Geology and Petrology of the Pribilof Islands Alaska

By TOM F. W. BARTH

INVESTIGATION OF ALASKAN VOLCANOES

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GEOLOGY AND PETROLOGY OF THE PRIBILOF ISLANDS, ALASKA

By Tom F. W. Barth

ABSTRACT

The Pribilof Islands, situated between 56°35′—57°11′ north latitude and 169°35′—170°24′ west longitude, are dominantly made up of lava flows and sills of basaltic habit (mainly olivine hyalobasanite), with minor amounts of pyroclastic tuffaceous material and glacial sediments. In parts of St. George Island there is a basement of periodotite. Basic dikes are common, and a unique occurrence of a composite aplite dike was noted from the southeast coast of St. George.

No trace of glaciation is seen on the surface of the islands, but the top of the basement peridotite, which is practically horizontal, is obviously glaciated and fossil shells are cemented directly on this glaciated surface. The fossils range in age from Pleistocene to Recent. Glacial sediments, commonly intercalated with basaltoid flows and sills occur in many localities on St. George Island, St. Paul Island, and Otter Island. The basal conglomerate has boulders of peridotite in many places. The sediments are coarse grained, polymict, and many are crossbedded; locally, the thickness is at least 325 feet.

By large fissure eruptions the Pribilof area was built up during the late Pleistocene. The area may have maintained a high average elevation in early Pleistocene. But later a general foundering of the area, in combination with fissuring, faulting, and outpouring of lava, reduced the area to a low position, oscillating around sea level, where it remained during the subsequent volcanic history.

The tuffaceous material contains fragments of peridotite, clear olivine, black-green hornblende, and cleavage flakes of feldspar of a rather unusual composition: about Or_{18} Ab_{82}.

The pyroclastic rocks are basaltic and chemically identical to the lavas; but a very small amount of a pumiceous glass of rhyolitic composition was found at Polovina Hill on St. Paul Island.

All dikes, flows, and sills are undersaturated in silica and correspond to olivine basalt-basanite; the average of seven flows shows 5 percent nepheline in the norm. One flow is chemically an olivine basalt, but usual in its mineralogic relations, possessing olivine and plagioclase as the only crystalline silicates; the groundmass is glassy. This rock is called glassy olivine basalt, Pribilof type in this report.

The dikes are petrographically olivine basalts, basanites, limburgites. When a glass base is present in dikes or flows, it tends toward a phonolitic composition. The glassy rhyolite does not represent a residual liquid derived from the alkalic magma of the lava flows.

The alkalic character of the Pribilof magma is assumed to reflect the tectonic environment—great crustal instability, vertical faulting, and block elevation in the hinterland of the orogenic island arc of the Aleutian chain.

INTRODUCTION

LOCATION AND PHYSICAL GEOGRAPHY

The Pribilof Islands are situated in the Bering Sea about 250 miles north-northwest of Dutch Harbor in Unalaska. The existence of these islands seems to have been known to the native Aleuts long before the first white men, piloted by the Russian hunter and explorer Gavrilo Pribilof, landed in 1786 on the southernmost island and named it St. George. In the following year the northern island, which was called "Peter and Paul", was descried and visited (Elliott, 1895; Grewingk, 1850, p. 185–191; Veniaminov, 1840).

The name "Pribilof Islands" is now generally applied to the whole group of islands. In the Aleut language they were called "Amig". Other names that have been applied to them are the "New Islands", the "Northern Isles", the "Seal Islands" as well as the Russian designations: "Lebedev Ostrova" and "Zubov". The largest island, originally named "Peter and Paul" is now usually referred to as St. Paul Island. The group consists of five islands for which geographical data are given below.

The Pribilof Islands

	Geographical position		Area (sq. miles)	Highest elevation (feet)
	Latitude N.	Longitude W.		
St. Paul Island	57°10′	170°15′	44	662.5
St. George Island	56°35′	169°35′	35.5	994
Otter Island	57°03′	170°24′	.77	285
Walrus Island	57°11′	169°56′	.02	----------
Sea Lion Rock	57°06′	170°18′	.003	----------

Walrus Island and Sea Lion Rock (being translations of the Russian Morzhovyy and Sivuchy respectively) are very small, and in stormy weather the breakers wash over them.

All these islands are made up of lava flows of basaltic habit and alkaline character (basalts, olivine basanite) with minor amounts of pyroclastic tuffaceous material and intercalated sedimentary beds. Excellent exposures are seen in the high sea cliffs (attaining in St. George Island an altitude of 984 feet). The outcrops are particularly good where the waves have cleaned and polished the rock surfaces; in other places the movement of the seals has made the ground bare and, indeed, polished the rocks (Jordan, 1898); in many places in the interior, soil and plant cover is so sparse that the hard rocks are excellently exposed.

FIELD WORK AND ACKNOWLEDGMENTS

The expedition to the Pribilof Islands took place in July and August 1948. The planning of the trips inside the Aleutian area, the establishment of the necessary local contacts, and in short, the burden of the arrangements for the expedition was borne by F. M. Byers to whom I wish to extend my hearty thanks.

In the field I enjoyed the pleasant company and interesting discussions of Mr. G. R. Arnett. Valuable information and kind assistance was always freely offered by the officials of the sealing operations, directed by the Fish and Wildlife Service; in particular my obligation to Dr. V. B. Scheffer, Branch of Wildlife Research, is gratefully acknowledged.

The material collected was in part worked up in the Department of Geology, University of Chicago. To the chairman of the department, Dr. W. H. Newhouse, I wish to express my gratitude for stimulating discussions and for free use of the facilities of the department; to Mrs. Ursula Chaisson I am greatly indebted for microscopic determinations of a great number of rocks.

