Pillowed Lavas, I: Intrusive Layered Lava Pods and Pillowed Lavas Unalaska Island, Alaska

and

Pillowed Lavas, II: A Review of Selected Recent Literature

By GEORGE L. SNYDER *and* GEORGE D. FRASER

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

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PILLOWED LAVAS, I: INTRUSIVE LAYERED LAVA PODS AND PILLOWED LAVAS, UNALASKA ISLAND, ALASKA

By George L. Snyder and George D. Fraser

ABSTRACT

Extensive sills of andesite and dacite intrude a thick sequence of argillites of Miocene age in the eastern Aleutians. The sills contain large volumes of pillowed lavas that grade into massive lava, layered lava, and breccia. Pillows range in diameter from 1 to 40 feet but are generally 5 to 10 feet; peperite, a mixed intrusive breccia of sedimentary and primary igneous debris, commonly fills pillow interstices and locally constitutes the entire thickness of a sill. Concentrically layered lava forms roughly equidimensional pods, as much as 600 feet thick, and extensive tubular and tabular sills; these layered lava pods are larger than any reported previously. Concentric layers in the lava pods are 1 foot or more thick; alternate layers differ in appearance and composition and generally weather differentially. Most of the rocks are completely albitized, but some glass is unaltered.

The sills and all the second-order structures were formed by magma intruding semiconsolidated muds. A modified "emulsion" theory best explains these and probably other large tracts of pillowed lava common in parts of the world. Tough, elastic chilled pillow skins maintain the droplike form of magma in contact with water or mud and serve the same function as fluid surface tension in a normal emulsion. Pillows were formed as unstable apophyses or immiscible droplike masses during turbulent digital advance of magma fronts and engulfment of mud and water in magma. The concentric layers of the lava pods probably result from laminar intrusive flow in tubes and tongues which channeled magma from a central source to the pillow-forming front. Compositional differences in successive layers of the layered lava pods, on the basis of evidence from analyzed samples in one lava pod, may be due to different amounts of included mud or to postsolidification differential alteration.

INTRODUCTION AND ACKNOWLEDGMENTS

Extensive andesite and dacite sills that are abundant on Unalaska Island (fig. 1) in the Aleutian Islands consist of large units of pillowed lava and layered lava pods—larger than previously described in the geologic literature—that grade into thick units of layered and nonlayered igneous rock. The pillowed lavas and lava pods were examined during reconnaissance geologic mapping of Unalaska Island in 1953 and 1954 (Drewes and others, 1961). Most of these structures, which are well exposed in large sea cliffs from Surveyor Bay to Cape Prominence along the southwest coast, were examined from the Motorship *Eider*, then of the U.S. Geological Survey; other field observations were made by landing parties. The pillowed lavas and lava pods are described in detail and their origin is explained.

This paper has benefited by many conversations with and suggestions from U.S. Geological Survey colleagues in the Aleutian Islands, Alaska, in Colorado, and, in Hawaii. We are particularly indebted to Harald Drewes and Richard Goldsmith for many critical suggestions, including those about the reorganization of parts of this manuscript. Besides Drewes the following people helped with the original field investigations: V. E. Ames, H. F. Barnett, Jr., W. B. Bryan, C. E. Chapin, E. H. Meitzner, R. P. Platt, H. B. Smith, and L. D. Taylor. Carl Vevelstad and Charles Best furnished logistic support during the Aleutian fieldwork.

GEOLOGIC SETTING

The rocks of Unalaska Island comprise an older group of sedimentary and shallow intrusive rocks, a group of plutonic rocks intermediate in age, and a younger group of volcanic rocks. The older igneous rocks, with which this paper is chiefly concerned, were emplaced in a submarine environment and were subsequently altered, whereas the younger volcanic rocks were extruded subaerially and are fresh. The rocks of Unalaska are typical of those of most other Aleutian Islands, although some islands do not contain plutonic rocks.

The oldest formation underlies most of the island; the texture of the sedimentary rocks and the structure of the igneous rocks differ from the northern to the southern parts of the island. Coarse conglomerate and tuff breccia are abundant in the northern part of the island and argillite and tuffaceous argillite are rela-

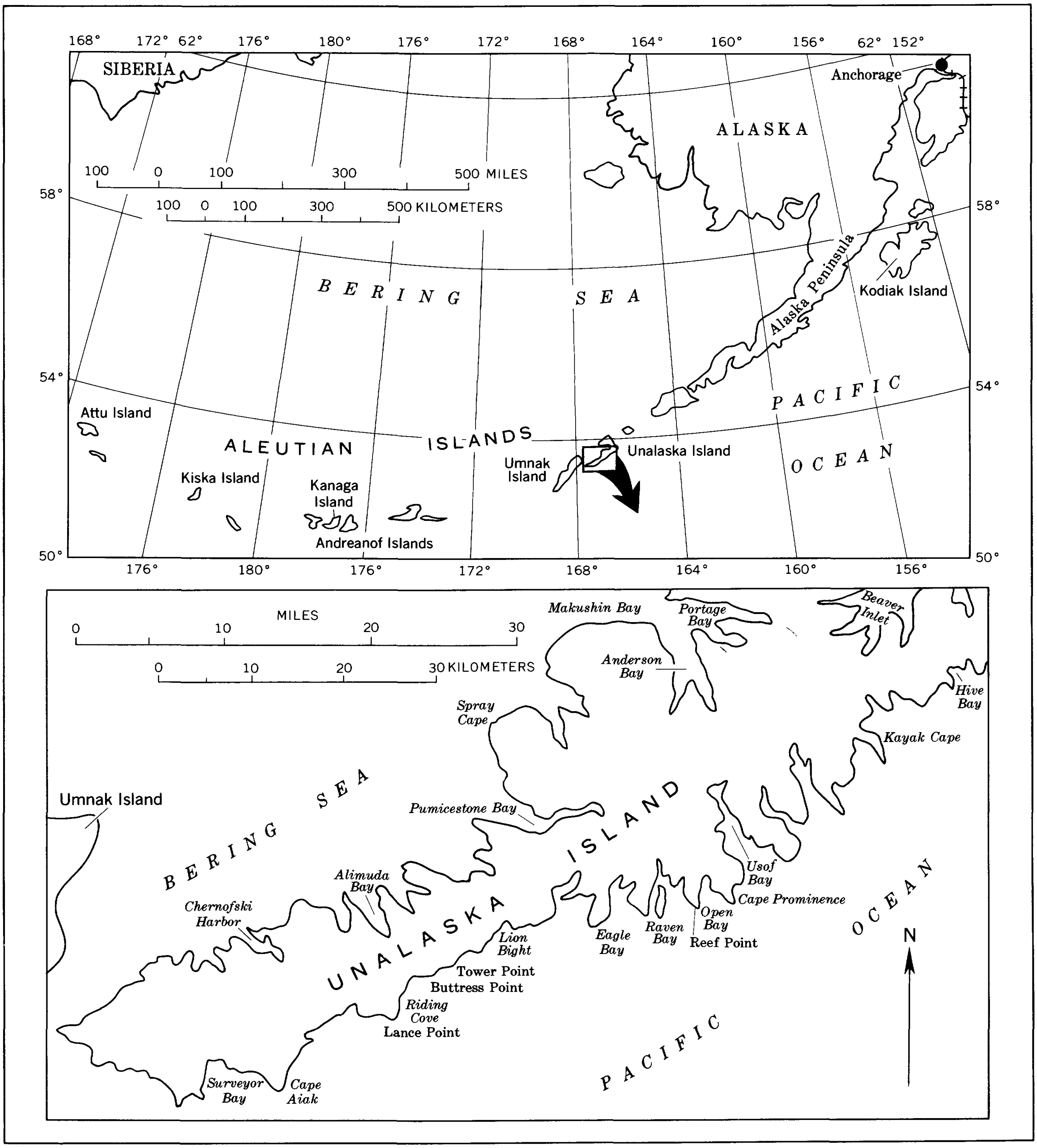

FIGURE 1.—Index map showing location of Unalaska Island and geographic localities mentioned in the text.

tively scarce, whereas argillite is abundant in the southern part of the island and rocks coarser than siltstone are relatively scarce. Sedimentary structural features attributable to shallow-water deposition are absent in the southern argillites. Sheets of pillowed lava and lava pods of andesitic and dacitic composition are most abundant in the clastic rocks in the southern part of the island. Some of the sedimentary rocks of the coarse northern facies contain lower Miocene fossils, but no fossils were found in the southern facies and these rocks may be older.

Granodiorite batholiths intrude the older rocks in the center of the island. Wide halos of mild alteration, dominantly albitization, envelop the batholiths, but one area at each end of the island is relatively unaltered.

Andesite and basalt of Quaternary age overlie the older rocks and the plutons in the northern part of the island. The young rocks form thick lenses of subaerial flows and pyroclastic cones along the line of young volcanoes that extend for hundreds of miles in the Aleutian Islands and the adjacent Alaska Peninsula. Surficial deposits, composed of till, ice, fluvial and beach deposits, and a blanket of ash and peat, cover much of these and older rocks.

DESCRIPTION OF PILLOWED LAVA AND LAVA PODS

The igneous rocks in the old sedimentary sequence include pillowed lavas, peperite sheets, large pods, and extensive sheets of structureless, layered, or columnar-jointed lava. These rocks are best exposed in large sea cliffs and wave-cut benches, particularly between Surveyor Bay and Cape Prominence on the south coast. The terms "lava," "pillowed lava," and "pod lava" will be used here for rocks intruded into mud, as well as for possible extrusive rocks, because the behavior of the magma during emplacement was lavalike even though it was confined by mud and water.

PILLOWED LAVA

PILLOWS

Pillows are separate or connected ellipsoidal masses of aphanitic igneous rock commonly less than 10 feet in diameter and generally occurring in thick sheets. The term "pillow" carries no genetic connotation but is "simply a morphologic term for ellipsoidal structure" (Stark, 1939, p. 207). The pillows on Unalaska Island generally are larger and more silicic than those from other areas. On Unalaska the pillows congealed in marine muds (Snyder and Fraser, 1958).

The Unalaskan pillows are distributed regularly or sporadically throughout sheets of lava as much as 600 feet thick, and they grade upward, downward, or laterally into structureless nonglobular lava (fig. 19). These relations are consistent with those previously reported by many other authors who note that pillows occur at the top, middle, bottom, or at several zones within flows, or that they constitute entire flows or grade into or are intimately interlayered with structureless lava.

The pillows are mostly loaflike or irregularly subelliptical to amoeboid in shape; only a few have V-shaped bottoms. The matrix between Unalaskan pillows is generally abundant, which causes their commonly irregular shapes and the scarcity of mutually impinging contacts. Most pillows are wider than they are high, but the proportions of others are reversed (figs. 13, 19). Some pillows have projections of lava extending into the surrounding matrix or projecting toward other pillows; and some adjacent pillows are connected by narrow necks of lava (figs. 10, 13, 19). Some necks are so narrow that appreciable relief is required on any exposure to see how the pillows are joined. The necks are smoothly continuous with the pillows, and in some exposures (fig. 13) masses of pillowed lava grade into structureless lava. In one outcrop on the east side of Raven Bay, delicate dendritic andesite(?) spines from a pillow layer penetrate a few inches into overlying argillite. At Open Bay, septa of overlying argillite appear to be dragged into a pillow layer.

Most Unalaskan pillows are 5–10 feet wide, but some are as small as 1 foot and others are at least 40 feet wide. Pillows elsewhere in the world are generally only 1–4 feet in diameter (see, for example, Burling, 1916, p. 235; Johannsen, 1939, p. 228; Cotton, 1952, p. 290; Henderson, 1953, p. 25), and Cotton (1952, p. 290) cites a maximum length of 12 feet. The largest pillows previously described are from New Zealand and, in separate localities, are 30 feet in diameter (Uttley, 1918, p. 113) and 80 feet long (Bartrum, 1930, p. 447–455). The distance separating Unalaskan pillows ranges from a few inches to tens of feet.

Unalaskan pillows do not commonly contain internal structural features, but there are notable exceptions. Radial columnar joints are formed in the pillows on the east shore of Alimuda Bay. Rinds, cores, or zones of glass occur in otherwise lithoidal pillows in the Chernofski Harbor area. Some pillows at the base of the sea cliff on the east side of Reef Point (see Drewes and others, 1961, fig. 84) and in many other areas have resistant purplish gray rims of albitized andesite surrounding cores of nonresistant greenish gray albitized andesite (fig. 2, table 1). The chemical composition of the rims and the cores is almost identical, except that the ferric-ferrous oxide ratio is greater in the rims. The different resistance to weathering of the rims and the cores is apparently controlled by slightly different mineralogy and texture. The rims probably were chilled glassy skins before alteration. Vesicles are scarce; where present they generally have a random distribution and seldom are distributed in zones.

Unalaskan pillowed lavas and related rocks range in composition from basalt to dacite but are generally in the andesite range. This suite probably is more silicic than most other pillow assemblages. Chemical anal-

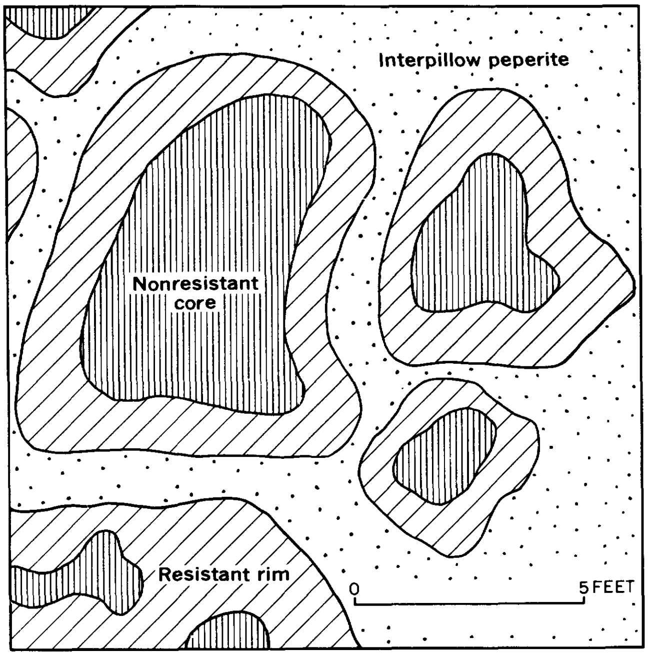

FIGURE 2.—Sketch of altered andesitic pillowed lava, Reef Point, Unalaska Island. Chemical analyses and petrographic descriptions of core and rim are given in table 1.

