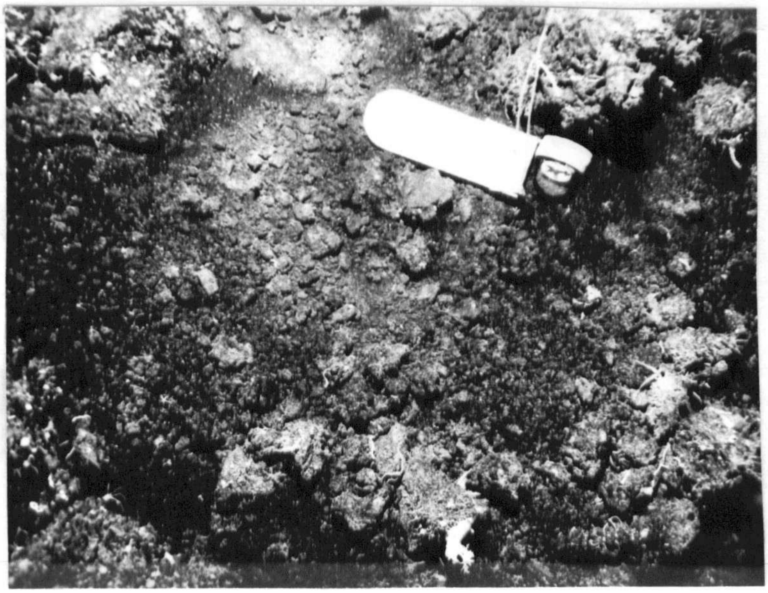


PLATE 27 - Type of rubbly subsrate which appears to be most common on the flanks of the summit ridge of Bowie Seamount. These photographs were taken at station 68 - 1. The compass is 3 inches in diameter and the vane is 10 inches long.



The grey-green part of the breccia matrix was found to be composed of unweathered, green glass shards with very few microlites, sponge spicules, and a few radiolarian tests. The refractive indices of the shards were found to lie between 1.585 and 1.589, a narrow range, which would indicate that the shards were derived during a single period of volcanic eruptions.

The creamy yellow portion of the matrix is seen, under the microscope, to consist of white, fine-grained material, palagonite, and a smaller proportion of sponge spicules and rhombic zeolite crystals. X-ray diffractograms revealed that this portion of the matrix is largely made up of X-amorphous material (i.e. amorphous to X-rays), with lesser amounts of quartz, plagioclase and montmorillonite, and traces of chlorite, illite mica and amphibole.

Glass, palagonite and the opaline silica of the sponge spicules probably make up the X-amorphous component. The zeolites and the montmorillonite are most likely the alteration products of the palagonite (Bonatti and Nayudu, 1965). The plagioclase occurs as microlites in the glass shards. The quartz may be detrital or it may perhaps have crystallized from gels and solutions within the matrix. Recrystallization of sponge spicules might also contribute some crystalline quartz to the system.

Whether the tuffaceous matrix of the pillow breccia is a syngenetic hyaloclastite, derived at the time of eruption from the decrepitating skins of the pillows and pillow fragments, with which it is now associated, or an explosion tuff derived independently, was not ascertained. However, the similarity, in thin section, of the properties of the pillow crust fragments and the shards of the matrix would suggest that the matrix is actually a syngenetic hyaloclastite (cf. Rittman, 1962, Carlisle, 1963, Honnorez, 1963, Solomon, 1969).

D. Vesicle Linings and Amygdules

1. Chemically precipitated linings

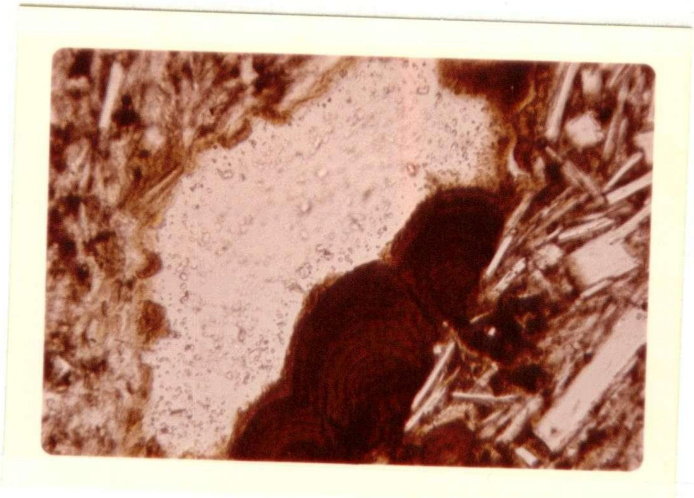
Vesicle linings and amygdules are generally restricted to microvesicles in the sideromelane of lapilli and chilled flow or bomb surfaces which can be seen in thin-section. Only in relatively old rocks, such as the deeply weathered basalt on Hodgkins Seamount, are the large interior vesicles lined or filled.

Many of the amygdules and linings are composed of red-brown, isotropic, iron oxides (Plate 28a), black, opaque manganese oxides, or sparry and fibrous calcite (Plate 28b). Most commonly, however, they consist either of yellow to pale greenish, anisotropic, low birefringent,

PLATE 28 - Photomicrographs of vesicle linings and amygdules.