ST. PAUL ISLAND

LAVA FLOWS AND BASIC DIKES

Lava flows and sills of basaltic habit make up the bulk of St. Paul Island. Some individual flows seem to merge into each other, but in many places they can be distinguished, and thicknesses from 10 inches to 7 yards were measured; still thicker flows probably exist. Some flows are vesicular, some are dense. In places the top part of a flow may be highly vesicular with a scoriaceous surface whereas the bottom part is dense. Figure 17 shows a peculiar difference in the orientation of the vesicles of two successive lava flows.

On the surface of the island no trace of glaciation is noticeable. Some of the lava flows have an even surface and are clothed with a thin layer of moss and grass. Others are very sparsely overgrown and may have a very uneven surface of lava "waves", spongy scoria, and lava foam, as if they were made yesterday. Between Fox Hill and the west coast is a rather extensive lava field with a magnificent display of miniature volcanic forms: a multitude of hornitoes, chimneys with foam and splatters, blowholes, diatremes, and miniature craters. The somewhat older lava flows surrounding North Hill are pitted with potholes and rutted with furrows, which are now covered by vegetation. In all probability they represent forms analogous to the hornitoes, craters, and other forms of the Fox Hill flow. They suggest multiple-vent eruptions arising from the confluence of lava flows from a large number of small and closely spaced orifices (aerial eruptions, according to H. Reck). However, the vents feeding the several orifices are highly hypothetical; in conformity to observable facts and in analogy with the explanation advanced by Thorarinsson (1951) for similar formations in the lava flows of Mývatn, Iceland, the miniature chimneys and blowholes of the Fox Hill flow are better explained as pseudocraters formed by steam from water trapped in hollows under the lava flow.

The sources of the many lava flows are not obvious. In the island itself the following observations are pertinent: The central portion rises to a height of 587 feet culminating in an old crater on Bogoslof

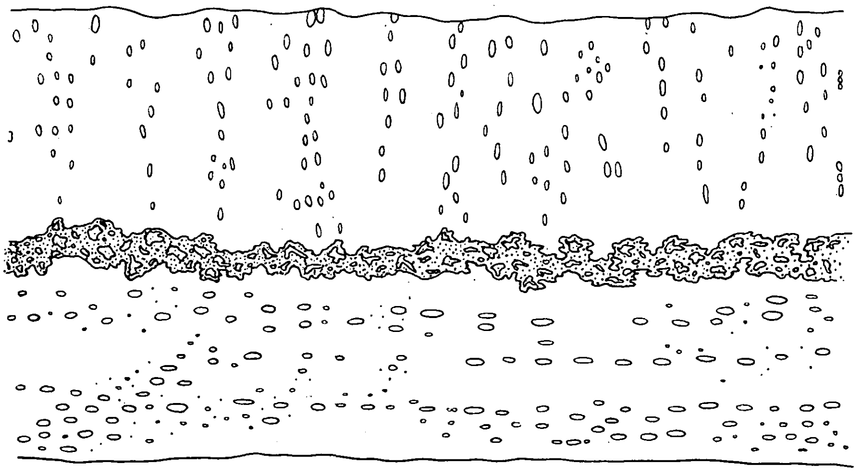

FIGURE 17.—Section one-third mile south of the village, St. Paul Island, through two flows, separated by a scoriaceous layer. In the top flow the vesicles are alined vertically; in the bottom flow they are arranged horizontally. Total thickness, 6½ feet.

Hill, out of which lava has flowed, as observed by Stanley-Brown (1892). A broad flow, easily discernible, extends eastward from the southern top and straight toward Lake Hill. At the southern edge of this flow is an extensive fissure trending about east-northeast and partly followed by a dike of vesicular, glassy chrysophyric hyalobasanite. Approximately 1¼ mile south of Bogoslof Hill, at a place called Kaminista, additional lava flows of olivine-rich basanites apparently originated in a system of fissures trending northeastward and southwestward.

Most of the St. Paul lava flow seem to have issued from fissures, of which only traces can now be seen, but the existence of such fissures, presumably in large numbers, at the sea floor of the Pribilof mound is probable (see p. 153).

PYROCLASTIC DEPOSITS

Bogoslof Hill, a volcanic cone, and a large number of explosion craters are prominent landmarks on the island (fig. 18). The explosion

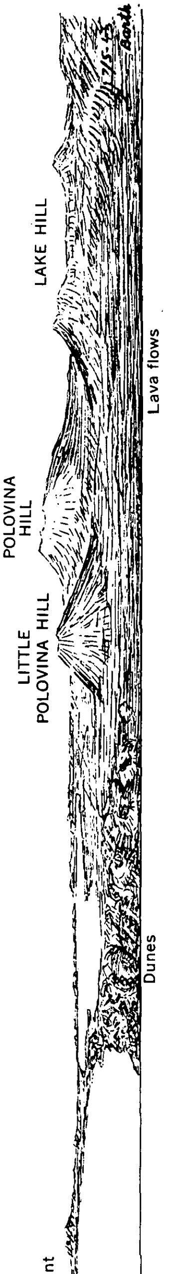

FIGURE 18.—View from North Hill looking eastward, St. Paul Island.

craters (tuff rings) cannot be regarded as potential sources of any extensive lava flow, for their products, in addition to the original vapor and gases, are pyroclastic material of various kinds now conspicuous in the crater ruins or deposited on the slopes of the cones and on the surrounding lava fields. (See figs. 19 and 20.)

Crater Hill (515 feet high) as an explosion crater whose semicircular southern wall is perhaps a ring dike; the other walls are of pyroclastic rocks. All the other craters, as marked on the map, are made up of pyroclastic and tuffaceous material and no traces of lava produced by these craters can be seen.