TABLE 1.—*Chemical analyses and petrographic descriptions of altered andesitic pillow lava, Reef Point, Unalaska Island*

[Analysts: P. L. D. Elmore, S. D. Botts, M. D. Mack and J. Goode. Rapid analyses by U.S. Geological Survey (Shapiro and Brannock, 1956); weight percentages are given to 2 or 3 significant figures, and the totals are omitted]

	1	2		1	2
SiO_2	61.2	62.2	K_2O	1.8	1.6
Al_2O_3	17.9	17.4	TiO_2	.80	.85
Fe_2O_3	3.2	1.3	P_2O_5	.30	.33
FeO	2.6	3.2	MnO	.21	.12
MgO	1.2	1.6	H_2O	1.4	2
CaO	1.7	1.4	CO_2	<.05	<.05
Na_2O	8	7.8			

1. New analysis of albitized andesite from purplish-gray resistant pillow rims (see figure 2) at base of active sea cliff on east side of Reef Point, Unalaska Island; collected within 2 ft of specimen 2. Texture: amygdular, porphyritic, felty. Phenocrysts: euhedral plagioclase, 7 percent; anhedral subspherical titanaugite(?) with striking pleochroism from grass green or bluish green to medium pink or light violet, 2.5 percent; magnetite, 0.4 percent. Groundmass: very fine grained intermeshed plagioclase, about 60 percent; apatite, 0.1 percent; cryptocrystalline mush, probably largely glass before alteration, about 30 percent. All plagioclase completely altered to albite; titanaugite(?) phenocrysts partially to completely altered chiefly to brassy yellow epidote but also to a yellowish-brown chlorite and albite (only in a thin selvage where the phenocryst is in contact with the matrix). Some completely altered subspherical pyroxenes resemble an albite-epidote-chlorite amygdule. All plagioclase and the glassy or cryptocrystalline groundmass is also intensely altered to kaolin and limonite, which gives the rock its dull purplish tint. Quartz (0.3 percent) fills vesicles.
2. New analysis of albitized andesite from greenish-gray nonresistant pillow cores (see figure 2) at base of active sea cliff on east side of Reef Point, Unalaska Island; collected within 2 ft of specimen 1. Texture: amygdular, porphyritic, spherulitic. Phenocrysts: euhedral plagioclase, 4 percent; titanaugite(?), 1.5 percent; magnetite, 0.2 percent. Groundmass: plagioclase, mostly spherulitic, some in irregular lathes, about 70 percent; apatite, 0.5 percent; microcrystalline aggregate of limonite-stained quartz(?) and penninite (which gives rock greenish tint), about 20 percent. All plagioclase completely altered to albite; all titanaugite(?) completely replaced by a complex intergrowth of the following minerals: quartz; pink radiating aggregates of kaolin(?); light-green chlorite "a," with abnormal interference colors; olive-green chlorite "b," with first-order interference colors; deep-green chlorite "c," nearly opaque; and leucoxene. Chlorite "c" is intimately mixed with the leucoxene and is everywhere surrounded by the kaolin(?); chlorite "a" is associated with chlorite "b." An intense kaolin alteration of all original plagioclase is responsible for the earthy appearance of the rock. Quartz (2 percent) fills vesicles. Several stylolitic seams truncate plagioclase phenocrysts, and one epidote vein cuts the rock.

yses and petrographic descriptions of albitized Unalaskan andesites are presented in table 1, and chemical analyses and petrographic descriptions of fresh, albitized, and contaminated(?) and albitized dacites are presented in table 2.

MATRIX

The interpillow matrix is an important part of all pillowed lavas. On Unalaska, pillows are separated from each other by peperite, fragmental igneous rock, argillite, or crustified chalcedony and quartz. Peperite (a mixture of sedimentary and igneous rocks) is the most common interpillow matrix, more abundant than purely igneous, sedimentary, or secondary infillings. Peperite is widespread in pillowed lava layers hundreds of feet thick. Structureless or layered lava in many sills or pods is overlain by a layer of pillows and peperite (figs. 4, 6, 13, 15).

Peperite is a mottled light-gray to pale-green breccia of mixed sedimentary and primary igneous debris. The breccia fragments, composing 30 to 70 percent of the rock, consist of predominant albitized felsite and green or gray argillite. The finely granular matrix is much altered and is probably a mixture of comminuted lava and original mud. Unalaskan peperites generally have a large sedimentary component, but they grade into wholly igneous breccias. Fragments of argillite are commonly plastically molded around pillows, and small tabular chunks retain varvelike bedding which is truncated at the edges of some fragments. Most Unalaskan peperites have been thoroughly chloritized and albitized, but relict structures and textures remain. The Unalaskan peperites locally resemble mottled green to white tuffs, but true tuff fragments lack the characteristic bedding of the marine muds that many peperite fragments contain. Coarse peperite is commonly gneissoid at intrusive contacts and is flow rather than pyroclastic breccia. Peperites, described in the literature from California, Montana, and Europe, have been universally ascribed to intrusion of magmas into incoherent, poorly consolidated or moist sediments.

Unalaskan peperite occurs mostly between pillows and only rarely as small sills and irregular masses not associated with pillows. The interpillow peperite, which grades into the selvage of igneous rock at the margin of each pillow, forms a very irregular network, as thin as 1 inch. Commonly the peperite is weaker than the pillows and weathers into pockets or hollows in a wave-cut bench or sea cliff; it is therefore difficult to sample. Tabular peperite bodies ranging in thickness from a few inches to several feet occur as concordant lenses and layers without pillows in a thick sequence of contemporaneously deformed laminated argillite and massive sills near Hive Bay. The argillite in these peperites bodies occurs as distinctly alined laminated chips or tabular fragments, some of which are bent plastically. The altered groundmass contains feldspar crystals. Several large masses of altered easily eroded peperite occur within the pillow-rich rocks on southwestern Unalaska. Smedes (1956, p. 1783) describes similar peperites from sills in Montana.

A sample of typical peperite from between the albitized andesite pillows, the analyses of which are given in table 1, is green to very pale green and contains ill-defined fragments of finely layered rock and of unlayered rock. Alternate fine layers are composed of chlorite and of fine- or coarse-grained albite plus quartz. The long dimensions of most crystals in these layers are oriented perpendicular to the layering. The layered fragments are probably altered argillite. The unlayered fragments consist of abundant albite spherules and a few crystals of quartz set in a chlorite matrix. Irregular masses of calcite replace parts of the unlayered fragments, especially the albite spherules. The unlayered fragments are probably altered andesite. Relict crystals of andesine (now largely albite) and unaltered crystals of magnetite and sphene are dispersed with the rock fragments. The rock fragments and crystals are all set in a very fine grained matrix of albite, chlorite, calcite, and quartz. This matrix may have been mud derived from both igneous and sedimentary sources, but its origin is obscured by pervasive alteration. Many albite and chlorite veins cut both matrix and fragments. Unaltered peperites have not been found on Unalaska.

Igneous breccia, clastic sediment, or vein quartz also separate pillows. A granular selvage of igneous rock separates some pillows that are close together. Pillowed lava also grades into pillow breccia by successive fragmentation of most of the pillows and, locally, intermediate stages of fragmentation may be observed (Drewes and others, 1961, fig. 85). Igneous or pillow breccias are commonly associated with pillowed lavas (for example, Fuller, 1931, p. 292; Hoffman, 1933, p. 194; Noe-Nygaard, 1940, pls. 3 and 4; Henderson, 1953, fig. 2, p. 27, 29, 31; Satterly, 1941, p. 28; 1948, p. 7; 1952, p. 13; 1954, p. 12; Carlisle and Zeck, 1960, p. 2053). Unbrecciated pillows occur locally in a matrix of contorted largely sedimentary rocks (fig. 19). Very small pillows are completely surrounded by siliceous argillite in a small area of the sea cliff on the east side of Buttress Point (fig. 10). In the Chernofski Harbor area large quantities of green jasperoid sediments are included among the pillows. Rarely argillite is folded into the centers of Unalaskan pillows. Locally, as along the coast west of Chernofski Harbor, secondary quartz and chalcedony are prominent as crusts between pillows.

The interpillow matrix must be considered in terms of the type of material that existed in the region at the time of pillow and pod formation. A thick section of stratified mud, now lithified to argillite, was invaded by magma. Parts of the argillite are volcanic derived, but the pyroclastic or epiclastic episode preceded pillow formation; and the source for the mud (on the basis of its texture, fine lamination, and continuous even stratification) was remote from the area of pillowed lava. In other geologic environments palagonitic ash has been generated locally by an explosive or decrepitative process at the time of pillow formation (Fuller, 1931; Waters, 1960). Some of the granular interpillow matrix on Unalaska may have a decrepitative origin, but deformed chunks of laminated argillite between pillows could not have been generated in this way. There is no direct evidence for explosion, or frothing, at the time of formation of these pillows. Contemporaneous tuff deposits, if they exist at all, are minor and incidental.

LAVA PODS

Lava pods are equant, tubular, or tabular bodies of concentrically layered igneous rock, which range in minimum dimensions from tens to many hundreds of feet and average several hundred feet in diameter. They form a continuous series ranging in shape from tabular sills (fig. 7) to isolated laccolithic intrusions (fig. 3), but, unlike some sills and laccoliths, lava pods are generally intimately associated with, or surrounded by, pillowed lavas (figs. 4, 17). The size of most lava pods is many times the average size of most pillows, but the smallest pods are about the same size as the largest pillows. Large pillows on Unalaska do not contain the repeated concentric layers that characterize lava pods. Many features are common to all lava pods and are described collectively in the following section. Local features, found in a few areas, are described separately.

GENERAL FEATURES

Lava pods on Unalaska are basalt, andesite, or dacite with a lithoidal and porphyritic texture and a dull purplish or greenish color. They appear as connected or disconnected bodies in thick sheets of pillowed lava and peperite. A sheet containing lava pods and pillows may grade laterally into a very large lava pod or a uniform columnar-jointed sill (for example, figs. 4, 17). Many lava pods are partly or completely columnar jointed; and jointing, where present, is commonly more prominent than compositional layers, which are about perpendicular to the joints in many places.

Lava pods are commonly several hundred feet in diameter. The largest lava pods are about 1,000 feet wide and 600 feet high (fig. 4 and Drewes and others,

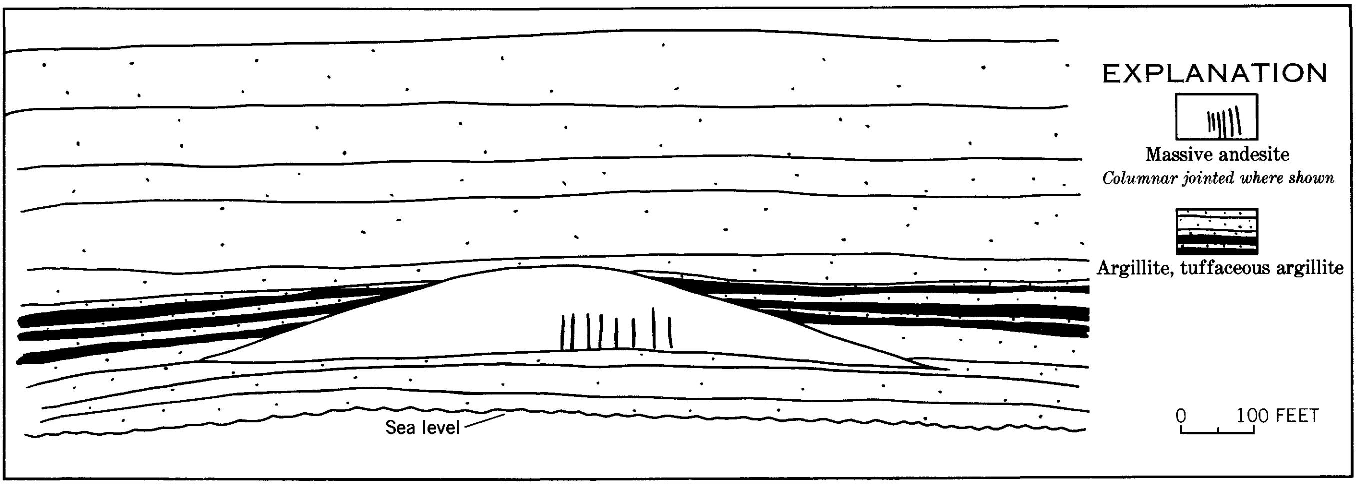

FIGURE 3.—Section of laccolith intruding rocks exposed in sea cliff south-southeast of Spray Cape, Unalaska. Drawn from a photograph.

1961, p. 598). Lateral dimensions generally exceed the vertical (an exception is shown in fig. 18). Many different shapes are seen in cross section (figs. 4, 7, 8, 14, 15, 16, 17, 18; Drewes and others, 1961, fig. 86).

The contact of a lava pod with the surrounding pillowed lava or massive lava may be sharp and curviplanar or gradational and irregular; the contact of a lava pod with surrounding argillite is always intrusive. Locally, the outermost layer of a lava pod may interfinger with pillows similar to it in composition and texture (fig. 19).

Differentially weathered concentric layers are a striking and characteristic feature of all observed lava pods and of some sills. Layered tabular lava pods or tubular lava pods in long section form a continuous series with massive sills. Intermediate stages in internal layering are represented by sills whose layers die out laterally or downward. Layers in sills and tabular pods parallel upper and lower contacts even where they bend around a blunt end (fig. 7). Alternate reddish and greenish layers weather differentially so that the bedrock exposures on many wave-cut benches resemble a freshly plowed field (fig. 8). The layers range in thickness from several inches to several feet. Reddish-gray resistant layers commonly are thicker than greenish-gray nonresistant layers, though locally they are about the same size. Interstitial quartz in the resistant layers and interstitial carbonate in the weak layers of a lava pod at Buttress Point (table 2) may explain the differential erosion in that area.

Chemical analyses of the resistant and nonresistant layers of albitized dacite in the Buttress Point lava pod are compared in table 2 with an analysis of fresh pillow glass collected from a small area of unaltered lava in the same igneous sheet just off the east edge of the area shown in figure 7; a closeup view of the layered lava at this locality is shown in figure 12. Attention is directed to columns 6, 7, and 8 of table 2 in which the recalculated water-free analyses are compared. The albitized resistant layer of rock is very similar to the fresh pillow glass except for a slight difference in Al_2O_3 content and a reversal in the amounts of CaO and Na_2O. Albitization during batholithic intrusion, possibly aided by connate waters, is probably responsible for this difference, according to Drewes and others (1961), and is suggested by analyses of other fresh and altered rocks given in their table 1. The chemical composition of the nonresistant layer differs markedly from that of the resistant layer and from that of the fresh glass. SiO_2 is appreciably lower in the nonresistant layer; Al_2O_3 is slightly higher, and iron, magnesia, and potash are much higher; CaO and CO_2 show a slight parallel rise over these constituents in the resistant layer, reflecting the presence of a small amount of calcite in the nonresistant layer. The origin of these differences in composition and the process of formation of the layers in the lava pods will be discussed in a later section.