(a) Concentrically banded growth of iron oxide beginning to fill a vesicle (Plane light) (Thin section 68 - 5)(x200)

(b) Amygdules of sparry calcite. The round, dark grey areas are empty vesicles and the black background is isotropic glass. (Partially crossed nicols) (Thin section 67 - 3 - A). (x80)



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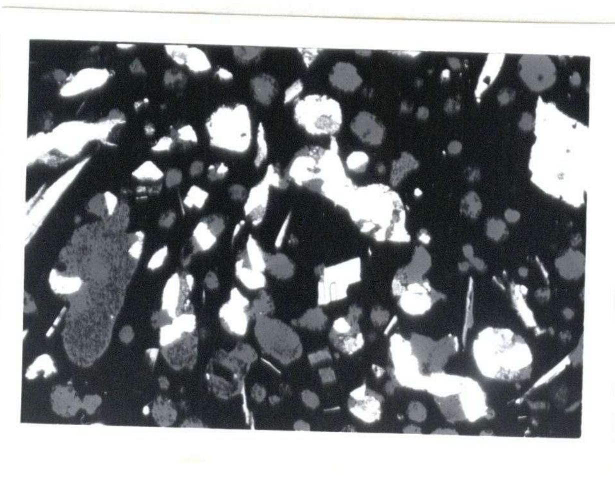

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fibrous minerals which are too fine-grained to identify (Plate 29), or of isotropic, golden yellow material (Plate 30a) with all the properties of palagonite, which is sometimes visible in the glass of the vesicle wall. These substances were included by Peacock (1928) under the term "palagonite". The former, which may actually be a fine fibrous zeolite growth, he called "fibro-palagonite" and the latter "gel-palagonite". Palagonite is thought to be a form of hydrated basaltic glass formed in a subaqueous environment but its mode of origin is in dispute. It is thought to form either by the reaction of hot lava with water (Peacock and Fuller, 1928), or by the gradual hydration and alteration of sideromelane (Moore, 1966). Found in these ways, palagonite is most commonly seen in among the undisturbed microlites and vesicles of the glass it replaces (Plate 33a).

Several of the variations in the composition of the amygdules and vesicle linings parallel geographically the variations in the tuff cements described above. Calcite amygdules are found only in the rocks capping the shallow summit peaks, and linings of manganese oxides occur only where such material is visible in quantity on the surface (e.g. station 68 - 8, Appendix B). The distribution of the other cavity-filling substances is apparently random.

PLATE 29 - Photomicrographs of vesicle linings and amygdules (continued)

(a) Vesicle linings of fine, fibrous, low-birefringent minerals (fibro-palagonite) (Plane light) (Thin section 67 - 5 - A)(x80)

(b) The same, through crossed nicols.

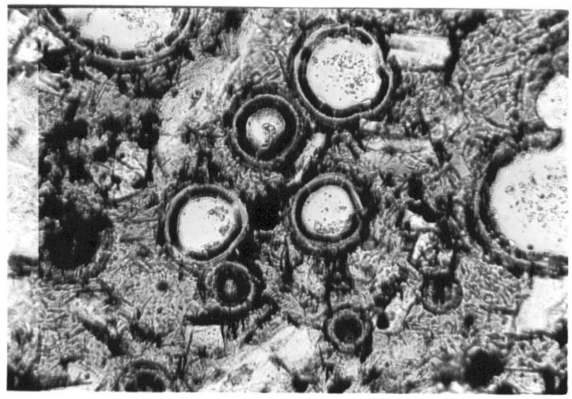
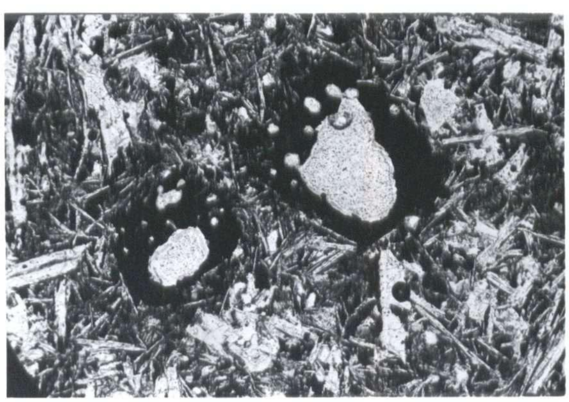


PLATE 30 - Photomicrographs of vesicle linings and amygdules (continued)

(a) Gel-palagonite lining and filling vesicles. The same material lines the surface of the rock fragment itself and has partly replaced the sideromelane within the rock. A breccia matrix of glass shards forms the upper right half of the picture (Plane light) (Thin section 68 - 1 - C) (x27)

(b) Segregation vesicles in the basalt of Hodgkins Seamount. The secondary linings are of black tachylyte, drawn from the matrix of the surrounding rock. A thin coating of fibrous minerals lines the cavities remaining in the tachylyte. (Plane light) (Thin section 68 - 8 - A) (x27)



2. Segregation vesicles

Some of the basalts on the summit of Hodgkins Seamount contain segregation vesicles (Plate 30b) such as those described by Smith (1967). These are secondary linings of glass, which are thought to be due to an increase in confining pressure on the lava after extrusion. The subsidiary surfaces of the segregation vesicles do, however, support chemically precipitated linings of manganese oxides and fibrous microcrystalline zeolites.