PLEISTOCENE SEDIMENTS

Pleistocene sediments occupy an intercalary position between the lava flows and are exposed in vertical sections along the steep sea cliffs. But, as they rarely appear on horizontal surfaces, they cannot be shown on the map. The most conspicuous deposit is at the extreme southeastern shore, straight east of the village on St. Paul Island, in a placed called Black Bluffs (see fig. 21), which contains water-laid poorly consolidated agglomerates, probably dumped by ice because of the polymict character—man-sized boulders mixed with pebbles, sand, and even clayey particles. Crossbedding is common, and in places conspicuous. Most of the material is derived from basaltic rocks. The graveyard of the village is on top of these beds.

In many other places in the sea cliffs intercalated sedimentary beds may be seen, for example between Village Cove and Tolstoi Point, at Zapadni Point, along the precipitous west coast (Rush Hill, 655 feet high, and Einahnuhto Bluffs).

The sediments contain fossils that range in age from Pleistocene to Recent. A list of fossils from both St. Paul Island and St. George Island is given on page 118.

ALLUVIAL SEDIMENTS

Recently formed alluvial sediments, mostly sand, cover about one-seventh of the area of the island. In most places the sand is loose and moves with the wind. Along the north shore, particularly west of Big Lake, impressive dunes are formed.

OTTER ISLAND

The Russian name for Otter Island is Bobroviy Ostrov. The island is situated 5 nautical miles south of St. Paul Island. Its western tip (fig. 22) rises to a height of 285 feet, displaying a continuous section of sedimentary layers dipping about 30° SW (fig. 23). The true thickness of the sediments here is at least 325 feet, indicating that a rather high land mass must have existed in the vicinity.

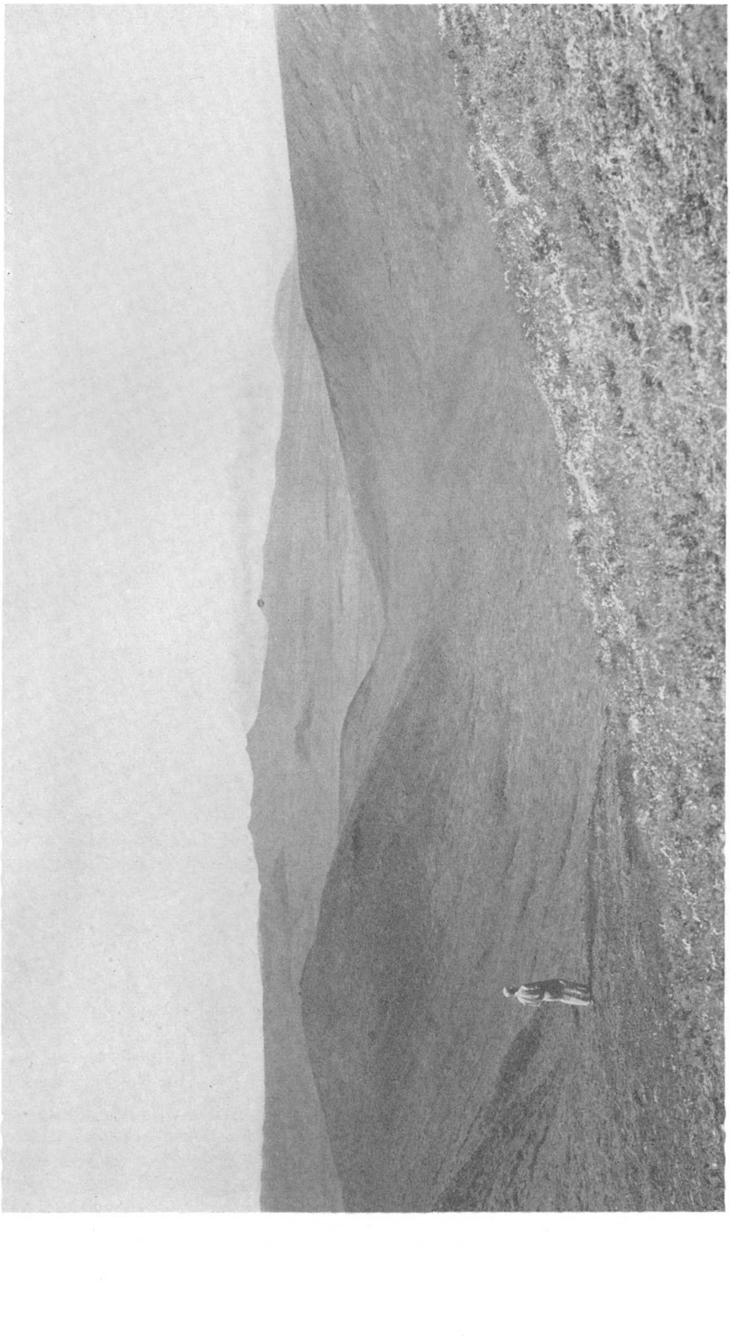

FIGURE 19.—Lake Hill, a tuff ring 280 feet high on St. Paul Island. Photograph by V. B. Scheffer.

FIGURE 20.—Crater Hill, St. Paul Island. Reindeer are wading in the far end of the lake. Photograph by V. B. Scheffer.