No reports of lava pods exactly like those described here were found in a partial review of the literature, though similar features are reported from other areas.

The exposures on Unalaska are unusually large, and possibly lava pods like these will be found in equally good exposures of pillowed lavas in other parts of the world. The nearest equivalents in the Aleutians occur in basaltic lava at Casco Point, Attu Island, Alaska

TABLE 2.—*Chemical analyses and petrographic descriptions of altered dacitic lava pod layers and associated unaltered pillow lava, Buttress Point, Unalaska Island*

[New analyses in columns 3 and 5 by P. L. D. Elmore, S. D. Botts, M. D. Mack, and J. Goode. Elmore and H. Thomas have made duplicate determinations of FeO and K_2O in the specimens represented in columns 2 and 3. The results are: 0.94 FeO and 2.2 K_2O for column 2, and 2.4 FeO and 0.83 K_2O for column 3. These results have been averaged in column 4. New analyses are rapid analyses by the U.S. Geological Survey (Shapiro and Brannock, 1956); weight percentages are given to 2 or 3 significant figures, and the totals are omitted]

	1	2	3	4	5	6	7	8
SiO_2	62.06	71.2	70.2	70.7	54.9	68.2	70.8	56.7
Al_2O_3	14.39	13.7	13.9	13.8	17	15.8	13.8	17.6
Fe_2O_3	1.71	2.5	2.3	2.4	3.8	1.9	2.4	3.9
FeO	1.80	.79	2.3	1.6	2.9	2	1.6	3
MgO	1.06	.82	.59	.7	3.2	1.2	.7	3.3
CaO	4.08	1.1	1	1.1	2.6	4.5	1.1	2.7
Na_2O	3.83	6.2	7.3	6.8	4.2	4.2	6.8	4.3
K_2O	1.09	2.2	.82	1.5	5.8	1.2	1.5	6
TiO_2	.66	.68	.70	.7	.87	.8	.7	.9
P_2O_5	.15	.28	.25	.3	.33	.2	.3	.3
MnO	.16	.17	.17	.2	.19	.2	.2	.2
H_2O	8.38	.77	1	.9	3.5	-------	-------	-------
CO_2	.01	.05	.08	.1	1	0	.1	1

1. Light dacite (Rittmann, 1952) vitrophyre from amygdular pillow lava along coast east of Buttress Point, Unalaska Island. Original analysis (Drewes and others, 1961, table 1, anal. 20) includes 0.07 percent BaO, 0.03 percent Cl, 0.04 percent F, and 0.04 percent S. Black glassy specimen was crushed to granule and coarse sand size and handpicked free of white amygdules before analysis. Texture: porphyritic, hypocrystalline, trachytic. Phenocrysts: slightly progressively zoned; corroded or perfectly euhedral plagioclase (An 37) with inclusions of apatite, 4 percent; euhedral colorless clinopyroxene, 1 percent; slightly pleochroic hypersthene, trace; magnetite, trace. Groundmass: brown glass containing scattered green blobs (chlorite?), about 75 percent; skeletal crystals of andesine in rectangular tablets 0.1 by 0.02 mm with acicular projections 0.03 mm long extending parallel to the crystals from the short ends, especially the corners of the lathes, about 15 percent; clinopyroxene(?) needles as large as 0.3 by 0.01 mm but generally about 0.03 by 0.001 mm, about 5 percent; the smaller clinopyroxene(?) needles are attached in a bristling array to the margins of the larger skeletal crystals and phenocrysts. Chalcedony and (or) zeolite amygdules and veinlets compose 4 percent of the rock (not included with other percentage estimates).
2. Albitized dacite from resistant lava pod layer at base of active sea cliff one-half mile west of Buttress Point, Unalaska Island. For exact location see figure 12. Original analysis (Drewes and others, 1961, table 1, anal. 24) includes 0.02 percent S. Texture: porphyritic, felty. Phenocrysts: euhedral plagioclase, 4 percent; colorless to light-green clinopyroxene, 1.5 percent; magnetite, 0.5 percent. Groundmass: zoned quartz, 14 percent; plagioclase laths with attenuated acicular ends like in specimen 1, about 40 percent; apatite, 0.1 percent; cryptocrystalline mush probably largely glass before alteration, about 40 percent. All skeletal groundmass crystals and all but a few ragged andesine patches (0.1 percent) in the plagioclase phenocrysts are albite; sericite in plagioclase phenocrysts, 0.1 percent; clinopyroxene generally very fresh. An intense kaolin and limonite alteration affects all plagioclase and the cryptocrystalline or glassy groundmass and gives the dull purplish tint to the rock. Olive-green chlorite or serpentine (0.2 percent) fills cavities.
3. New duplicate analysis of specimen 2 performed on a different but adjoining hand specimen.
4. Average of specimens 2 and 3.
5. New analysis of albitized contaminated(?) dacite from nonresistant lava pod layer at base of active sea cliff one-half mile west of Buttress Point, Unalaska Island; collected within 1 ft of specimens 2 and 3. For exact location see figure 14. Texture: porphyritic, felty. Phenocrysts: euhedral plagioclase, 3 percent; colorless clinopyroxene, 0.5 percent; magnetite, 1 percent. Groundmass: intergrown aggregate of small plagioclase with irregular overgrowths on sides and on ends of crystals, about 60 percent; amoeboid areas of clear orthoclase, 4 percent; calcite, 1.5 percent; apatite, 0.1 percent; remainder (about 28.5 percent) is interstitial amoeboid areas of green opaque chlorite(?), which gives the rock its dull light-green color, and very cloudy alkali feldspar(?). The chlorite(?) may represent included mud or may be devitrified glass. Except for a few ragged andesine patches (0.2 percent) in the plagioclase phenocrysts, all the plagioclase is altered to albite or kaolin. Late clear, olive-green chlorite or serpentine (0.2 percent) fills voids.
6. Column 1 (pillow glass) recalculated to 100 percent omitting H_2O.
7. Column 4 (resistant lava pod layer) recalculated to 100 percent omitting H_2O.
8. Column 5 (nonresistant lava pod layer) recalculated to 100 percent omitting H_2O.

(Olcott Gates, H. A. Powers, J. P. Schafer, and R. E. Wilcox, written communication). A map of this wave-cut bench that is more than 1,300 feet long shows an intricately faulted sequence of pillowed basalt, sandstones, siltstones, and tuffs. Here pillowed basalts contain faintly layered columnar-jointed pods of uniform basalt 150 feet long; sheets of massive lava 25 feet thick are interbedded in the sequence. Another concentrically jointed basaltic dome, on the north shore of central Kanaga Island, also resembles the lava pods on Unalaska. Recent examples of the Unalaskan sills and lava pods may be present in the sea-floor muds of Pratt Depression northeast of Little Sitkin Island (Snyder, 1957, p. 167, pl. 22).

Similar structural features are reported from New Zealand, Oregon, Quebec, and Radnorshire. Bartrum (1930, p. 447, 455) describes ovoid masses of lava in Auckland, New Zealand, as much as 80 feet long, with radiating columns. He believes these masses represent giant pillows derived from submarine flows. Lava tube fillings formed subaerially are similar to the Unalaska lava pods in many areas but generally are much smaller. (See for example, Wentworth and Macdonald, 1953, p. 46, fig. 23.) Waters (1960, fig. 2, p. 354) reports two of these masses, about 35 feet high, in an olivine basalt in Oregon. They have radiating columns and a crude concentric structure near their margins. Wilson (1938, p. 77) describes massive andesite from Quebec "in irregular poorly defined masses of varying size within pillowed andesite." Jones and Pugh (1948, p. 43–94) have described and mapped clusters of laccolithic bodies in shale at Radnorshire; these bodies are unlayered, range from 10 to possibly 700 feet in diameter, and, although believed to have been intruded into unconsolidated muds, are not associated with pillowed lavas. Endogenous volcanic domes in many areas resemble generally the Unalaskan lava pods in shape and in internal concentric banding (Williams, 1932, p. 145; Coats, 1936, p. 71–74; Cotton, 1952, p. 163), but they are not found with pillowed lavas. Concentric joints and concentric layers of alternate nonvesicular and vesicular lava are common in many pillows, and some of them contain concentrically oriented inclusions of wallrock (Lewis, 1914, pl. 21).

DESCRIPTIONS OF LAVA PODS IN SPECIFIC AREAS

The relations between lava pods, sills, peperite, pillowed lava, and argillite are well displayed in the sea

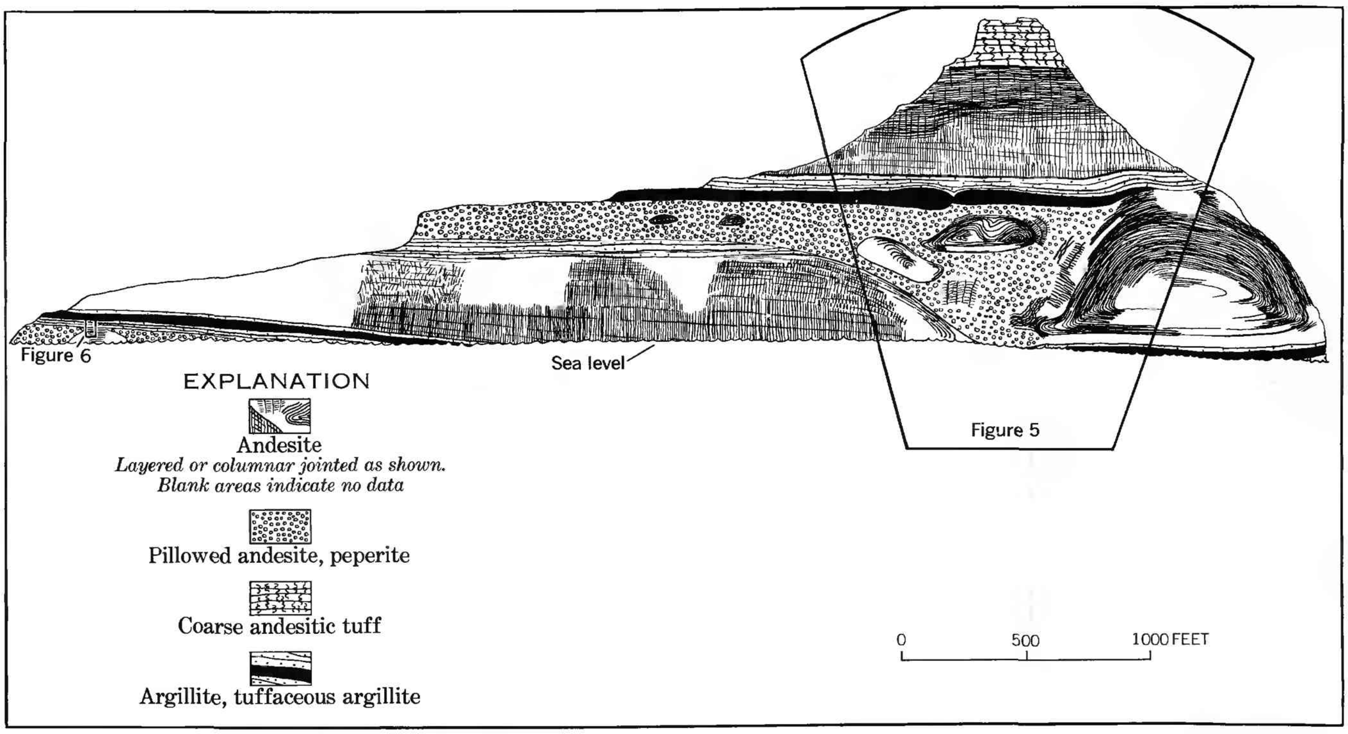

FIGURE 4.—Sketch showing geologic relations in sea cliffs on south and southwest sides of Tower Point, Unalaska Island; drawn from a series of photographs. Overlapping areas of figures 5 and 6 shown by insets. Lava pod on right, also shown in Drewes and others (1961, fig. 86), is the largest one known with completely exposed concentric layering.

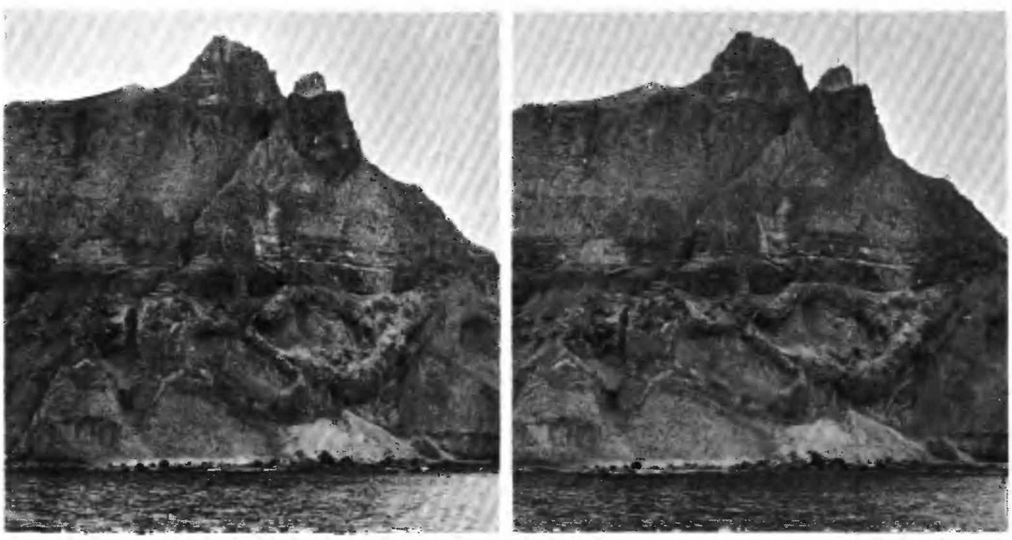

FIGURE 5.—Stereophotograph of 1,200-foot sea cliff, Tower Point, Unalaska Island. The largest boulders on the beach are the size of a large house. An igneous sheet of layered lava pods surrounded by pillowed lava and peperite underlies the lower half of the cliff. Argillite shows prominent horizontal bedding near the center of the cliff. A thick sill (?), columnar jointed near its base and horizontally layered near its top at the prominent break in slope, underlies the top part of the cliff. Horizontally bedded coarse tuff underlies the uppermost crags. Photographs by H. F. Barnett, Jr.