E. Post-volcanic Deposits

Surficial material of non-volcanic origin is rare or only locally abundant in the area.

Ice-rafted rocks are rare on Bowie Seamount and have so far been found in abundance only among the relatively old, spheroidally weathered basalts of the northeast ridge. The summit terraces appear to be almost devoid of this foreign material, for only one ice-rafted pebble was identified despite the extensive sampling in that area.

In contrast, ice-rafted material on the summit of Hodgkins Seamount seems to be very abundant. Glacial debris constituted fully 50% of the single dredge haul taken from there and ranged from sand-size detritus to boulders 30 cm. across. Copious quantities of ferro-manganese accompanied the glacial debris in the dredge.

The ferro-manganese is found both as concretions, partly blanketing altered basalt boulders (Plate 31a) and as slabs broken from a rubbly substrate (Plate 31b). It therefore probably forms a discontinuous pavement in the area of dredging.

It apparently reached its present maximum thickness of 5cm. before the arrival of the ice-rafted material, for the glacial boulders bear little more than a brown stain or, at most, a thin veneer a fraction of a millimetre thick. It would appear from this that the ferro-manganese is still accumulating but at a very slow rate. Barnes and Dymond (1967) record growth rates of 0.5 - 40 mm./10^6 yr. for oceanic nodules. The results of other authors, who favour slow accretion, are compatible with these figures and the rate of growth of the ferro-manganese crust on Hodgkins Seamount also appears to fall within these limits.

If the formation rate has been constant throughout its growth history, the altered rocks which support a 5 cm. thickness may be well over 1 million years old. Apparently, then, this part of the summit of Hodgkins Seamount is relatively much older than the summit region of Bowie Seamount, which was active at least until the end of the Pleistocene.

PLATE 31 - Ferro-manganese nodules from Hodgkins Seamount (Station 68 - 8)

(a) A large ferro-manganese nodule with a nucleus of weathered basalt.

(b) The under side of a fragment of ferro-manganese pavement showing a weathered, rounded basalt cobble picked up from the substrate.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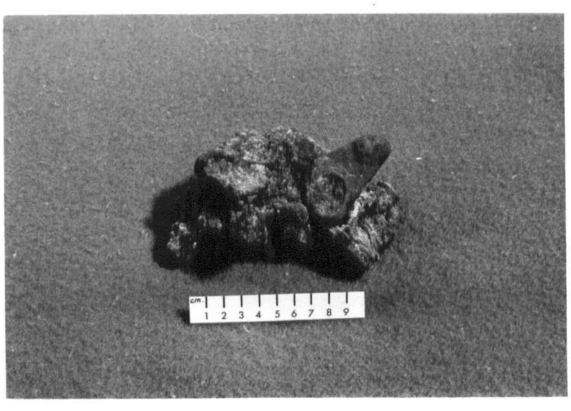
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F. Chemical Weathering

The rocks and tephra found on Bowie Seamount are very fresh and generally show, at most, rusty iron stains but deeper weathering has also been found.

Palagonite, for instance, may be present as a thin skin where chilled margins of sideromelane exist. Palagonite may occur as the initial hydrated phase in the gradual chemical weathering of basaltic glass (Moore, 1966) but it is also thought to be a syngenetic hydration and alteration product, formed when the sideromelane is still very hot (Peacock and Fuller, 1928).

In the area of study, the occurrence of palagonite appears to be restricted to those localities where the rocks are obviously relatively old. For example, palagonite is the dominant constituent of the tuffs on Hodgkins Seamount (Plate 32a), which, according to suggested rates of accumulation of ferro-manganese, may be over 1 million years old. On the other hand, in the region of the summit terraces and peaks of Bowie Seamount, where the rocks are known to be very young, some younger than 18,000 years, palagonitization was usually absent or only incipient.

This pattern also appears elsewhere on Bowie Seamount. For instance, the pillows and pillow breccias of the east

PLATE 32 - Palagonite in the basaltic rocks

(a) Palagonite tuff from Hodgkins Seamount. Grains of palagonite and a fragment of weathered basalt are clearly visible in a cementing matrix of ferro-manganese. (Station 68 - 8)

(b) The palagonitized upper surface of a pillow fragment from Station 68 - 1.


cm.
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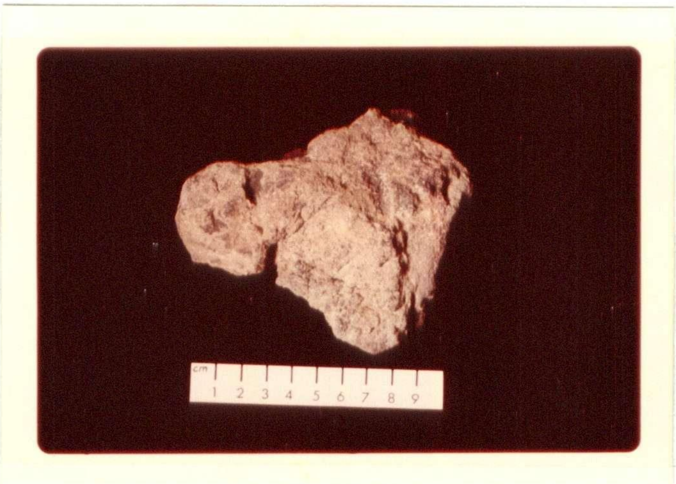
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flank of the summit ridge (Station 68 - 1) are thought to be relatively old, for they are coated with ferro-manganese and they support the manganese-coated remains of long dead siliceous sponges, an apparently exterminated fauna which also appears on the old rocks of Hodgkins Seamount and the northeast ridge. Furthermore, incipient weathering, marked by the precipitation of ferric oxides, has left only a core of fresh basalt at the centre of each pillow fragment. Conversely, a similar deposit on the west flank of the summit ridge (Station 68 - 7) is thought to be relatively young, for it is free of ferro-manganese and virtually free of any organic growth or signs of weathering. Here again, palagonite is apparently present only on the older rocks, for it is present in the sideromelane of the pillow skins and hyaloclastic matrix of the supposedly older rocks at Station 68 - 1 (Plates 30a, 32b and 33a), but absent altogether in the younger rocks of Station 68 - 7 (Plate 6). It is the author's opinion, therefore, that the palagonite, in these rocks is a product of the weathering of chemically unstable sideromelane.