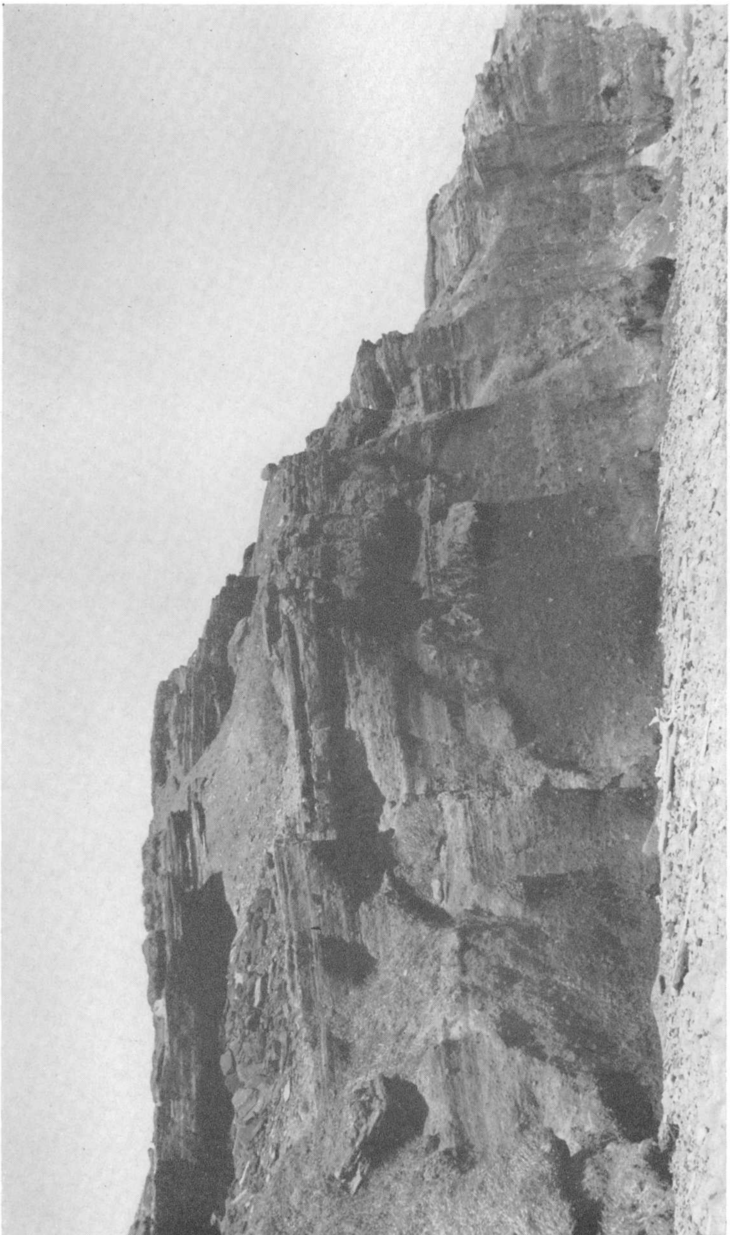

FIGURE 21.—Black Bluffs, east of the village, St. Paul Island.

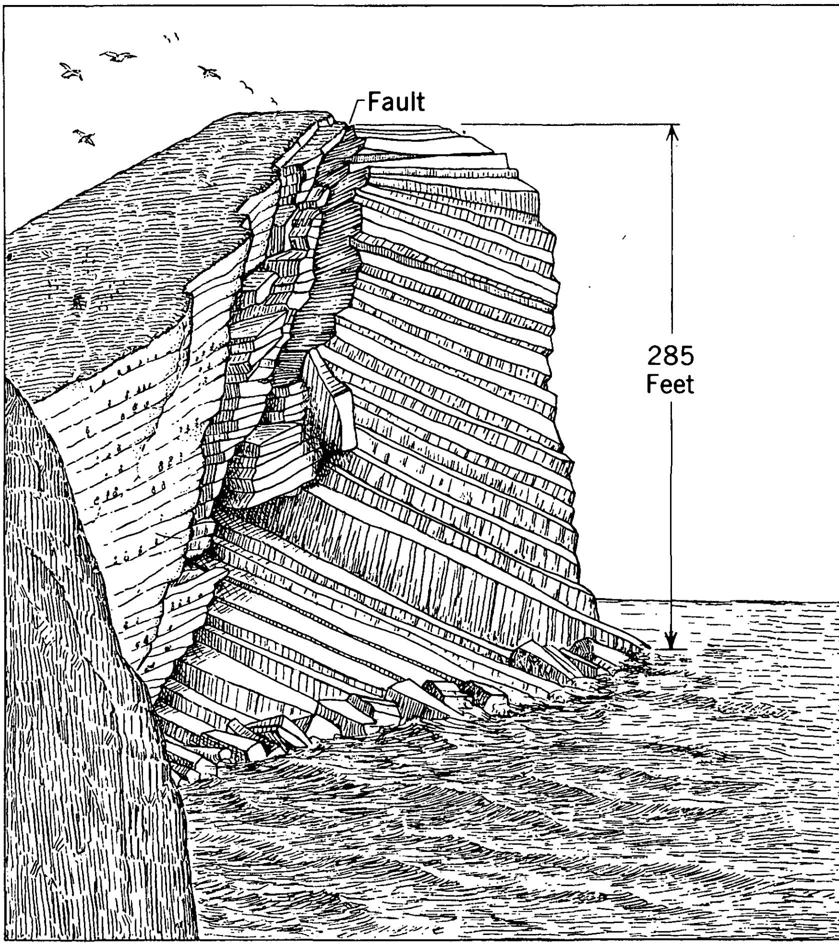

FIGURE 22.—View of western tip of Otter Island, looking south.

Most of the island is made up of lava flows of hyalobasanitic composition. At the eastern tip the flows were disrupted by a pyroclastic explosion.