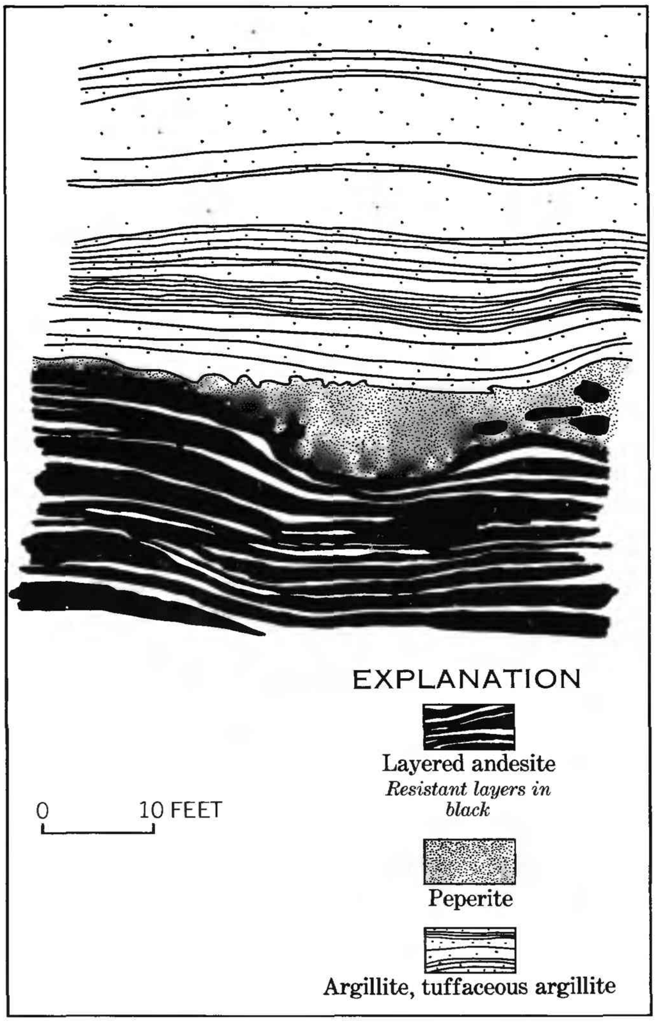

FIGURE 6.—Upper contact of layered lava pod with argillite, exposed in small headland near head of cove west of Tower Point, Unalaska Island; drawn from a photograph. Siliceous and calcareous sedimentary inclusions are abundant in the layered lava in the wave-cut rock bench surrounding the headland.

cliffs and tidal benches of seven areas, which are described in detail in the following sections.

TOWER POINT AREA

The vertical exposure in a rock bench, sea cliff, and ridge crest at Tower Point is about 1,200 feet, and the exposed section comprises 3 argillite units, a tuff unit, a sill or flow unit, and 2 sheets containing pillowed lava mixed with lava pods (figs. 4, 5; Drewes and others, 1961, fig. 86). The largest complete cross section of a lava pod is exposed here and, the relations between sedimentary, igneous, and mixed units are unusually well shown.

The base of the section is a sheet of pillowed lava containing lava pods, which is conformably overlain by a thin argillite unit. A thick zone of greenish-white peperite lies along the contact between the lava pod and the argillite, as shown in figure 6. Siliceous and calcareous xenoliths derived from the sedimentary rock are included in the lava pod as much as 30 feet below the contact.

The lower argillite unit is concordantly overlain by a mixed igneous and sedimentary unit occupying half the height of the sea cliff (fig. 5). On the west side of the point the mixed igneous and sedimentary unit consists of a basal sill with columnar joints and faint layers, a medial argillite wedge, and a sheet of pillows, peperite, and lava pods. The pillow and pod sheet thickens and constitutes the whole unit on the east side of the point, and the medial argillite layer is apparently represented only by the interpillow peperite. The largest complete cross section of a concentrically layered lava pod dominates the lower half of the east end of the cliff.

The upper half of the Tower Point section, above the mixed igneous and sedimentary unit, consists successively of thin argillite, a thick sill(?) jointed and faintly layered near its base and well layered near its top, and a coarse blue-green tuff. The lowermost layer of the argillite (shown in black in fig. 4) has not been visited in the field and its origin is not known. This may be a particularly massive baked argillite, as shown, or it may be a layer of black glass or dense lava similar to that exposed in the middle of the Riding Cove sea cliff several miles to the west. This layer has been partially drawn into boudins on the south side of Tower Point and appears to be cut on the east side of the point by the large concentrically layered lava pod mentioned previously.

BUTTRESS POINT AREA

Three mixed igneous and sedimentary units and a tuff unit are exposed in the 1,200-foot sea cliffs at Buttress Point (fig. 7). The relations between sills, pillows, and lava pods are shown unusually well. Some of the rocks are analyzed chemically in table 2.

The basal unit is a sheet of pillowed lava and lava pods. A layered lava pod is exceptionally well exposed in both rock bench and sea cliff on the east side (figs. 8, 9). The layers of this pod generally are parallel, but they merge with each other locally. The top of the pod abuts against a small lens of tuffaceous argillite, siliceous argillite, and tuff (visible in the upper left corner of fig. 9). Tiny pillows in siliceous argillite near this contact (fig. 10) consist of lava lithologically similar to that in the lava pod and possibly continuous with it.

The west end of the Buttress Point exposures contains a prominent lens-shaped lava pod (fig. 11) which is completely surrounded by pillowed lava. Layered lava interfingers with pillowed lava at the upper contact of the pod. A closeup of the layered lava is shown in figure 12. Chemical analyses of albitized resistant

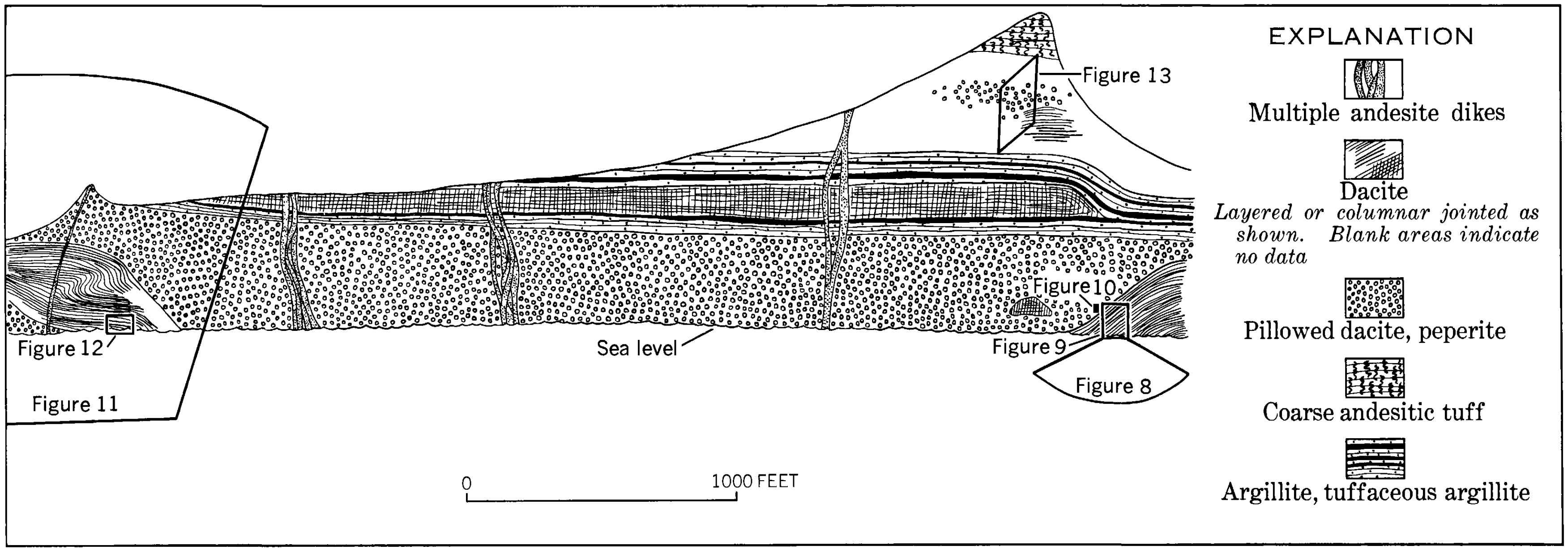

FIGURE 7.—Sketch showing geologic relations in sea cliffs on southeast and southwest sides of Buttress Point, Unalaska Island; drawn from a series of photographs. Overlapping areas of figures 8 through 13 shown by insets. Note abrupt termination of faintly layered columnar-jointed sill in right central part of diagram.

FIGURE 8.—Photopanorama of layered lava pod in wave-cut rock bench on east side of Buttress Point, Unalaska Island. Photographed at low tide and from the same place as figure 9 but from the opposite direction. Man in right middle distance for scale. Photopanorama constructed by John Stacy.

and nonresistant layers shown in this photograph are compared (table 2) with an analysis of fresh pillow glass collected from a small area of unaltered lava in the same sheet immediately east of the edge of the area shown in figure 7.

A thick argillite unit is wedged apart by a sill in the middle part of the Buttress Point sea cliff (fig. 7). The sill is columnar jointed and faintly layered. It pinches out abruptly toward the east, and the layers remain parallel with the contact at the blunt termination.

A third unit of mixed rock in the upper part of the cliff contains layered lava grading upward, through a gneissoid zone, to pillowed lava (fig. 13). The elongate masses of peperite in the transition zone resemble nonresistant layers of the lava below and are parallel with them. Several of the pillows are higher than they are wide; this shape suggests that they were surrounded and supported by a fluid or plastic medium during formation. The pillowy zone grades upward into massive structureless rock at the skyline.

A coarse blue-green tuff caps this section and is probably correlative with the tuff capping the Tower Point section. A similar and probably correlative tuff caps all the highest hills in this part of the island. It is not safe to correlate argillite units or igneous sheets even between adjacent headlands, because argillite in one section may be represented by interpillow peperite in an adjoining section, and igneous sheets may change character markedly along strike. Vertical multiple dikes cut the rocks of this section and resemble the dikes that were feeders of the sill on Cape Aiak.

TOWER POINT-LION BIGHT AREA

Two of the best exposed lava pods are in sea cliffs between Tower Point and Lion Bight. The first, about a mile east of Tower Point, is exposed so well on three successive small headlands that its three-dimensional shape can be clearly seen to resemble that of a derby (fig. 14). This pod is as thick as the sheet of pillowed lava in which it occurs, and it appears to crosscut part of the bedding of the overlying argillites. It is divisible into two distinct units: (1) an older upper carapace of crudely layered or roughly columnar to massive lava that appears to grade laterally into the pillowed lava; (2) a younger derby-shaped lava pod, apparently self-contained, which crosscuts the layering of the carapace along its east margin. The derby-shaped pod is layered and unjointed in its semispherical upper part and faintly layered but remarkably well jointed in its lower part, even out to the edges of the derby's brim. Another lava pod exposed in three dimensions, but semiellipsoidal rather than derby shaped, may be seen in any of three successive headlands about midway between Tower Point and Lion Bight (fig. 15). It also lies in a lava sheet containing pillows and lava pods, and it resembles the derby with its carapace of crudely layered, roughly columnar older lava and its core of well-layered lava that is remarkably uniformly jointed along its base.

SURVEYOR BAY AREA

Another lava pod which appears to be slightly younger than parts of the surrounding igneous sheet is exposed in the sea cliff at Surveyor Bay. This pod is hourglass shaped, and the lava is prominently layered and nonglassy. The narrow central part of the pod transects a sheet of dacitic(?) glass. Small apophyses from the lava pod cut the glass near the base of the sea cliff. The upper margin of the lava pod is gradational with an overlying nonglassy pillowed lava.

CAPE PROMINENCE AREA

The section exposed in the sea cliffs on the southwest side of Cape Prominence (fig. 16) is composed of a thick lower sheet of pillowed lava containing lava pods,

FIGURE 9.—Layered albitized dacite in active sea cliff on east side of Buttress Point, Unalaska Island. Upper contact of lava pod against small lens of tuffaceous sediment shown in upper left of photograph; for detail see figure 10. Photographed from the same place as figure 8 but from the opposite direction.

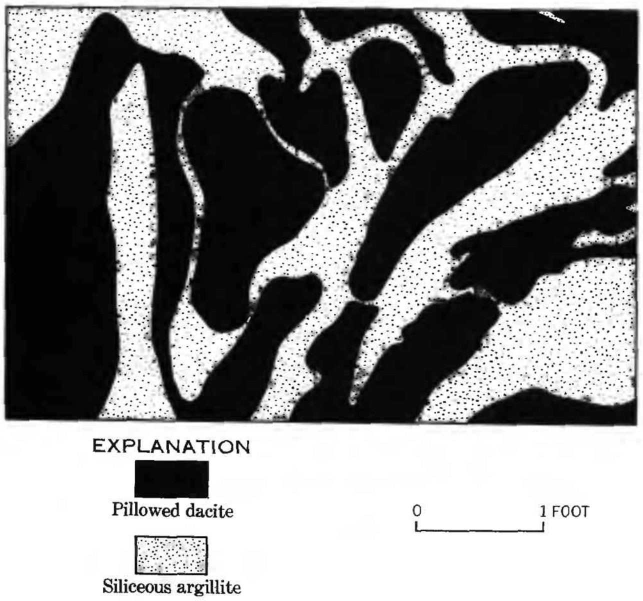

FIGURE 10.—Tiny pillows in sedimentary matrix within 10 feet of upper contact of layered lava pod exposed in sea cliff on east side of Buttress Point, Unalaska Island; drawn from a photograph.

a thin but persistent central sheet of bedded argillite, and a thick upper sheet of columnar lava, pillowed lava, and coarsely bedded tuffaceous argillite. Part of the bedding of the central argillite sheet is definitely cut by the upper margins of two large lava pods of the lower igneous sheet. The upper tuffaceous argillite frays out into pillowed lava along an intricate digitated contact. The pillowed lava appears to engulf and replace the argillite at its base, side, and top throughout a zone, 100 feet wide and 100 feet deep, shown on the northwest (left) side of figure 16. The columnar sill, which cuts the argillite shown in the center of figure 16, apparently formed a pillowed carapace in the partly engulfed mud above.