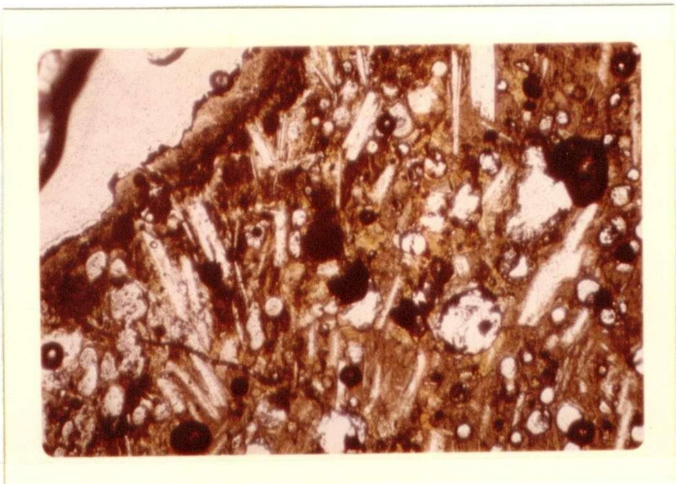
Evidence for weathering other than palagonite and iron staining is rarer. The tuffaceous matrix of the pillow breccia described above contains zeolites, montmorillonite, chlorite and illite, which are most likely the products of weathering of the glass shards. Weathered andesite on the northeast ridge was found by X-ray diffraction to contain a similar mixture of quartz and clay minerals. Many of these samples have weathered deeply and as a result have become quite rounded (Plate 33b) Most of the rocks found so far on Bowie Seamount are fresh or only slightly weathered, with the exception of the weathered rocks of the northeast ridge. The samples recovered from its neighbour, Hodgkins Seamount, are relatively deeply altered. In view of their apparent age, this alteration is probably due to weathering. The fragments of lava, some of which have weathered into rounded shapes, are a rich tan colour, changing gradually to light grey towards the centre. This colour change is not a function of crystallinity, but of degree of alteration. The rocks examined are holocrystalline and the tan zone, generally about 5cm. thick, is seen in thin-section to be simply more thoroughly weathered than the light grey area. An X-ray diffractogram of the tan material revealed, besides primary plagioclase: serpentine, magnesian calcite, hematite, montmorillonite, and minor quartz, calcite, apatite and illite.

The tuffs of Hodgkins Seamount are composed of yellow palagonite, rhombic zeolite crystals and altered lapilli (similar to the alteration above) cemented with varying

PLATE 33 - Two types of alteration observed in the area of study.

(a) Palagonitization. The sideromelane matrix of the rock has been altered to gold and red palagonite near the margin . Note that the palagonite does not affect the mineral grains. (Plane light) (Thin section 68 - 1 - C) (x27)

(b) Weathering. The light margin of the rock has been largely altered to clay. The thin outer skin, which flakes off readily, is composed entirely of clay. Such alteration eventually causes the rock fragment to become rounded as it is seen here. (Station 68 - 5).




cm.
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amounts of hydrated manganese oxides (Plate 32a). Other than the palagonite and zeolites, montmorillonite is the only major weathering product present, though chlorite and illite occur in trace amounts (c.f. pillow breccia matrix from Station 68 - 1 above).

V. SUMMARY AND CONCLUSIONS

1. Bowie Seamount is a combination central and fissure type of volcano, which has formed over an area of complex fracturing of the crust. The assumed northeast fracture set has apparently been the dominant feeder of the system and extrusions along at least 30 miles of its length are responsible for the present elongate shape of the mountain. The main centre of eruption occupies the southwestern half of the ridge where it crosses the northwest trend of Hodgkins and Davidson Seamounts and the majority of the other seamounts on the Pratt - Welker chain. The intersection of the two structures may have provided the magma with a zone of relatively easy access to the surface, resulting in the creation of a larger volcanic pile over that area. However, eruptions were not restricted to the summit and northeast ridges alone. Other lobes of the mountain were probably formed by activity along subordinate

fissures in the crust, and parasitic flank eruptions must also have been common.