ST. GEORGE ISLAND

PERIDOTITE

Peridotite is perhaps the most interesting rock in St. George Island (pl. 20). Its existence was noted by Stanley-Brown (1892) who says (erroneously) that it dips northeastward at about 45°. It is exposed in sections in the sea cliffs from Cascade Point in the south to within 3,300 feet of Tolstoi Point in the northwest. It is overlain by sediments and by several lava sills and flows. The upper surface of the peridotite is worthy of special description. It is obviously a surface

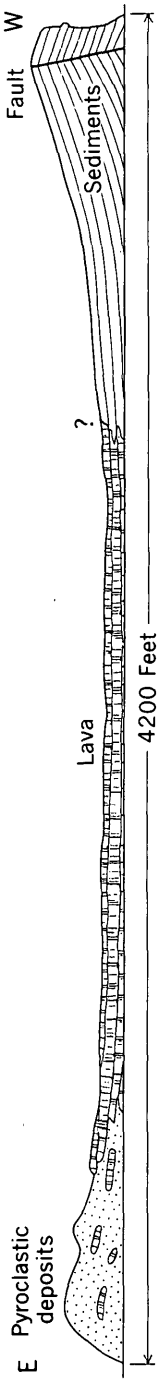

FIGURE 23.—Section of Otter Island. From east to west are pyroclastic rocks, lava, and sedimentary rocks.

eroded by glaciation; it is nicely polished by the ice, and furrows and striae are conspicuous in places. In other places a brownish-black weathering varnish can be seen, and weathered boulders of brecciated peridotite are truncated by the surface (fig. 24). The surface is almost exactly horizontal and in vertical section the peridotite may easily be mistaken for a flow. Over this horizontal surface the younger lavas have flowed, but in many places they are separated from the peridotite by a sedimentary layer (figs. 25, 26).

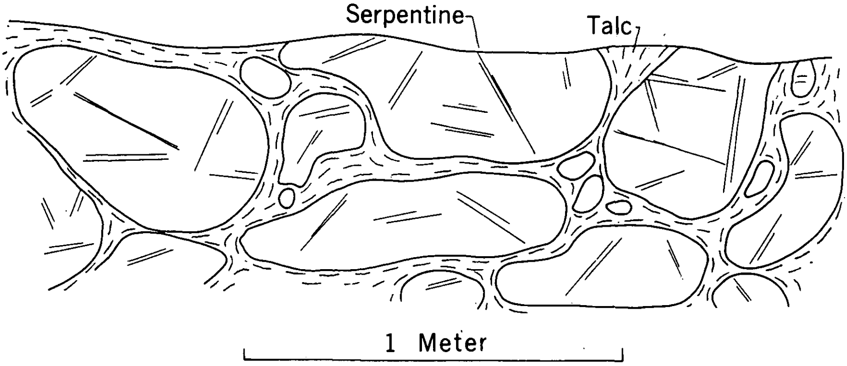

FIGURE 24.—Vertical section through upper part of the peridotite, northeast of Garden Cove, showing weathered boulders, with serpentinized olivine in the joints, in a talc matrix. (See p. 119.)

The best exposures are at Garden Cove. The erosion surface of the peridotite there is about 30 feet above sea level. The peridotite itself is massive; on large clean surfaces, polished by the sea, no structure can be seen. The joints, in places very conspicuous, have no system except that they do not seem to be flat lying. All dip angles are steeper than 45°.

APLITE

An aplite granite intrudes the peridotite just south of Sea Lion Point. Elliott (1887) called it a "large dike of bluish or greenish-grey phonolite, in which numerous small crystals of spinel [sic] are found". But Stanley-Brown, who looked for this occurrence was unable to rediscover it. It represents a dike or neck, approximately 325 feet wide with fine-grained chilled margins and a coarse-grained core, the upper portion being truncated by the erosion surface of the peridotite. The aplite is, therefore, younger than the peridotite and older than the overlying lava flows and sedimentary layers.

LAVA FLOWS AND BASIC DIKES

Lava flows of basaltic habit make up the bulk of the island. The flows are analogous to those found in St. Paul Island. Many flows show the similar differences in vesiculation from top to bottom as

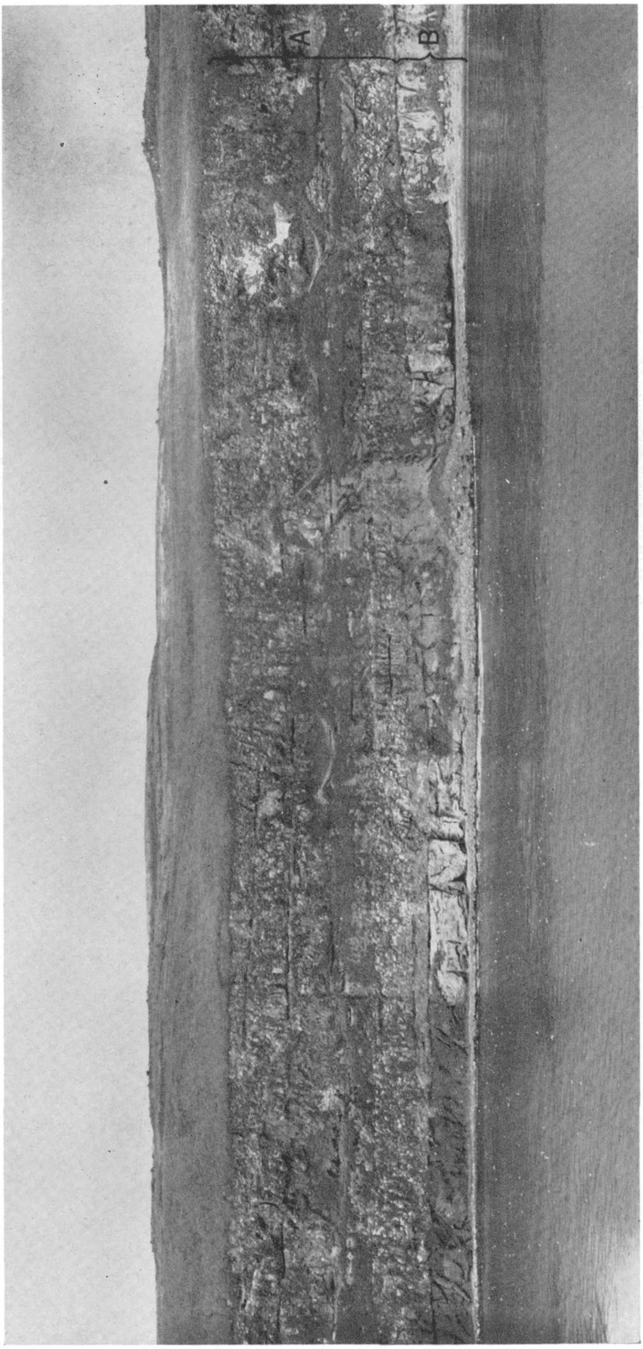

FIGURE 25.—Sea cliffs north of Garden Cove showing flows, sill and intercalated sediments (*A*) and overlying peridotite basement (*B*). Photograph by U. S. Navy.