Southeast of the area shown in figure 16 on Cape Prominence, the igneous rocks in the upper sheet previously mentioned are conformable to sedimentary layers above and below, but the sheet is divided by a central necklace of at least 12 deltoid lava pod "beads" (fig. 17). The lava pods stretch out for about half a mile, and their bases maintain a roughly accordant level. The

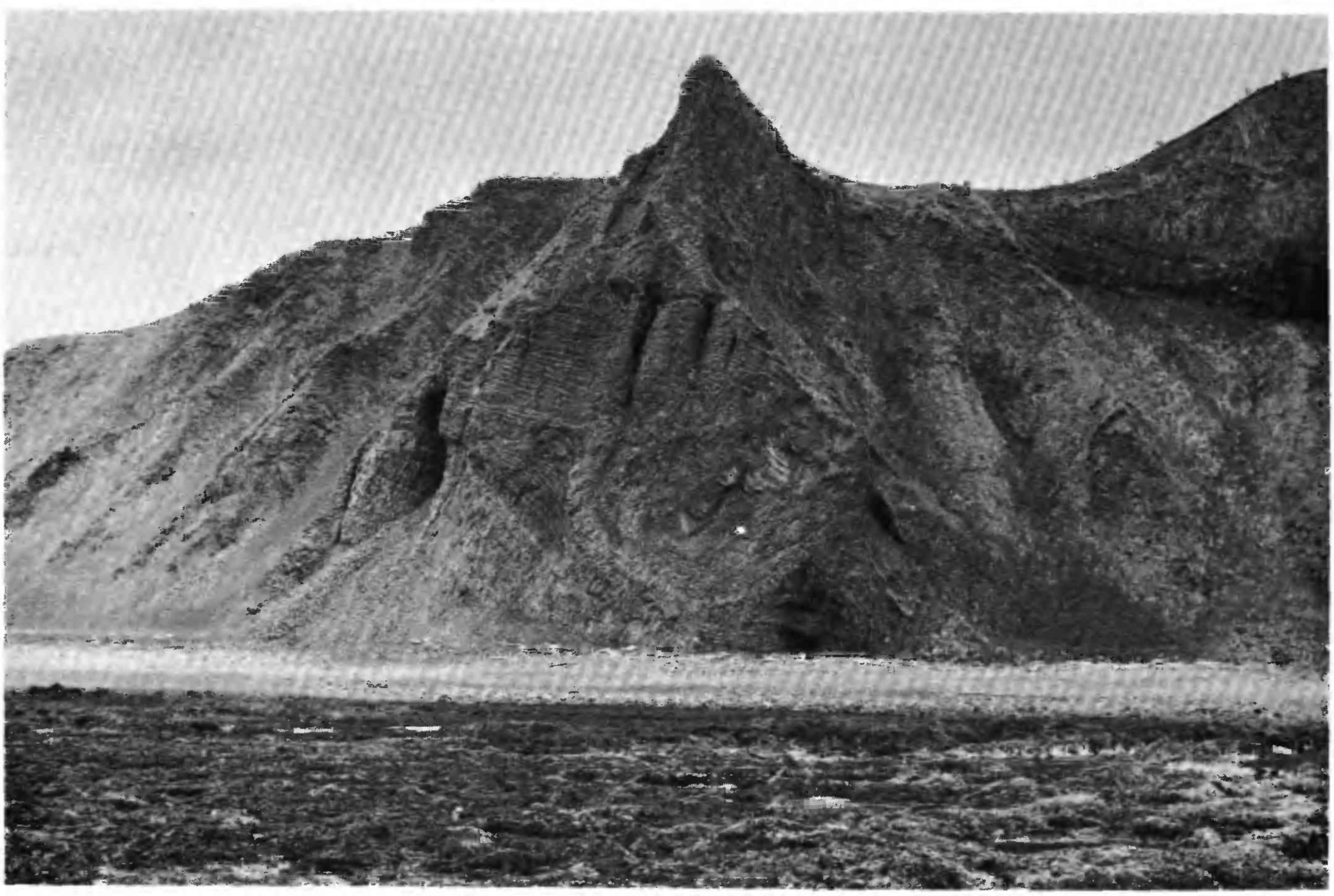

FIGURE 11.—Layered albitized dacite lava pod in sea cliff west of Buttress Point, Unalaska Island. Rocks in wave-cut rock bench in foreground and steep cliff above layered lava in center of picture are pillowed lava. Dark agillite strata and a massive sill show in upper right. Figure 12 is a closeup of the layered lava at the base of the sea cliff just left of the small cave shown in the center of the photograph.

FIGURE 12.—Layered albitized dacite lava pod in active sea cliff west of Buttress Point, Unalaska Island. Closeup of central part of Figure 11. Specimens for chemical analyses 2, 3, and 5, table 2, were collected from the resistant and nonresistant layers just over the geologist's head. Resistant layers contain quartz, and nonresistant layers contain a carbonate.

pillowed lava at this level has a distinct but discontinuous parting. This parting probably represents the base of the second phase of a two-phase emplacement for this igneous sheet, the lava pods being included in the second phase. Vertical multiple dikes are the youngest rocks exposed.

EAGLE BAY AREA

Another area with layered lava pods arranged at an accordant level is visible in the sea cliff at the east entrance to Eagle Bay (fig. 18). This exposure is also an example of a layered lava pod whose vertical dimension is larger than its lateral dimension in the plane of exposure.

LANCE POINT AREA

Exceptional sea cliff exposures 1½ miles west of the tip of Lance Point permit detailed observations of typical relations between pillows, peperite, lava pods, and argillite (fig. 19). Irregular lenses of baked deformed green argillite occur in the center of interstitial masses of peperite. Connecting necks between classical pillows, irregularly shaped masses of structureless lava, and layered lava pods are common, more common than is apparent in figure 19. Many of the pillowy masses which are shown as separate bodies in this two-dimensional drawing can be seen to be connected in the three-dimensional exposures on the cliff face.

ORIGIN OF PILLOWED LAVA AND LAVA PODS ON UNALASKA

Pillowed lava and lava pods on Unalaska Island have been formed by the intrusion of fluid magma into semiconsolidated and unconsolidated ocean-bottom muds. Pillows were formed as unstable apophyses or immiscible masses during digital advance of magma fronts and engulfment of mud and water in magma. The peperite matrix of most pillowed lavas is a mixed igneous-sedimentary flow breccia formed while both lava and sediments were in various states of fluidity or plasticity. Lava pods were large contained masses, tongues, or ducts of magma whose concentric internal layers were

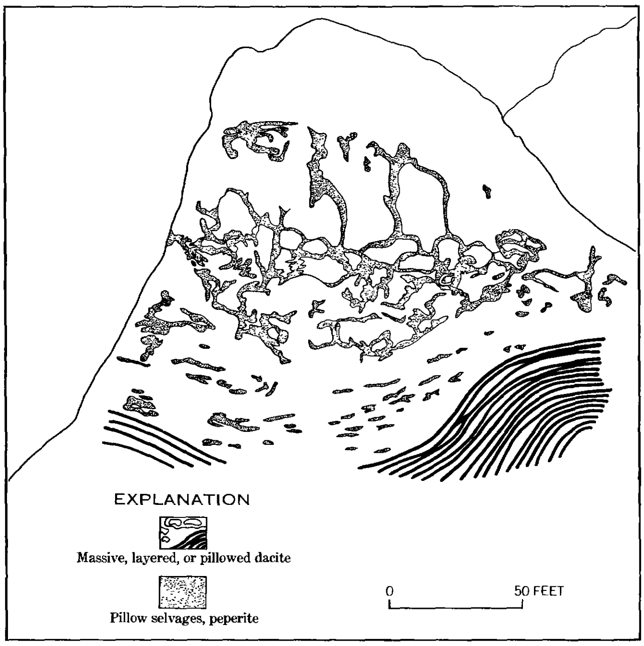

FIGURE 13.—Massive and pillowed lava overlying layered lava in cliff exposure high on Buttress Point, Unalaska Island; drawn from a photograph by H. F. Barnett, Jr.

formed by flow in a congealing and possibly contaminated magma.

INTRUSIVE ORIGIN

The lateral gradation and vertical alternation of pod and pillow lava with massive sills substantiate the theory of the intrusive origin of the pod and pillow lava. Further evidence is given by local detailed relations, summarized below.

Delicate apophyses of some pillows, such as those at Raven Bay, penetrate overlying argillite. Other pillows, such as those at Buttress Point and Chernofski Harbor, lie in a deformed but purely sedimentary matrix. Layers of pillows in exceptional exposures (figs. 4, 16) cut across or completely cut out argillite layers.

Peperite is a special type of igneous flow breccia with abundant sedimentary fragments. Both its igneous and its sedimentary components appear to have been liquid or plastic at the same time. This material is not pyroclastic in the conventional sense, for no evidence of explosions or lava fountains was found. Peperite is probably intrusive in origin, for it is found throughout sheets of pillows stratigraphically above sheets of contemporaneous massive or layered lava (figs. 4, 6, 13, 15). Here sediment had to exist above the lava at the time of emplacement, though doubtless it was quietly wedged or floated upward by the intruding magma. All sheets of pillows examined, some hundreds of feet thick, have their pillows set in a peperite matrix from top to bottom. The entire sedimentary component of the peperite could not have come from basal contamination nor could it have filtered in from above; deformed stratified chunks prove it was not precipitated contemporaneously.

Four types of evidence of intrusive contact of layered lava pods or sills with overlying argillite have been observed: (1) truncation of sediment beds (figs. 4, 16); (2) development of contact breccia and peperite (figs. 6, 13); (3) development of small pillows in contact sediments (fig. 10); and (4) warping of overlying sediment layers (fig. 7). No examples of sedimentary contacts between a layered lava pod and overlying argillite have been observed. Most of the lava pods are so intimately related to the surrounding pillowed lava (figs. 4, 7, 11, 13, 16, 17, 18, 19) that there can be no doubt that they are practically the same age as the rest of the igneous material. (See also columns 6 and 7, table 2.) Several layered lava pods are definitely younger, if only by a short time, than the surrounding igneous rock (fig. 14), but none are older.

The Unalaskan globular intrusions considered as a whole are flows into tenuous mud close to the sediment-water interface (Wells, 1923, p. 68). Lewis (1914, p. 652) discusses the semantic problem of what to call an intrusive flow. In many places Unalaskan pillowed lava is demonstrably intrusive, though it obviously possesses

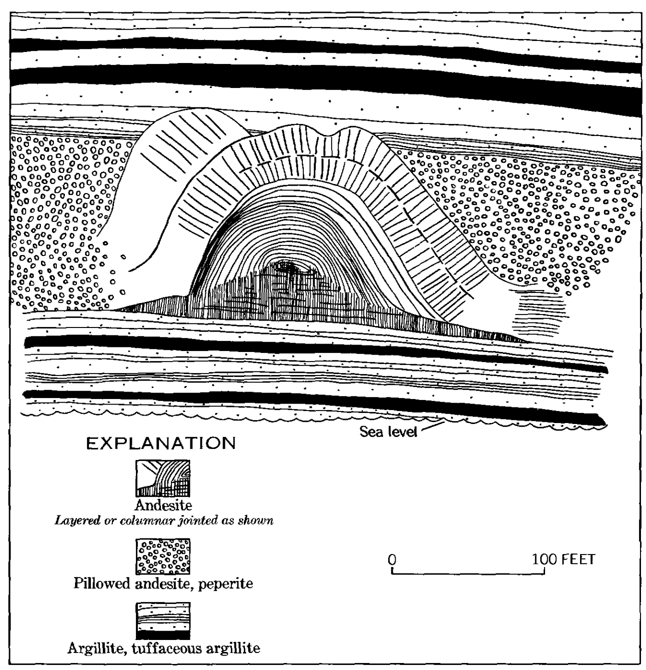

FIGURE 14.—Derby-shaped layered lava pod exposed in three successive small headlands along coast east of Tower Point, Unalaska Island; drawn from a series of photographs. Dissection is sufficiently complete to indicate that a cross section taken perpendicular to the coast would be identical. Central derby is younger than coarsely columnar carapace which grades laterally into pillowed lava.

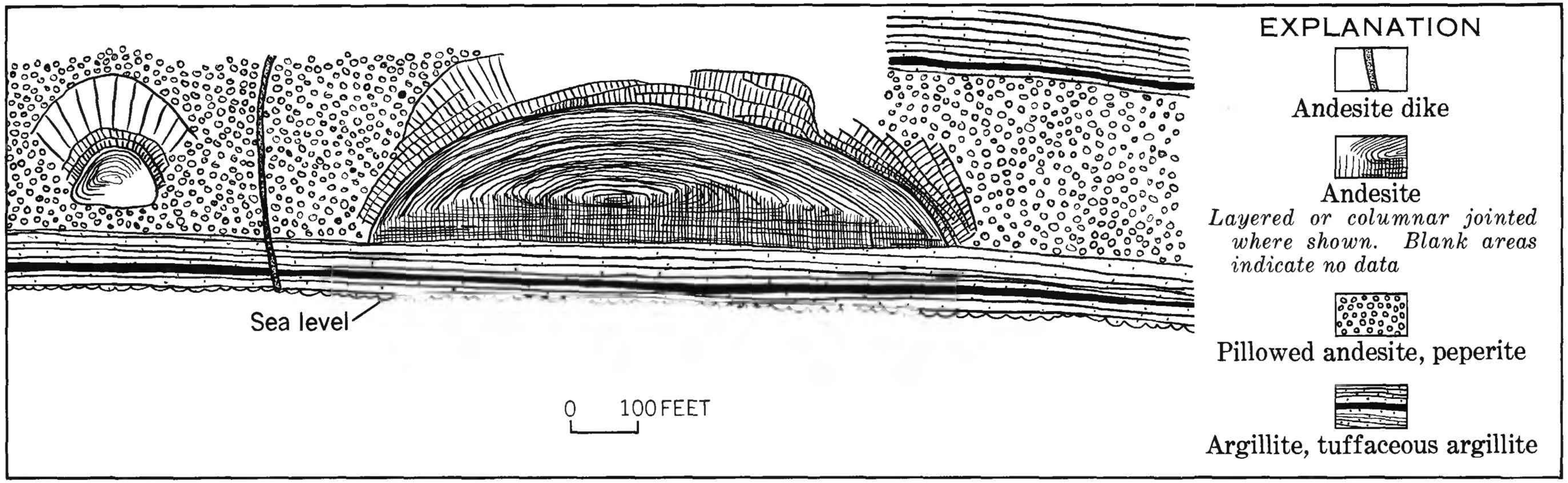

FIGURE 15.—Restored section of semiellipsoidal layered lava pod exposed on three successive small headlands midway between Tower Point and Lion Bight, Unalaska Island; drawn from a photograph. Dissection is sufficiently complete to indicate that a cross section taken perpendicular to the coast would be identical. Central ellipsoid is younger than coarsely columnar carapace which grades laterally into pillowed lava.