2. Two terraces exist near the summit of the seamount, one at a depth of 35 to 55 fathoms, and the other at a depth of 120 to 140 fathoms. They are apparently Pleistocene features, formed by contemporaneous wave erosion and shallow water vulcanism during low sea level stands. The upper terrace was apparently formed less than 18,000 years ago and the lower terrace at an earlier Pleistocene interval. The final phase of volcanic eruptions took place after the formation and submergence of the lower terrace which was probably originally an uninterrupted plateau capping the seamount at sea level. The peaks which rise from the 130 fathom terrace are thought to be the products of this activity. These late volcanic cones were apparently also truncated when they had built up to the new sea level of 13,000 to 18,000 years ago but were later surmounted by further, small tuff cones after they had, in turn, submerged. There is no evidence to indicate further activity after this episode.

A boulder of fresh basalt from the summit furnished a potassium - argon age of 75,000 $\pm$ 100,000 years B.P. The main bulk of Bowie Seamount, according to Michkofsky (1969), should be older than 0.69 million years, having formed primarily during a period of magnetic reversal.

3. The volcanic pile is apparently composed of equal amounts of flow rock and tephra, which form natural slopes of 10° to 20°. The lava flows formed as both pillow flows and as normal massive flows, pillow flows being the most common. Both types have intensely chilled upper surfaces where they came into contact with sea water. Many, if not most, of the flows are broken up into loose rubble, some forming breccias of pillow fragments in a matrix of hyaloclastic vitric tuff. Unsorted deposits of lapilli and larger lava blocks are the dominant clastic deposits on the surface. Tuff, ash and volcanic bombs, common in the region of the summit, probably originated during shallow water and subaerial eruptions when the volcano was active at sea level.

4. The feeders under the seamount open below to what must be a complex system of magma chambers and conduits in the mantle and crust. The various rock types, which range from alkali olivine basalts to andesites, may owe their origins to the tapping of differentiating magma at different levels in these reservoirs. Ultramafic and feldspathic cumulate inclusions suggest that the magma remained quiescent in reservoirs within the crust long

enough for extensive differentiation to take place. Corroded feldspathic and gabbroic xenoliths, which may have been derived from wall-rocks and floor-rocks, bear fresh harrisitic crystal growths. This suggests that the walls and floors of a magma chamber or conduit within the crust were, perhaps, being slowly attacked by the magma while, at the same time, serving as surfaces of nucleation for fresh mineral phases.

5. The process of chemical weathering in the area of study is not very clear, but glass is apparently the most unstable phase and is the first material to be affected. Palagonite was generally absent on the chilled sideromelane surfaces of fresh extrusive material and more common in areas of older rocks. It is, therefore, thought to have formed as the initial phase of weathering of the sideromelane. In those areas where rock fragments have weathered deeply enough, rounded forms are common. In all cases, the main minerals produced by weathering appear to be zeolites and montmorillonite.

6. Lithification of tephra deposits to form tuffs has apparently taken place on the surface. Hydrated iron and manganese oxides commonly form the cements and in shallow water, where biochemical activity is high, calcite is also

a cementing agent. The contents of amygdules and microamygdules in the rocks may be similar to the cementing compounds in the vicinity, though most are composed of "gel-palagonite" and "fibro-palagonite". Ferro-manganese forms a discontinuous pavement of 5 cm. thick concretionary slabs in an area of relatively old, weathered rocks on neighbouring Hodgkins Seamount. The rate of growth of these concretions appears to be slow and of the same order of magnitude as that recorded for similar open ocean occurrences by other authors. The rocks on the summit of Hodgkins Seamount, which are host to the ferro-manganese, may, therefore, be well over one million years old.

7. Ice-rafting is an important agent of sedimentation in the area, especially on the summit of Hodgkins Seamount. The summit of Bowie Seamount is almost free of glacial debris and it is thought that this is due to its shallowness or exposure during stages of the Pleistocene epoch, and to burial of glacial material by more recent volcanic deposits.

VI. REFERENCES

Barnes, S.S., and Dymond, J.R., 1967, Rates of accumulation of ferro-manganese nodules; Nature, V. 213, pp. 1218 - 1219.

Bonatti, E., and Nayudu, Y.R. 1965, The origin of manganese nodules on the ocean floor; Am. J. Sci., V. 263, pp. 17 - 39.

Bouma, A.H., 1962, Sedimentology of some flysch deposits - a graphic approach to facies interpretation; Elsevier, Amsterdam.

Brady, L.F., and Webb, R. W., 1943, Cored bombs from Arizona and California volcanic cones; J. Geol., V. 51, pp. 398 - 410.

Carlisle, D., 1963, Pillow breccias and their aquagene tuffs, Quadra Island, British Columbia; J. Geol., V. 70, pp 48 - 71.

Cox, A., 1969, Geomagnetic reversals; Science, V. 163, pp 237 - 245.

Curray, J.R., 1965, Late Quaternary history of the continental shelves of the United States <u>in</u> The Quaternary of the United States; Princeton University Press, pp. 723 - 735.

Dalrymple, G.B., and Moore, J.G., 1968, Argon-40: Excess in submarine pillow basalts from Kilauea Volcano, Hawaii; Science, V. 161, pp 1132 - 1135.

Engel, A.E.J., and Engel, C.G., 1964, Composition of basalts from the mid-Atlantic Ridge; Science, V. 144, pp. 1330-1333.

——————————, 1964, Igneous rocks of the East Pacific Rise; Science, V. 146, pp. 477 - 485.