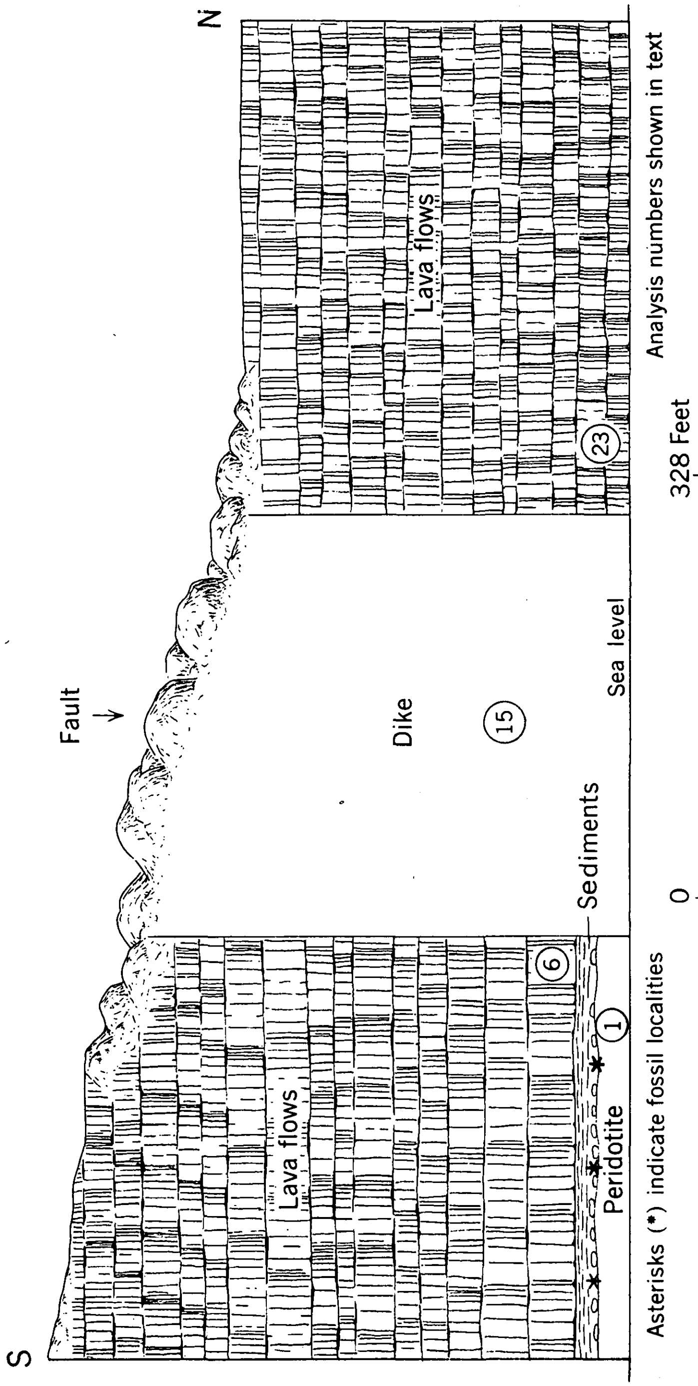

FIGURE 26.—Section about two-thirds of a mile south of Tolstoi Point, St. George Island. Numbers correspond to those of the analyzed rocks. No. 23 is described on page 115.

those described on p. 104. Thus a flow extending from Tolstoi Point and half a mile southwestward along the coast has a dense, granular hyalobasanitic bottom part (pyroxene, plagioclase, and glass, with only 2 percent olivine) merging upward into a holocrystalline, highly vesicular chrysophyric basalt containing at least 20 percent strongly corroded olivine phenocrysts (see fig. 28*E*). Both in mineralogy and texture the top and bottom part could scarcely be more dissimilar. In figure 26 this flow is marked as 23.

At Tolstoi Point (fig. 27) it seems that seven flows, all horizontal, make up the whole cliff; that makes an average flow thickness of more than 25 feet (cliff is 200 feet high). But in other places most flows are thinner; they are usually separated by scoriaceous layers. North Sea Lion Hill and South Sea Lion Hill are exogenous lava domes. Ulakiya Hill is partly lava, partly loose, pyroclastic material. Similarly constructed are also Maynard Hill and Gull Hill. There is no doubt that these rather high hills (Ulakiya Hill reaches an altitude of 932 feet) represent loci of lava outpour. But lava flows have also issued from fissures. A vertical fault is seen in the sea cliff about two-thirds mile south of Tolstoi Point, trending straight westward for about 2½ miles, then turning toward southwest. It is, at least in parts, filled by a semicrystalline porphyritic dike of olivine hyalobasanite; lava flows have issued from it around Ulakiya. Another fault, trending west-southwestward, forms an impressive scarp (called Esogemunga) across the western tip of the island. The south wall represents an elevated ridge, Samlalogh Ridge, rising higher in the east than in the west in relation to the north wall, the maximum displacement being 490 feet. West of this fault line, the entire western tip of the island is mainly pyroclastic material. Fox Castle is simply a volcanic neck that penetrated the pyroclastic deposits. It is believed that most of the lava flows of this island, as was the case in St. Paul Island, came from fissures that are now under the sea.