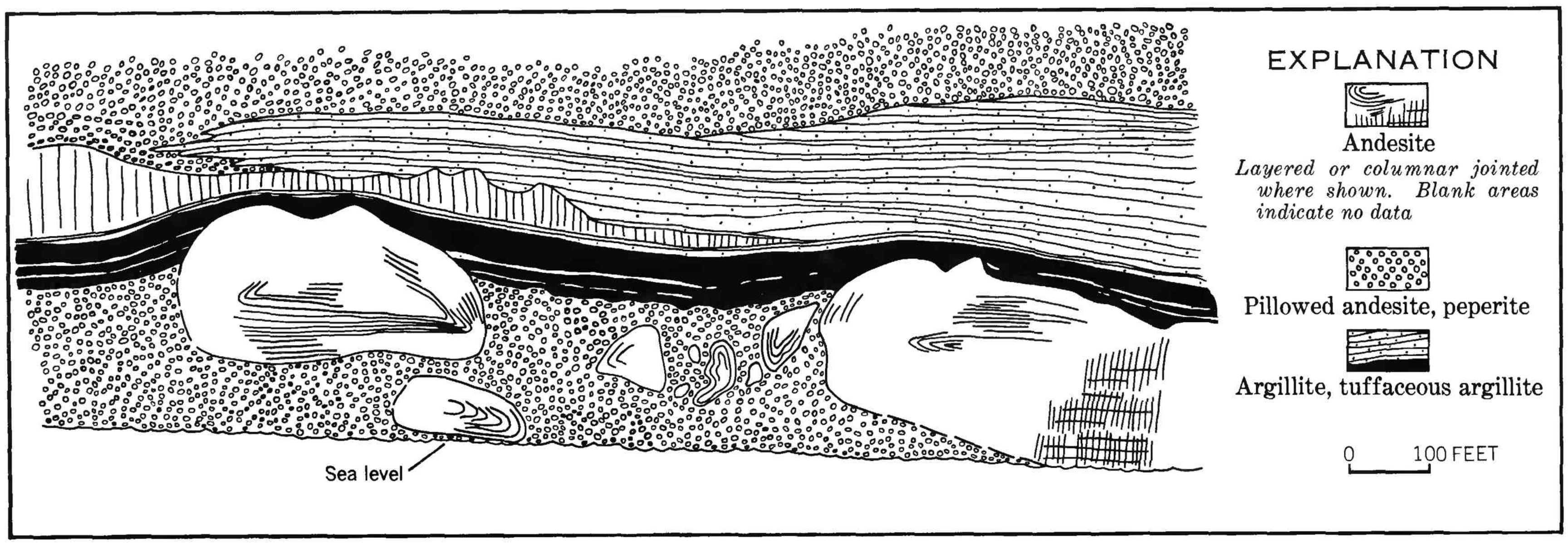

FIGURE 16.—Sheets of pillowed lava containing layered lava pods exposed in sea cliff on southwest side of Cape Prominence, Unalaska Island; drawn from a series of photographs. Lower layered lava pods cut bedding of prominent overlying argillite layer. Upper thick-bedded tuffaceous argillite frays out laterally into pillowed lava and is cut by columnar-jointed sill below.

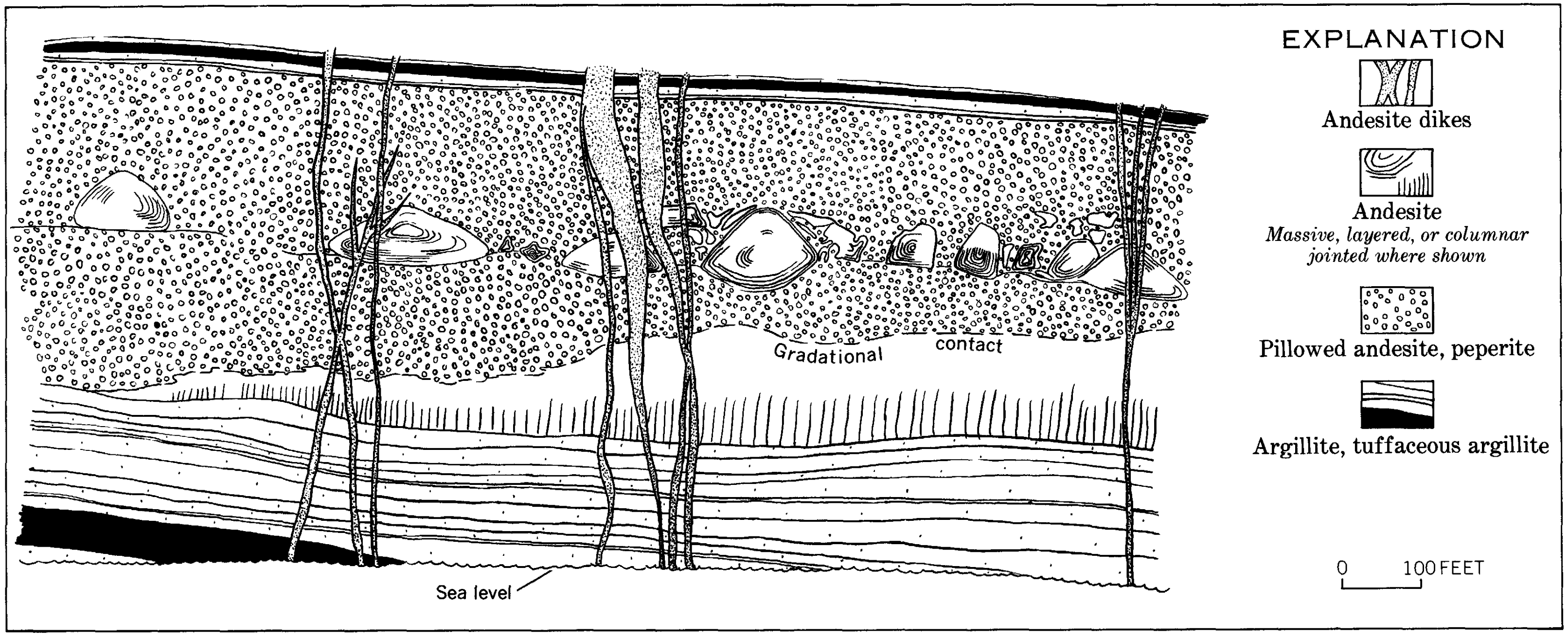

FIGURE 17.—Sheet of layered deltoid lava pods in pillowed lava in sea cliff on south side of Cape Prominence, Unalaska Island; drawn from a series of photographs. Except for a small gap, this figure is a continuation of figure 16 from the right. Pillowed lava surrounding deltoids has a distinct seam or parting coincident with the accordant base level of the deltoids.

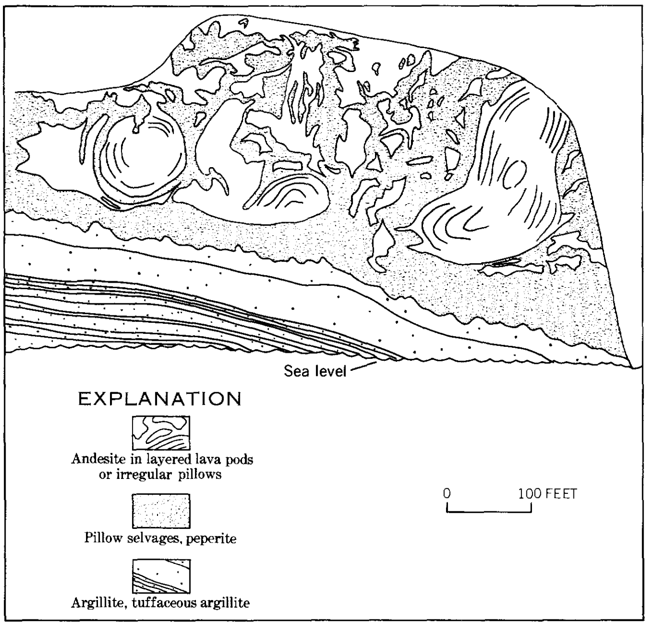

FIGURE 18.—Association of layered lava pods with peperite and irregularly shaped pillows in sea cliff at east entrance of Eagle Bay, Unalaska Island; drawn from a photograph. Note accordant base level of the layered lava pods.

flowlike attributes. Basal muds were not the only muds incorporated in the lava, nor were the flows blanketed by new mud from above. Inclusions and large blocks in the tops of sheets of pillows cannot be explained, as some have claimed, by basal contamination or by contemporaneous precipitation of sediment, but they must have been derived from overlying sediments at the time the magma was emplaced. Exceptional exposures on Unalaska offer evidence for intrusion not found in many areas, and the old concept of intrusive pillows (Platania, 1891, p. 42) would seem to be a necessary working hypothesis in many areas where pillows occur in a sedimentary matrix.

The Unalaskan pillows probably formed beneath deep water, as shown by the primary features of the enclosing sedimentary rocks, and as supported by observations of geologists in other areas. The thick argillite section is nearly all fine grained and well laminated. Northeast of the pillow-rich area some argillite layers can be traced from headland to headland for miles. Coarse sediments, agglomerates, tuff breccias, local unconformities cut and fill structures, and fossils—all present in shallow marine volcanic deposits elsewhere on the island and elsewhere in the Aleutians—are virtually absent in the argillite-pillowed lava section. This evidence suggests that regionally stable and uniform conditions of sedimentation existed. Magmas were intruded into the muds of a deep basin whose sediments came from a remote source.

The scarcity or absence of vesicles and the lack of pumice, scoria, bombs or essential lapilli in the pillowed lavas is unusual, because andesites and dacites are normally explosive. Likewise a magma fluidity approaching that of pahoehoe, indicated by textural and

FIGURE 19.—Pillowed lava in sea cliff exposure 1½ miles west of tip of Lance Point, Unalaska Island; drawn from several photographs. Baked deformed argillite occurs in center of peperite masses. Lava necks typically connect pillows with each other and with a layered lava pod at the lower right.

structural features of the lava, is also unusual, because the normal habit of andesite and dacite is short viscous block-lava flows intercalated with massive agglomerates and tuff breccias formed explosively. Thus, the textural and structural evidence suggests that juvenile volatiles were retained by the magma at pressures above the critical point of water. This may explain the remarkable fluidity of the magma. In fact, the large amount of water (6 to 9 percent) trapped in unaltered pillow glass suggests that both connate and juvenile water are present (table 2, column 1; also Drewes and others, 1961, table 1; subaerial vitrophyre of similar composition contains only 0.2 percent H_2O). According to Sosman (1947, p. 287) a pressure gradient toward an intrusion is possible, and magma may actually absorb water from surrounding rocks. Rittmann (1936, p. 52) suggests a depth of at least 2,000 m for nonexplosive submarine eruptions. A sticky blanket of mud may lessen the required water load on this part of Unalaska.

Others have also favored a deepwater marine environment for pillowed lavas (Daly, 1903, p. 77; Harker, 1909, p. 64; Dewey and Flett, 1911, p. 244; Park, 1946, p. 308), and Harker suggests an intrusive rather than an extrusive origin for the pillows.

EMPLACEMENT IN MUDS AND DEVELOPMENT OF MUD-MAGMA EMULSION

Abundant fluid mud was available during the pillow-forming epoch on Unalaska. That the sediments were very fluid is shown by penecontemporaneous folding in the thick argillite section along the south coast of Unalaska Island. The original thickness of unconsolidated sediment during intrusion cannot be directly estimated, but seismic and core studies show that an unconsolidated layer of sediments exists in most ocean areas. In the central and eastern Pacific Ocean, for example, this layer averages about 0.5 km thick (Raitt, 1956, p. 1635; Press *in* Benioff, Gutenberg, Press, and Richter, 1958, p. 725; Hamilton, 1959, p. 1407). In places such unconsolidated sediments may contain 50 to 80 percent water by volume (Kuenen, 1950, p. 383). In a basin receiving volcanic sediments, mud accumulates rapidly and probably retains water to considerable depth. When fluid sediments of this type are penetrated by an intrusive column of magma, the magma must bulge out and intrude the sediments, probably along bedding planes, before it ever reaches the sediment-water interface (Wells, 1923, p. 68). Magmas that retain their flowlike forms after penetrating a sedimentary layer must have intruded mud that was extremely watery.

Abundant pillows at contacts between intrusive masses and a wet sedimentary matrix and the striking resemblance in shape between pillows and drops of liquid suggest that some force akin to surface tension is instrumental in the formation of the Unalaskan pillows. The pillow-peperite mixture probably is a giant emulsion, with the lava in the pillows equivalent to the liquid of highest surface tension in the emulsion. The idea of an emulsion was first suggested by Lewis (1914, p. 639) who speculates that "it may well be found * * * that some of the pillows that are intermingled with the finer marine muds and oozes have been injected into the semifluid and immiscible sediment and thus have formed a sort of giant emulsion." This idea was amplified by Fuller (1940, p. 2022) who says:

> The ellipsoidal structure of basaltic lavas is considered by the writer to have been formed as the gigantic disperse phase of an emulsion in which the disperse medium was essentially aqueous. As in all emulsions, the dispersal of the fluid with the higher surface tension may have been attained either by the agitation of the two phases or by its entry as detached units. Aside from the magmatic force, the agitation is attributed principally to the explosive action of generated steam, but its effect would have varied according to the pressure. In submarine extrusions and where deepseated intrusions encountered ground water, the superheated steam would have retarded the chilling of the basalt and would have contributed to the mobility of the gigantic emulsion, thus permitting the wide development of the compacted structure in massive formations.

Molecular surface tension, however, can scarcely contain 40-foot "drops" of heavy lava, and the customary chilled pillow skin is required to perform the task. The great strength and elasticity of lava skins are well demonstrated in Hawaiian pahoehoe: "While a pahoehoe toe is active the skin remains tough and flexible. It is so resistant to rupture that one can jump on the top of a small toe and cause the internal liquid to squirt out the end without breaking the skin on the top" (Macdonald, 1953, p. 174).

Some pillows probably form by detachment of lobes and layers from the more massive parts of sills and pods, and these probably break into smaller globules by a process analogous to the formation of drops when immiscible liquids are stirred together. The surface digitations common on fluid flows(see below) may be important in furnishing abundant contact surfaces for the formation of chilled skins. Probably some incipient dikes will form along the tops of sills and, because they lack support and are in contact with mud, will collapse and separate into pillows. "Sprouting" on active aa flows has been observed in Hawaii (Macdonald, 1953, p. 178), and it probably is an effective mechanical mixer. This sprouting hypothesis finds support in several places where layered pod lava grades into pillows (fig. 19).

ORIGIN OF LAYERS IN LAVA PODS AND SILLS

The layers in lava pods and sills formed while the magmas were still moving, as suggested by their many parallel undulations, local deformation, and transition to breccia or pillows. They had to form in a great variety of container sizes and shapes, including sills perhaps miles long and 600 feet thick. Consequently, any static process, any process which is exclusively cellular and confined, or any process which is known to operate only on a very small laboratory scale cannot be considered. Contraction, convection, crystal settling, and chemical diffusion (that is, Leisegang's rings) are among the hypotheses that might be invoked to explain the pod layers which have to be rejected at the outset.