Engel, C.G., and Engel, A.E.J., 1963, Basalts dredged from the northeastern Pacific Ocean; Science, V. 140, pp. 1321 - 1324.

---------- , Fischer, R.L., and Engel, A.E.J., 1965, Igneous rocks of the Indian Ocean floor; Science, V. 150, pp. 605 - 610.

---------- , and Engel, A.E.J., 1966, Volcanic rocks dredged southwest of the Hawaiian Islands; U.S. Geol. Surv. Prof. Paper 550-D pp. D104 - D108.

Finch, R.H., 1933, Block Lava; J. Geol., V. 41, pp. 769 - 770.

Fuller, R.E., 1931, The aqueous chilling of basaltic lava on the Columbia River Plateau; Am. J. Sci., 5th series, V. 21, pp. 281 - 300.

Funkhauser, J.G., Barnes, I.L., and Naughton, J.J., 1966, Problems in the dating of volcanic rocks by the potassium-argon method; Bull. Volcanol., V. 29, pp. 709 - 717.

Hills, L.V., and Baadsgaard, H., 1967, Potassium-argon dating of some lower Tertiary strata in British Columbia; Bull. Canadian Petrol. Geol., V. 15, pp. 138 - 149.

Honnorez, J., 1963, Sur L'origine des hyaloclastites; Bull. Volcanol., V. 25, pp. 257 - 263.

Hopkins, D.M., 1967, The Cenozoic History of Beringia, a synthesis <u>in</u> The Bering Land Bridge; Stanford University Press, Stanford, California, pp. 451 - 484.

Hurley, R.J., and Nayudu, Y.R., 1961, Postglacial volcanism in the Gulf of Alaska; Abstracts, 10th Pacific Science Congress, Honolulu, pp. 372 - 373.

Jones, J.G., 1966, Intraglacial volcanoes of southwest Iceland and their significance in the interpretation of the form of the marine basaltic volcanoes; Nature, V. 212, pp. 586 - 588.

Kenney, T.C., 1964, Sea Level movements and the geologic histories of the post-glacial marine soils at Boston, Nicolet, Ottawa and Oslo; Geotechnique, V. 14, pp. 203 -230.

Kittrick, J.A., and Hope, E.W., 1963, A procedure for the particle size separation of soils for X-ray diffraction analysis; Soil Sci., V. 96, pp. 319 - 325.

Kjartansson, G., 1966, Stapakenningin og Surtsey, a comparison of table mountains in Iceland and the volcanic island of Surtsey off the south coast of Iceland, Natturufraedingurinn, V. 36, pp. 1 - 34.

——————, 1967, Volcanic forms at the sea bottom, in Iceland and Mid-Ocean Ridges - "Rit" 38, 209 pp., Societas Scientiarum Islandica, Reykjavik, Iceland.

Macdonald, G.A., 1949, Hawaiian Petrographic province, Bull. Geol. Soc. Am., V. 60, pp. 1541 - 1596.

——————, 1960, Dissimilarity of continental and oceanic rock types; J. Petrol., V. 1, pp. 172 - 177.

——————, 1967, Extrusive basaltic rocks in Basalts; Hess and Poldervaart Ed., Interscience Publishers (John Wiley & Sons), New York-London-Sydney, pp. 1 - 61.

Mathews, W.H., 1947, "Tuyas", flat-topped volcanoes in northern British Columbia; Am. J. Sci., V. 245, pp. 560 - 570.

McBirney, A.R., 1963, Factors governing the nature of submarine volcanism; Bull. Volcanol., V. 26, pp. 455 - 469.

Menard, H.W., 1964, Marine Geology of the Pacific, McGraw - Hill, New York-San Francisco-Toronto-London.

Michkofsky, R.N., 1969, Magnetics of Bowie Seamount; (M.Sc. thesis lodged in University of British Columbia Library.

Moore, J.G., 1966, Rate of palagonitization of submarine basalt adjacent to Hawaii; U.S. Geol. Surv. Prof. Paper 550-D, pp. D163 - D171.

----------, 1967, Base surge in recent volcanic eruptions; Bull. Volcanol., V. 30, pp. 337 - 363.

----------, and Fiske, R.S., 1969, Volcanic substructure inferred from dredge samples and ocean bottom photographs, Hawaii: Bull. Geol. Soc. Am., V. 80, pp. 1191 - 1201.

Muir, I.D., and Tilley, C.E., 1961, Mugearites and their place in alkali igneous rock series; J. Geol., V. 69, pp. 186 - 203.

Nayudu, Y.R., 1962, A new hypothesis for the origin of guyots and seamount terraces; Am. Geophys. Union Monograph, V. 6, pp. 171 - 180.

Peacock, M.A., 1928, The petrology of Iceland. Part 1 - The basic tuffs; Trans. Roy. Soc. Edinburgh, V. 55, pp. 53 - 76.

----------, and Fuller, R.E., 1928, Chlorophaeite, Sideromelane and palagonite from the Columbia River Plateau; Am. Mineralogist, V. 13, pp. 360 - 382.

Pettijohn, F.J., 1957, Sedimentary Rocks; Harper & Row, New York.

Raitt, R.W., 1954, Bikini and nearby atolls; U.S. Geol. Surv. Prof. Paper 200-K, pp. 507 - 527.