PYROCLASTIC DEPOSITS

Pyroclastic materials have a wide distribution in the island. All the volcanic cones evidently showed explosive activity with lava flows alternating with pyroclastic ejectementa. In addition large areas are covered with very thick pyroclastic deposits.

Tuffaceous materials in some places are mixed with other pyroclastic deposits. Along the north shore between Myak and Suskaralogh Point, and just west of the Staraya Artil Rookery, tuffaceous deposits attain a minimum thickness of 836 feet. At Myak the island plateau plunges precipitously into the sea, forming a shear cliff, 820 feet high, made of scoria, lava foam, and other pyroclastic materials, tuff, and sediments, intercalated by flat-lying sills of basalt.

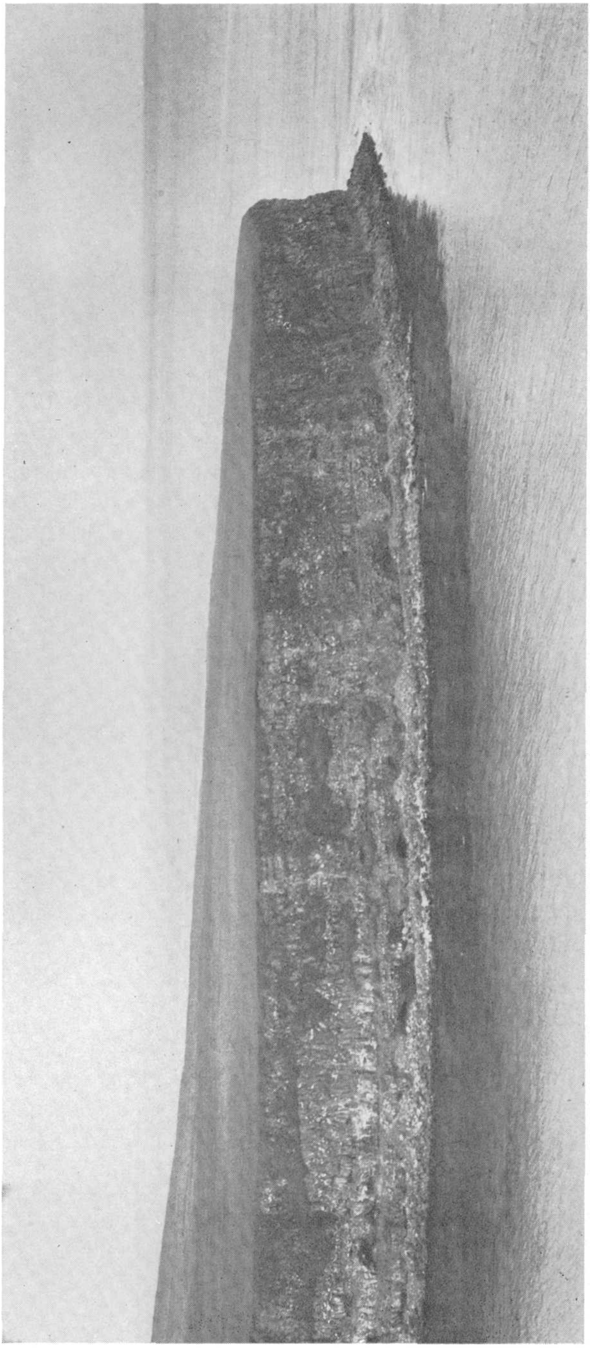

FIGURE 27.—Tolstoi Point, St. George. Photograph by U. S. Navy.

Somewhat farther west the tuffaceous mass has been dissected by wave erosion and shaped into a most impressive landscape of deep vertical gullies and high weird pinnacles, all composed of loose whitish or yellow tuffs, with numerous small brown dots that may represent altered pieces of basalt. The mineral composition has not been completely determined. Close to Staraya Artil Rookery the tuff contains fragments of peridotite and odd fragments of large mineral crystals: clear green olivine, large cleavage flakes (2 cm long) of black-green hornblende, and of milky-white feldspar. Only in one place (top of deposit west of Myak) was it possible to observe any bedding (the dip is about 45° S.). In all other places the tuff is not bedded.

FOSSILIFEROUS SEDIMENTS

Fossiliferous sediments crop out in sections in the sea cliffs at several places: Right at the village shores is a sedimentary layer, 10 feet thick, the bottom of which is at high tide mark. It extends eastward for about 1¼ miles then wedges out. It is composed of sand and yellow tuff with rounded pebbles of basalt (fig. 30). Another thin sedimentary layer, about 20 inches thick, follows the sea cliffs west of Zapadni Bay. An almost-continuous section is exposed over a distance of about 5 miles along the east coast. The character of the sediment differs considerably and changes abruptly from place to place: clay, boulder clay, sand, till, tuff, pyroclastic deposits. Figure 26 shows the section at the sea cliff, two-thirds of a mile south of Tolstoi Point.

The base is of peridotite showing no change from bottom to top. The upper surface of the peridotite is an erosion surface. It is horizontal, which, at the first glance, makes the peridotite look like a flow. The surface has ice striae and appears polished and coated with a brownish-black weathering varnish; weathered boulders are truncated by this surface (fig. 24).

The basal conglomerate on top of the peridotite has boulders of peridotite in places, but contains predominantly rounded pebbles of basalt. Fossil shells are cemented to the glaciated surface. The conglomerate is well consolidated and about 8 inches thick. It is overlain by a layer of sand, about 6½ feet thick, rather unconsolidated, containing casts of fossil shells which can be seen on freshly opened surfaces, but which disappear as phantoms when touched: all $CaCO_3$ is gone. It is overlain by alternating beds of clay, sand, and pyroclastic deposits, each bed from 2 to 9 inches thick; the total thickness is about 13 feet. On top of the sedimentary sequence is a columnar dense basalt flow.