Nearly all the layered patterns that are found on Unalaska are approximated in miniature by flow laminae in thin pahoehoe flows on the island of Hawaii. Repeated concentric flow layers or "laterale Scherflächen" of alternate physical character are known from subaerial cylindrical lava tubes in Hawaii and on Vesuvius (Philipp, 1936, p. 342). Concentric flow layers in a few surface domes (Williams, 1932, p. 145; Coats, 1936, p. 71–74) are analogous but less perfect, probably because of low-pressure conditions that permit general autobrecciation of the type described by Curtis (1954, p. 465). Analogy, therefore, suggests that a similar but high-pressure flow process caused these Unalaskan structures, even though composition and scale differences can be large. Very similar flow patterns, with an even greater departure in composition and scale factors, can be seen in photographs from physics and engineering laboratories where watery liquids and even gases are dyed or marked with particles in laminar flow systems (Prandtl and Tietjens, 1934, plates 1–27). Contrasting layers, regular and repeated, can be seen in all systems. The layers undulate, merge, and divide, but they do not cross. Physical similitude, in spite of enormous differences in materials and sizes, can be understood by referring to the equation of the dimensionless Reynolds number (R):

$$R=\frac{\rho v d}{\mu},$$

where ρ=density; v=velocity; d=diameter of the conduit or depth of the tabular flow system; and μ=viscosity. If this number is lower than about 500, laminar flow must take place for any reasonable conduit shape, even a flow system with a free surface. Rouse and Howe (1953, p. 129) say the following about critical Reynolds numbers:

> Because different lengths are used in the Reynolds number to describe different boundary forms (the diameter of a pipe, the spacing of parallel boundaries, or the depth of free-surface flow), and because convergent boundaries tend to stabilize the flow and divergent boundaries to promote instability, the critical Reynolds number may be expected to have different magnitudes for different boundary conditions. A value of about 2,000 is generally accepted for pipes, 1,000 for parallel boundaries, and 500 for flow with a free surface. The appropriate values for non-uniform boundary shapes, the variety of which is obviously without limit, may be determined only through experimental measurement.

Because the two most important parameters of the Reynolds number, viscosity and velocity, are unknown for initial conditions on Unalaska, the Reynolds number can only be used as a criterion to deduce the direction of change in state of the magma with falling temperature (from turbulent toward laminar conditions) and the necessary final laminar condition. As a magma cools, slows, and eventually stops moving, μ becomes very large and v approaches zero. In addition, d, originally probably large enough to induce turbulence in a hot, fluid magma, is reduced piecemeal; flowing magmas form into toes, lobes, or apophyses of successively smaller dimensions, and peripheral cooling reduces the dimensions of any still-mobile fraction. Thus, all the variables in the Reynolds number change with time in a direction that reduces the size of the number, so that eventually only laminar flow is possible in a moving magma. The magmas at Unalaska must have passed through a stage in which laminar flow was general, and the regular internal layered patterns described seem to be reasonably attributable to such flow.

In laboratory systems the fluid flow layers disperse as soon as motion stops. In magmas motion may continue until viscosity is high enough to preserve the layers. The terminal relation between viscosity and motion is critical, for if motion stops too soon the layers disperse, and if motion continues too long brecciation may destroy the fluid structure. Among the many factors which control viscosity, entrapment of volatiles under high pressure may have been especially important on Unalaska. This would provide a long period of fluidity during which the laminar sorting process (see below) could operate. Sustained movement is further insured by the great size of the sills and pods, and the tenuous nature of the confining mud. The effect of chilling is difficult to evaluate because we do not know how thoroughly the thick masses were chilled by stirred-in mud.

The mechanical process by which a flowing liquid or plastic material sorts and arranges dyes, particles, or any heterogeneous components into visible regular layers or lines is basically rotary within the system of laminar flow. This conclusion is based on field observations in areas remote from Unalaska. The large, viscid, evolving, and freezing systems of geology permit us to see rotation inside flow layers. Where layers are large enough to see and the particles within layers are also visible, each discrete layer apparently has boundary conditions which impose on it an internal velocity profile not unlike the velocity profile known to exist inside a water pipe. The interior of a layer moves faster than the boundary. Such differential movement induces a controlled internal turbulence or rotation (evinced by the swirling trachytic flow structure of petrography) which moves impurities, crystals, or vesicles toward the static margins of each flow layer where, because of the relatively stopped condition, many of them become trapped and immobilized. There is, moreover, some evidence that the layers become larger as the melt becomes more viscous, and some layers are bonded together so that a new layer, with a much larger radius of controlled turbulence, is formed. Minute layered systems are folded and refolded recumbently (Balk, 1937, fig. 17, p. 51). In this way, layers seem to grow. The molecular or infinitesimal flow layers, which physicists treat mathematically, can evolve, in a cooling melt, into the visible layers that geologists see and map.

Curiously some flow layers retain a pasty mobility long after the bulk of the rock is brittle enough to fracture. On Novarupta dome, Alaska, and on Kilauea Volcano, Hawaii, we have seen piecemeal extrusion of individual flow laminae (from a fraction of an inch to several inches thick) into voids opened by fracture of the lava. Extrapolating from this we presume a differential translational mobility, together with an imperfect rotary movement, to be generally present in layers of extremely viscid systems (Balk, 1937, fig. 17, p. 51). Andrade (1951) shows the rotary nature of laminar flow and the laminar nature of vortical flow but he does not relate these to the generation and evolution of individual layers in a cooling melt.

On Unalaska initial uncontrolled turbulence occurred as the huge masses of liquid burst through their walls into tenuous mud. This turbulence mixed in the muds and created the emulsion for marginal pillows. The chaotic or turbulent conditions were rapidly damped as the contaminated magma was chilled; and fluid laminar flow followed turbulent flow. The contaminants, together with original and derived heterogeneous components in the cooling magma, were then sorted and arranged by the laminar process. Where layers are preserved and deformed and where the layered rock grades into autobreccias with a crude gneissoid pattern, some sort of laminar flow continued into the plastic state and even into the solid state. Where columnar joints are dominant and flow layers weak, lava was probably ponded and motion stopped before the fluid was viscous enough to perfect and preserve the flow structure.

The difference in chemical composition between the resistant and nonresistant layers cited (table 2) for the Buttress Point lava pod can be explained either by sorting during laminar flow or by later differential alteration. If the obvious effects of the late albitization can be neglected for the moment, the composition of the nonresistant layers could be approximated by adding illite-chlorite clay (plus minor calcite) to the original magma. Analyses of unaltered and tuffaceous argillites which make up the sedimentary rocks in this part of the island are not available, but it is probable that the original composition approximated an illite-chlorite clay (plus minor calcite). Possibly argillitic muds stirred into the magma during initial turbulence were streaked out and sorted into regular layers during subsequent laminar flow. Or possibly postsolidification hydrothermal solutions, which moved along regularly disposed but compositionally similar flow surfaces in the lava pod, differentially changed alternate layers with the result observed.

RECONSTRUCTION OF A TYPICAL IGNEOUS EPISODE

A typical igneous episode started with upward penetration of andesitic and dacitic magmas into a thick layer of deep submarine mud, which is now thin-bedded argillite. Penetration continued to a point where the heavy magma began to bulge out into the lighter unconsolidated bottom muds somewhere beneath the floor of the sea. The magmas spread out horizontally in an intricately lobate manner within the muds and engulfed much mud along the magma-sediment interface. On contact with the mud, pillows formed, especially at the tops and sides of the lobes and tubes. Extension of the active intrusive front took place by extension of the supplying lobes and tubes, in many places with immediate formation of surrounding pillows and peperite. Some of the large lobes and tubes were pinched off and formed closed lava pods (for example, figs. 14, 15) similar to the giant "pillows" of Bartrum (1930) in New Zealand. Many apparently closed lava pods are cross sections of ducts that supplied magma. Layered sills, in some places, may be long sections of elongate lobes or tubular ducts. Lava pods with accordant base levels (figs. 17, 18) probably are cross sections of tubes which connect laterally and in depth with a central supplying duct. Conformable flow layers with concentric cross sections formed in the constantly stiffening lavas as they moved through the supplying tongues or were squeezed by the overlying weight of mud and water into large pods. Later these layers may have been accentuated by differential hydrothermal alteration, and still later they were accentuated by weathering. Similar genetic relations between sills, feeder ducts, and laccoliths are inferred by Griggs (1939, p. 1102) and Hunt and others (1953, p. 141) but the igneous bodies they describe were emplaced in solid rock and are neither internally layered nor surrounded by pillows. Intermediate depth conditions between the sills of Griggs and Hunt and the lava pods of Unalaska may be recorded by the small dolerite laccoliths of Radnorshire (Jones and Pugh, 1948, p. 43–94). Pillows have not been described from this area, but the laccoliths are believed to have been intruded into unconsolidated muds; it has been noted by Jones and Pugh (1948, p. 71) "the largest and most continuous bodies occur at the lowest horizon, and at each successive horizon upwards the dolerite masses become more and more divided * * *."

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Pillowed Lavas, II: A Review of Selected Recent Literature

By GEORGE L. SNYDER *and* GEORGE D. FRASER

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

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PILLOWED LAVAS, II: A REVIEW OF SELECTED RECENT LITERATURE

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ABSTRACT

A review of literature after 1914 on pillowed lavas discloses general agreement, but important exceptions, on some aspects of pillow formation and contradictory ideas about other areas of fact or interpretation. Most students believe pillow formation is due to the juxtaposition of hot fluid magma and a cold fluid, generally water or mud, but pillows do occur rarely in locations where the presence of excess water has not been demonstrated. Many thick layers of pillows containing interstitial sediments are probably near-surface intrusive bodies rather than extrusive bodies. The distinction previously made between pillow and pahoehoe structure is valid. There is no general agreement on the time of pillow formation with respect to the time of emplacement of the magma body. Pillows are most common in subsilicic igneous rocks, but they are found throughout a broad spectrum of compositions.

INTRODUCTION

The authors have a varied background upon which to base a survey of lava structures. Snyder studied the structures of subaerial and submarine lavas and near-surface intrusions in the Aleutians Islands and Alaska Peninsula from 1949 through 1954. Fraser studied similar and also some of the same structures in the Aleutian Islands from 1952 through 1954. Fraser studied also lava structures on Hawaii from 1956 through 1959 and currently is engaged in geologic mapping in the area adjacent to the north edge of Yellowstone National Park. In 1953 and 1954, the authors jointly studied many remarkable pillows and larger lava pods that are well exposed on Unalaska Island, Alaska. These have been described in previous publications (Drewes and others, 1961; Snyder and Fraser, 1963). The present short review of literature after 1914 on pillowed lavas is an outgrowth of the interest developed during study of the lava structures on Unalaska. The following discussion is a product of the authors' experience with the Unalaskan and other features and represents an attempt to resolve or delineate several aspects of pillow formation about which there has been disagreement among many geologists.

IS WATER NECESSARY?

Ellipsoidal lava structures have puzzled geologists since at least 1834. According to Tyrrell (1929, p. 37) the term "pillow" was first used in 1890 by G. A. J. Cole and J. W. Gregory to describe ellipsoidal structures in the variolitic rocks in the area of Mount Genèvre on the border of France and Italy. Many diverse theories have been advanced to account for the formation of ellipsoids or pillows, and many early hypotheses are well summarized by Daly (1903, p. 65–78), Dewey and Flett (1911, p. 202–209, 241–248), Sundius (1912, p. 317–333), Lewis (1914b, p. 591–654), and Johannsen (1939, p. 228, 229). There would be little advantage in recounting the older literature here, and the interested reader is referred to the aforementioned authors for the proper historical perspective. Since Lewis' classic paper in 1914, most observers have considered pillows to be general, though not infallible, criteria of submarine or subaqueous extrusion or extrusion into local water bodies, over damp ground, or under ice (Capps, 1915, p. 45–51; Burling, 1916, p. 237; Sampson, 1923, p. 572; Foye, 1924, p. 337; Buddington, 1926, p. 824; Moore, 1928, p. 59; Bartrum, 1930, p. 447, 455; Fuller, 1931, p. 292; Burrows and Rickaby, 1934, p. 15; H. T. Stearns, 1938, p. 252–253; McKinstry, 1939, p. 202–204; Fuller, 1940, p. 2022; Noe-Nygaard, 1940, p. 5–67; Wilson, 1942, p. 64; Park, 1946, p. 305, 308; Cotton, 1952, p. 290; Henderson, 1953, p. 23, 31; Stearns, 1953, p. 207; Murthy, 1954, p. 293; Gage, 1957, p. 38; Gass, 1958, p. 242; Kudryashova, 1958; Malde and Powers, 1958, p. 1608; Byers, 1959, p. 326, pl. 48; Waters, 1960, p. 356, 361; Wilson, 1960, p. 97; Yagi, 1960, p. 919). Wager and Bailey (1953, p. 68) and Bailey and McCallien (1956, p. 472, 475) report basic pillows with fine-grained margins against a matrix of granophyre or porphyry, which they believe to have resulted from nearly simultaneous injection and mixing of basic magma and cooler acid magma. Reynolds (*in* Wager and Bailey, 1953) believes that at least part of these pillows were formed by injection of basic lava into water and later by injection of granitic material. Other authors suggest that some pillows formed wholly subaerially (Lewis, 1914a, p. 32; Cooke, James, and Mawdsley, 1931, p. 43, 48; Hoffman, 1933, p. 192, 194 [for an opposed account see Fuller, 1931, p. 292]; Stark, 1938, p. 225–238; Simmons, 1946, p. 192–193 [for an opposed account see Reid and Dewey, 1908, p. 269]). Several authors have noted the tendency of melts of artificial or natural substances to form cellular structures (Bénard, 1900; Dauzère, 1908; Osborn, 1946; 1947; 1949) and Green (see accounts in Lewis, 1914b, p. 644, and in Osborn, 1949, p. 77) actually observed spheroidal masses in subaerial lava from the 1859 flow of Mauna Loa. Osborn (1949, p. 73, 76) has attributed these structures to convection flow and concludes that "* * * the structures in lava variously called ellipsoidal, pillow, or globular may have formed by convection flow modified by horizontal movement of the lava stream and followed by rather rapid quenching." The general absence of pillow structure in most subaerial flows, however, militates against the general effectiveness of all subaerial mechanisms. We believe that the juxtaposition of hot fluid magma and a cold fluid, generally water or muds, is generally necessary for pillow formation.