Richards, A.F., 1965, Geology of the Islas Revillagigedo, 3. Effects of erosion on Isla San Benedicto 1952 - 61 following the birth of Volcan Barcena; Bull. Volc., V. 28, pp. 381 - 403.

Rittman, A., 1962, Volcanoes and their activity; John Wiley & Sons, New York-London.

St. Amand, P., 1957, Geological and Geophysical synthesis of the tectonics of portions of British Columbia, the Yukon Territory and Alaska; Bull. Geol. Soc. Am., V. 68, pp. 1343 - 1370.

Scrimger, J.A., 1969, Bowie Seamount - preliminary survey for instrument package placement; Defence Research Establishment Pacific Technical Memorandum 69 - 7.

Shepard, F.P., 1963, Submarine Geology; Harper & Row, New York-Evanston-London.

Smith, R.E., 1967, Segregation vesicles in basaltic lava; Am. J. Sci., V. 265, pp. 696 - 713.

Solomon, M., 1969, The nature and possible origin of the pillow lavas and hyaloclastite breccias of King Island, Australia; Quart. J. Geol. Soc. London, V. 124, pp. 153 - 169.

Sutherland Brown, A., 1968, Geology of the Queen Charlotte Islands, British Columbia: British Columbia Department of Mines and Petroleum Resources Bull., V. 54.

Thorarinsson, S., 1964, The submarine eruption off the Vestmann Islands 1963-64, Bull. Volcanol., V. 27, pp. 435 - 445.

————————, 1965, Sitt af hverju um Surtsey-jargosid, some facts about the Surtsey eruption. Natturufraedingurinn, V. 35, pp. 153 - 181.

Wager, L.R., Brown, G.M., and Wadsworth, W.J. 1960, Types of Igneous cumulates; J. Petrol., V. 1, pp 73 - 85.

————————, 1968, Rhythmic and cryptic layering in mafic and ultramafic plutons, in Basalts; Hess and Poldervaart Ed., Intrscience Publishers (John Wiley & Sons), New York-London-Sydney, pp. 573 - 622.

Washington, H.S., 1926, Santorini eruption of 1925: Bull. Geol. Soc. Am., V. 37, pp. 349 - 384.

Wilcox, R.E., 1965, Volcanic ash chronology in The Quaternary of the United States; Princeton University Press, Princeton, New Jersey, pp. 807 - 816.

Yoder, H.S. Jr., and Sahama, T.G., 1957, Olivine X-ray determinative curve; Am. Mineralogist, V. 42, pp. 475 - 491.

Yoder, H.S., and Tilley, C.E., 1962, Origin of basalt magmas: an experimental study of natural and synthetic rock systems; J. Petrol., V. 3, pp. 342 - 532.

Zbyszewski, G., 1960, L'eruption du volcan de Capelinhos, Ille de Faial, Azores, Bull. Volcanol., V. 23, pp. 77 - 100.

APPENDIX A

Equipment used during ship work

EDO Western Sonar - Model 185 with 12 KHz Transducer

Alden Precision Graphic Recorder - Model 419

Gifft Depth Recorder - Transciever

Alpine Geophysical X-band radar transponder - model 427-D

Decca Radar - Model 828

Varian Associates Marine Proton Precession Magnetometer - model V-4937

E.G. & G. International Camera - model 200, and light source - model 210

Ocean Research Equipment Pinger - model 250B

Pettersson grab sampler

Twelve inch pipe dredge

Dietz - Lafond snapper

APPENDIX B

Sample Descriptions from Each Station

Station 67 - 1

Lapilli Tuff - brown; unsorted, subangular to rounded lapilli and ash; weakly cemented (cement of iron oxides and organic calcium carbonate); mantled by the red coralline alga Lithothamnion and siliceous sponges.

Cow-dung Bombs - flat, 2 - 3 cm. thick; bread crust fracture on upper surface; interior more or less hollow.

Inclusion - coarse, crystalline plagioclase, olivine and magnetite.

Station 67 - 2

Volcanic conglomerate - yellowish brown; poorly sorted, well rounded lapilli, frosted crystal grains, abraded shell fragments; strongly cemented surface crust (red ferruginous and black manganiferous cements), weakly cemented below crust; ice-rafted cobble cemented in surface crust.

Pillow fragments - roughly pyramidal; fresh vesicular basalt; quenched surface of sideromelane with no sign of palagonite.

Vitric-crystal tuff - dark brown to reddish brown and yellow; sand size grains; thin-bedded, with graded bed topped by thin laminated bed, (c.f. 67 - 6).

Unconsolidated material - heterogeneous mixture of angular, unsorted cinders, lapilli ash and some shell material (c.f. 67 - 10).

Indeterminate - various angular and clinkery basalt pebbles.

Station 67 - 3

Lapilli tuff - red; unsorted, angular to rounded lapilli and ash; strongly cemented (cement is ferruginous, hence the red colour); encrusted with red coralline algae.

Lapilli tuff - dark brown; unsorted, angular to subrounded lapilli and ash; friable, weakly cemented (cement of organic carbonate).

Inclusion - coarse aggregate of pyroxene crystals.

Indeterminate - various basaltic pebbles 1 - 4 cm. across.