EVIDENCE FOR THE INTRUSIVE ORIGIN OF SOME PILLOWS

Because much of the argument about pillow origin has been concerned with proof or disproof of subaqueous origin, most geologists have accepted an extrusive origin as axiomatic, and intrusion has seldom been considered. Wilson (1918, p. 121), for example, defines pillow structure as "a flow phenomenon characteristically developed in extrusive lava only"; so it is not surprising when he later (1942, p. 64) concludes that "it is scarcely conceivable that [pillow] forms could develop in magma confined in a dike." McKinstry (1939, p. 204) has stated that "'typical' pillows are pretty certainly diagnostic of extrusive origin * * *" and many others (Thomson, 1947, p. 4; Pichamuthu, 1957, p. 19) have felt that pillow structure was a convenient criterion with which to distinguish extrusive igneous rocks. However, "typical" pillows, pillow breccias, or globular, ellipsoidal, or spheroidal structures similar to pillows have been reported in dikes (Clapp, 1917, p. 260, 285; Worth *in* Wells, 1923, p. 67; Ellitsgaard-Rasmussen, 1951, p. 83–101; Chapman, 1955, p. 1541), in dikes, stocks, and lopoliths (Lawson, *in* Moore, 1930, p. 138), in sills (Ransome, 1894, p. 195, 201, 202, 209; Uttley, 1918, p. 114; Gage, 1957, p. 37), in a volcanic plug (Woodworth, 1903, p. 17–24), and in irregular intrusions (Ransome, 1893, p. 104; Lawson, 1914, p. 7; Clapp, 1917, p. 285; Benson, 1943, p. 120; Jones, *in* Vuagnat, 1952, p. 297; and Chapman, 1955, p. 1541). Ransome (1894, p. 195) reports a pillowed "fourchite" sill with continuous zones of locally intense contact metamorphism in sandstone adjacent to its upper and lower surfaces. Yagi (1960, p. 913, 915) cites metamorphosed shale above sheets of pillow-containing alkali rocks. The presence of marine sediments in masses, blocks, and igneous-sedimentary breccias within the layer of pillows is often cited as proof of submarine origin. In many places the bedding in the blocks of sediment may be truncated against the pillows (for example, Satterly, 1941a, p. 130; 1941b, p. 11). Park (1946, p. 309) speaks of "many fragments ranging in size from small chips to blocks 30 feet or more across * * * engulfed in the lavas." Several workers have noted sediments within individual pillows (Fox and Teall, *in* Lewis, 1914b, p. 603, see also pl. 21; Satterly and Armstrong, 1947, p. 8; Thomson, 1947, p. 4). Buddington (1926, p. 827) reports pillow lavas with interstitial limestone that grade upward into breccias with a limestone matrix. These observations prove a watery origin, and they should also suggest an origin by intrusion into watery sediments because many other igneous-sedimentary breccias in the absence of pillows do result from intrusion.

Phrases from the literature such as "isolated pillows," pillows "with chilled margins intact and sometimes with intervening cavities filled with shale," and brecciated lava which "is in fact a macadam-like agglomerate" (Bailey and McCallien, 1957, p. 47) suggest that some rock interpreted as pyroclastic (agglomerate) could actually be flow breccia in lava or peperite. Intrusion, and mixing of mud and magma seem possible. Similarly, Bartrum and Turner (1928) describe some curious New Zealand rocks, and their descriptions would fit rocks we have seen on Unalaska. They document two cases of mixed sedimentary and igneous rock (p. 107, 110) and one of intrusive pillows (p. 110), but do not stress these ideas in interpretation of large volumes of "crushed" or "shattered" rock which occur enigmatically between layers of unshattered pillows. The crushed rocks appear to be sediments "entangled in associated lava" (p. 129), and all have a high percentage of altered, comminuted material that could be either igneous or sedimentary. Two previous field parties thought that most of this rock was sedimentary. Bartrum and Turner insist that it is nearly all igneous. Perhaps some is peperite brecciated by its own movement, and more than one pillowed sheet may be intrusive.

According to Macdonald (1939, p. 336) the term "pépérite" was first used by Scrope in 1827 for certain basaltic tuffs and breccias of the Limagne region, France, which had formed from the intrusion of basaltic magma into poorly consolidated sediments. The term has found wider usage in Europe than America, but rhyolitic pépérites have been described from Marysville Buttes, Calif. (Williams, 1929, p. 168, Pl. 16b), basaltic pépérites, from San Pedro Hill, Calif. (Macdonald, 1937, p. 330; 1939, p. 329–338), and basaltic and andesitic pépérites, from the Elkhorn Mountains, Mont. (Smedes, 1956, p. 1783.) In all three localities the resulting breccias have been ascribed to the intrusion of magmas into incoherent poorly consolidated or moist sediments.

Elsewhere sedimentary material between pillows is so common that it has been noted in nearly all descriptions and even forms part of the definition of pillow structure quoted (from Tyrrell) in the recent A.G.I. Glossary (Howell, 1957, p. 221). One of the three following explanations is generally given for the presence of this material: (1) Contamination from below the extrusive lava sheets; (2) infiltration from later deposits or contemporaneous precipitation; or, (3) mixing during intrusive flow into water-rich mud. Evidence supporting the last explanation has been cited for the rocks of Unalaska Island (Snyder and Fraser, 1963). Capps (1915) records the squeezing of soft sediments into basal pillows with a diminution in the amount of interstitial sediment upward in the sheet of pillowed lava; such an observation correctly indicates extrusion onto soft mud. Others record primary stratification of sediment within the tops of pillow layers (for example, Prest, 1951, p. 13), and such observations suggest an infiltration hypothesis. In many pillow layers, however, the muds, which are commonly fossiliferous, permeate the entire pillow sequence or are confined to the top part where they are mixed in as deformed chunks. The basal layers of some pillow-containing sheets are massive or the sheet is very thick so that mud could not have squeezed through from below. This relation has been interpreted by several (for example, Lewis, 1914b, p. 630ff) as evidence for shallow (with respect to the sea floor) intrusion into mud and is exactly the interpretation we give to the Unalaskan pillows. We believe that similar sedimentary or igneous-sedimentary matrices in pillowed lavas in other areas should lead one to suspect an intrusive origin.

PILLOWS VERSUS PAHOEHOE

In Lewis' classic review of the pillow literature before 1914, he compares pillows with the pahoehoe structures of fluid basalts and concludes that they were formed by analogous processes. H. T. Stearns (1938, p. 252, 253), Wilson (1942, p. 63), and Macdonald (1953, p. 173, 174) sharply disagree with this description, and Macdonald has formulated criteria for distinguishing a heap of pahoehoe toes from pillowed lava. In pahoehoe budding, as described by many authors, a small stream or arm of molten lava runs rapidly out for a short distance from the main lava flow, stiffens, expands, cracks, and permits another short stream to issue forth (the first bulbs and arms may be covered by subsequent lava, but commonly pahoehoe toes are a terminal phenomenon of a single eruption). The connecting necks between pillows on Unalaska (Snyder and Fraser, 1963), and perhaps pillows elsewhere, do not extend from cracks where lava extrudes from one pillow to form another, but rather the neck and pillow surfaces all form a continuous smooth surface, and in some places the whole mass (fig. 13) grades into massive lava which suggests that the entire mass must have been liquid at about the same time. We agree that pillows are morphologically distinct from interconnected pahoehoe toes even though connecting necks between pillows are probably more common on Unalaska Island than in many other areas. The attenuated necks between pillows form a pattern on clean tidal flats or other good exposures which superficially resembles the anastomosing, amoeboid imbrication of some types of subaerial pahoehoe. The principal differences between pillowed lavas and heaps of pahoehoe are abundant matrix and a much greater volume of nonconnected globular structures in true pillows. Furthermore, most vertical exposures of pillowed lava exhibit at least 1 or 2 pillows with greater vertical than horizontal dimensions (for example, Snyder and Fraser, 1963, figs. 13, 19). This is difficult to explain by the gradual piling up of the lava from bottom to top, as would be necessary with pahoehoe. Vertically elongated pillows require the support of a mud or peperite matrix or adjacent plastic pillow masses during their solidification.

The superficial similarity between pillows and pahoehoe has been unnecessarily confusing. Practically every modern textbook with a section on pillowed lavas describes an observation about the recent lava pillows actually seen by Anderson (1910, p. 633, 639) in the process of formation on Samoa. Actually, Anderson's original observations and photograph make it plain that he was observing pahoehoe forming by a budding process which happened to take place at the shoreline. Globular pahoehoe toes were formed similarly both above and below the waterline, and the only difference in the two structures was a roughly granular surface on the submarine toes as compared to the normal corded pahoehoe surface. Fraser examined large areas containing subaerial pahoehoe on the island of Hawaii and found that few pillowlike bodies of any degree of perfection, in section or in plan, were present, and none of the deposits contained an abundant sedimentary matrix like that of the Unalaskan pillows or many other pillows. This evidence supports the views of Sampson (1923, p. 572) and Buddington (1926, p. 824) who believe that a great volume of pillows form only in contact with water. The cross sections of Hawaiian pahoehoe toes and tubes are ellipsoidal, but nonconnected ellipsoids are mostly confined to the stagnant edges of a few flow units or are locally formed near secondary vents and probably are never abundant. Of the six differences between pahoehoe toes and pillows noted by Macdonald (1953, p. 174), the more abundant matrix between pillows and the greater number of vesicles in pahoehoe are most important in comparing Unalaskan pillows and Hawaiian pahoehoe.

TIME OF PILLOW FORMATION

Three sets of time relations between the formation of pillows and the emplacement of the magma have been invoked to explain the time of pillow formation: (1) the pillows form abundantly at the moment of contact of the magma with an aqueous medium or during subsequent mixing and movement of the magma; (2) the pillows are formed after the magma is emplaced and activity subsides; or (3) the pillows form consecutively as the magma advances in a series of toes and buds, the lowermost pillows then being slightly older than the uppermost pillows (see previous discussion of pahoehoe). Most students favor the first explanation but there is no general agreement. Reid and Dewey (1908, p. 269) and others speak of a flowing mass of spheres rolling on the sea bed. Stark (1938, p. 234) and Satterly (1941a, p. 122) note the extreme distortion of pillows in some flows, suggesting that they were formed before the close of movement. M. G. Hoffman (1933, p. 192), who thinks that pillows are formed by the turbulence caused by underlying surface irregularities, mentions that "at the time of formation of the pillows most of the mass was in motion." Henderson (1953, p. 31) thinks that "the pillows form as globules of lava with tough glassy skins and are transported as entities to their final place of deposition"; according to this explanation the pillows must be transported individually rather than in an emulsionlike mass because he states (p. 26) that "each pillow was deposited subsequently to the pillows on which it rests." Osborn (1949, p. 76), working with cellular artificial glasses, notes that "the final pattern of cells is essentially the same as that which first appears, and commonly this pattern is affected by the direction and speed of movement of the liquid across the mold." Foye is adamant, however, in his belief that the explanation represented by (2) is most applicable for the pillows in the basalts of Triassic age in Connecticut. He states (1924, p. 337), "The field evidence is conclusively in favor of the view that the pillow structure developed in lava flows which had come to rest before the structure was formed," and (p. 341), "Again, the pillows were developed after the sheet ceased to flow and not as a result of its advance." Cooke, James, and Mawdsley (1931, p. 43, 48) feel that the pillows which commonly occur only at the tops of northern Canadian flows were formed after the extrusion of the underlying massive lava. Lewis (1914a, p. 32; 1914b, p. 647) is the chief advocate of (3), but others have subscribed to the process of individual bulbous budding (Clapp, 1917, p. 283; Macgregor, 1928, p. 19; Burwash, 1933, p. 50). McKinstry (1939, p. 203) feels "* * * that each pillow is a distinct entity and, in a sense, an individual flow which cooled within its own crust; that the ellipsoidal shapes could not have come into being while the material was in place as a part of a thick mass of lava * * *." Thomson (1935, p. 6; 1948, p. 6) and Wilson (1942, p. 64; 1960, p. 97, 101) agree that fitted pillows show that the lower ones formed earlier, although F. Hoffman (*in* Lewis, 1914b, p. 597) concluded long ago that fitted pillows prove contemporaneous formation. Actually, both of these attitudes are too restrictive. Fitted pillows show either that the lower pillows are earlier or that the entire mass was simultaneously in a plastic state. Wilson (1960, p. 97) stated that pillows were formed as "globules about in the same way that oil globulates when mingled with cold water * * *" and that they were transported individually to their final resting place "partly from the buoyancy of the vesicular lava and partly from the uplift effect of escaping steam." This mechanism of transport may be locally important, but it cannot be operative in areas where many pillows are interconnected complexly (Snyder and Fraser, 1963, figs. 13, 19) or where evidence for abundant gas emission is negative, as on Unalaska. Fuller's emulsion theory (1940, p. 2022), which was previously cited in detail (Snyder and Fraser, 1963), requires abundant formation of pillows during initial contact or flow mixing of magma and an aqueous medium, as in relation (1), followed by transport of the pillows as a body. We feel that this explanation of the time of formation of the pillows is the most important one for Unalaska. Continuous lobate budding, as in relation (3), may be a locally important process on Unalaska. Deformed and brecciated pillows, locally present, cannot have formed after cessation of motion, as in relation (2).

COMPOSITION OF PILLOWED LAVA

Most geologists realize that pillows are most common in subsilicic lavas (Howell, 1957, p. 221; Johannsen, 1939, p. 228; Park, 1946, p. 308). Some geologists would restrict the formation of pillows to basalts or related basic lavas (Dewey and Flett, 1911, p. 202, 245; Lewis, 1914b, p. 595, 646; Tyrrell, 1929, p. 38; Daly, 1933, p. 419). As late as 1953 it has been stated that "Andesitic pillow lavas have not been reported, * * *. Pillow lavas, so far as is known, develop only from pahoehoe flows of basalt" (H. T. Stearns, 1953, p. 207); and "Pillow structure is * * * known only in basic lavas" (Reynolds, *in* Wager and Bailey, 1953, p. 70). These statements are certainly mistaken. Andesitic and more silicic pillowed lavas are well known from the Keewatin rocks of the Canadian shield. Between 1928 and 1954 the Ontario Department of Mines published at least 30 papers describing andesitic pillowed lavas and at least 14 papers dealing with pillows of trachytic, dacitic, or rhyolitic composition (for chemical analyses see Satterly, 1941a, p. 125, 131; 1941b, p. 10; Hogg, 1954, p. 16). Pillowed andesites have also been reported in Quebec (Cooke, 1919, p. 76; Cooke, James, and Mawdsley, 1931, p. 40; Wilson, 1938, p. 77; 1942, p. 59–62; 1960, p. 97, 101), in Alaska (Buddington, 1926, p. 825), in Ireland (Geikie, *in* Lewis, 1914b, p. 608), in New Zealand (Bartrum, 1930, p. 447), and in Guam (N. D. Stearns, 1938, p. 7), and pillows are known in Norwegian rhomb porphyry lava (Dons, 1956, p. 14). Mafic alkalic pillows on the Nemuro Peninsula (Yagi, 1960, p. 918, table 3) are latites according to the chemical classification of Rittmann (1952). Ultrabasic pillows are possible too. Glassy limburgite pillows have been analyzed in Southern Rhodesia (Macgregor, 1928, p. 49). Analyses of vitrophyric olivine-rich picrite basalt pillows on Cyprus compare well with Nockold's average peridotite (Gass, 1958, p. 248, 249). The pillows of andesitic and dacitic composition on Unalaska, as illustrated by the new analyses cited previously (Snyder and Fraser, 1963), reinforce the view that, although pillows may be most common in subsilicic igneous rocks, they may be found throughout a broad spectrum of compositions.

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