Station 67 - 4

Basalt - flow top; fragments probably spalled from the surface of a lava flow; dark grey, glassy basalt of the same composition as the rocks of 67 - 6; quenched surface of sideromelane with thin palagonite skin; slightly weathered along fractures.

Vitric-crystal tuff - ochre yellow; sand size grains; finely laminated; (c.f. 67 - 6).

Station 67 - 5

Lapilli tuff - black; unsorted lapilli and ash; occurs as a slabby crust, cemented with manganese oxides.

Bombs - range from flattened cow-dung variety to highly deformed, globose forms with involute and ropy surfaces; quenched skin of sideromelane.

Station 67 - 6

Vitric-crystal tuff - dark brown to reddish brown and yellow: sand size grains; thin-bedded, with graded bed topped by fine horizontal laminations; ferruginous cement imparts the variety of colours.

Lapilli tuff - red; thin crust only; unsorted fragments; ferruginous cement.

Pillow fragments - pyramidal shape; bread-crusty, chilled, upper surface of sideromelane without palagonite; plagioclase and hornblende - rich vesicular basalt.

Cow-dung bombs - fresh and black with bread crust upper surface; also weathered yellow varieties with hollow centres.

Inclusions - common; feldspathic and gabbroic; coarsely crystalline.

Unconsolidated material - heterogeneous, unsorted mixture of ash, lapilli and cinders of undetermined affinities.

Indeterminate - unconsolidated material above; nondescript boulders and cobbles of composition similar to the pillow fragments.

Station 67 - 7

Unconsolidated material - well rounded, sorted lapilli with frosted crystal grains (c.f. 67 - 2).

Andesitic rock - angular, blocky, irregularly jointed boulders of non-vesicular rock slightly weathered along fractures.

Station 67 - 8

- unsuccessful; hard bottom.

Station 67 - 9

Unconsolidated material - small amount of crystal and vitric sand; insufficient sample for use.

Station 67 - 10

Unconsolidated material - unsorted, subangular to rounded, fresh, black lapilli and ash; some fragmented but unworn shell material.

Basalt - boulder; fresh, dark grey, vesicular basalt with prominent olivine and augite phenocrysts.

Station 67 - 11

Unconsolidated material - brown-stained cinders, lapilli, and ash; insufficient sample for use.

Station 67 - 12

Unconsolidated material - poorly sorted, subrounded to rounded, brown lapilli and ash with abundant yellow-stained shell material; staining of lapilli and shell material is due to iron oxides.

Station 67 - 13

- unsuccessful

Station 67 - 14

Unconsolidated material - poorly sorted, subrounded to rounded, fresh, black lapilli and ash with abundant shell material.

Basalt - boulder; fresh, dark grey, vesicular, olivine basalt, encrusted with calcareous organisms.

Station 67 - 15

Unconsolidated material - brown-stained cinders lapilli and ash; quantity too small to work with.

Station 68 - 1

Bombs - Fusiform bombs, some undamaged, others with the outer surface spalled off; also bombs similar to 67 - 5; thin palagonite skin sometimes present on the sideromelane quenched surface.

Pillow fragments - pyramidal fragments with radii of 5 to 30 cm.; also crudely pillowed forms; rock type is a dark grey, finely vesicular, olivine basalt; sideromelane outer surface with well developed palagonite skin; rocks generally weathered along fractures.

Pillow breccia - pillow fragments, as above, and smaller pebble-size pillow crust fragments, set in a matrix of vitric tuff.

Flow top - flat, flow surface, apparently from non-pillowed flow; bread crust surface of sideromelane with palagonite skin; rock is weathered as above.

Station 68 - 4

Unconsolidated material - ponded sediment; 50 - 50 mixture of small lapilli and Globigerina ooze; sample too samll to use.

Station 68 - 5

Andesite - weathered cobbles of finely vesicular, light grey andesite, each enveloped in a sheath of clay; many fragments are rounded due to deep weathering.

Ice-rafted detritus - smooth, round cobbles of granodiorite.

Station 68 - 6

- unsuccessful; few chips of weathered rock and a small amount of calcareous clay; insufficient material for use.

Station 68 - 7

Pillow fragments - large fragments of pyramidal shape, also pebble-size fragments of pillow crusts; fresh, dark grey, highly vesicular basalt with sideromelane chilled surface; palagonite is absent.

Station 68 - 8 (Summit of Hodgkins Seamount)

Pillow fragments - pale grey to tan; deeply weathered, vesicular basalt.

Palagonite tuff - yellow; sand-size palagonite grains and a few weathered lapilli cemented with varying amounts of ferro-manganese; rhombic zeolite crystals are common.

Concretionary ferro-manganese - as nodules with weathered basalt boulder nucleii, and as slabs; composed of laminated and botryoidal, dark brown ferro-manganese oxides and hydrated oxides; maximum thickness 5 cm.

Ice-rafted detritus - size range from sand-size material to boulders 30 cm. in diameter; wide range of compositions: graded lithic and arkosic arenites, phyllite, amphibolitic greenstone, tremolite - garnet schist, tuff, porphyritic dacite, granite, diorite and magnetite-rich gabbro. None of these rocks has a distinctive enough lithology to trace to its origin.

Indeterminate - basalt pebbles of irregular shape; deeply weathered to a tan colour; many have weathered into rounded shapes.

Station 68 - 9

Basalt - boulder; fresh, dark grey, vesicular, olivine basalt.