Toward the north the section is terminated by an olivine basanite dike about 300 feet wide. On the north side of the dike both peridotite and sediments have disappeared; there is nothing but lava flows (fig. 26). This dike seems to follow a fault which according to the topography may extend inland toward Zapadni Bay. (See pl. 20.)

A remarkable sediment is deposited two-thirds of a mile south of Garden Cove, directly on the glaciated surface of the peridotite. Almost unconsolidated, it is made up of well-rounded pebbles, ranging from 2 inches to 6 feet in diameter, inbedded in sand (fluvio-glacial moraine?). Farther to the southwest the moraine gives place to other types of sediment: clay and sand, usually crossbedded. Southward, these sediments become very thick, and are intercalated with basaltic flows. In places they are highly metamorphosed. Still farther south two distinct beds of sediment, each about 60 feet thick, separated by a thick basalt flow or sill, can be seen in the bluffs. The total height of the cliff is approximately 200 feet. At the top of the lower sediment bed, the overflowing lava has picked up and incorporated big chunks of sediment (fig. 30).

Finally it should be emphasized that my investigation of these sediments has been strictly of a reconnaissance nature. The short time spent on the islands was mostly used in obtaining petrographic and volcanologic data. Much more work should be done in sedimentology and paleontology; careful studies of the various profiles are necessary, and an identification of the source material of the various sedimentary beds should be attempted.

Data from such studies may become of great importance to the study of Pleistocene geology. They may unravel details of glaciation and land elevation, in particular they may serve to correlate in space and time the lava outpours with epirogenic movements or changes in sea level.

FOSSILS

Fossil shells from the Pribilof Islands were collected by Ilia Wossnessensky more than one hundred years ago (Grewingk, 1850) and by Elliott in 1872–74 (1875, 1887, 1895). Later investigators include Stanley-Brown (1892), Dawson (1894), Dall (1892, 1896, 1899, 1919), Gilmore (1908) and Hanna (1919).

A few shells collected during the summer of 1948 were studied by Dr. Charles E. Weaver who decided that the fossils were probably of Pleistocene age. Subsequently, my collection was compared with the material from the region in the Alaskan collection of the Geological Survey. Mr. F. S. MacNeil prepared the following report:

St. Paul:

Black Bluffs, east of the village.

Pelecypoda:

Cardita (*Cyclocardia*) sp., a completely decorticated specimen.

Astarte sp. cf. *A. rollandi* Bernardi

St. Paul—Continued
- Einahnuhto Bluffs, west coast under Rush Hill.
  - Gastropoda: *Colus* sp.
  - Pelecypoda:
    - *Astarte* sp. cf. *A. rollandi* Bernardi
    - *Panomya*? fragments of a heavy large pelecypod with an irregular surface.

St. George:
- East coast at Sea Lion Point.
  - Gastropoda: *Natica* sp. cf. (*Tectonatica*) *clausa* Broderip and Sowerby—internal molds.
  - Pelecypoda:
    - *Laevicardium* (*Cerastoderma*) sp. cf. *L. californiense* (Deshayes), internal molds.
    - *Serripes* sp. cf. *S. gronlandicus* (Bruguiere), internal molds.
    - *Mya* sp. cf. *M. arenaria* Linnaeus var.? internal mold.
    - *Saxicava* sp. cf. *S. arctica* Linnaeus, internal mold.
- East coast at Garden Cove.
  - Gastropoda:
    - *Colus* sp., internal mold.
    - *Trichotropis bicarinata* Sowerby, internal mold.
  - Pelecypoda:
    - *Astarte?* sp., poor internal mold.
    - *Cardita* (*Cyclocardia*) sp. cf. C. *crebricostata* (Krause), fragments.
    - *Laevicardium* (*Cerastoderma*) sp. cf. *L. californiense* (Deshayes), internal molds and fragments.
    - *Serripes*sp. cf. *S. gronlandicus* (Bruguiere), internal and external molds.
    - *Macoma* sp. cf. *M. calcarera* (Gmelin)
    - *Mya* sp. cf. *M. arenaria* Linnaeus
    - *Saxicava* sp. cf. *S. arctica* Linnaeus, internal molds.

All collections are roughly contemporaneous and probably of early Pleistocene or, at the earliest, late Pliocene age. The Hanna collection (1918) from near Tolstoi Point, St. George Island, is from rock like that at Sea Lion Point and Garden Cove and contains several forms which are believed to be extinct.

Paleontological evidence of a more uncertain character is connected with scattered remains of mammoth in the Pribilof Islands. It is said that in 1836 a tooth was found on St. George Island (Dall, 1892, 1896) and a tusk in the sands of Northeast Point on St. Paul Island. Dawson (1894) concluded that this indicates a former connection with the mainland. In 1897, two teeth of a mammoth and bones of a bear, apparently distinct from the polar bear were obtained from a lava cave at crater on Bogoslof Hill, St. Paul Island (Maddren, 1915). Preble and McAtee (1923) think that the remains were transported to the island by ice and that their occurrence has no special geologic significance.

PETROGRAPHY

PERIDOTITE

The distribution of peridotite, shown on plate 20, commands special interest in that it seems rather unrelated to any other rock type in the area. It is massive; the joints, which in places are very conspicuous, have no system. The original rock was made up of anhedral, randomly oriented crystals of olivine; now the crystals have separated along cleavage planes and grain boundaries where they are altered to serpentine (fig. 24) with a very small amount of magnetite (fig. 28A). Serpentine occurs partly in irregular bands dissecting the rock in all directions, partly as fine veinlets growing into the individual olivine crystals. Olivine shows $\beta=1.665$, $\gamma=1.687$, corresponding to Fo_{92}, Fa_8; the serpentine is magnesian without any iron.

Chemically and mineralogically (see following table) this rock seems unrelated to any other rock type in the Pribilof area. Gen-

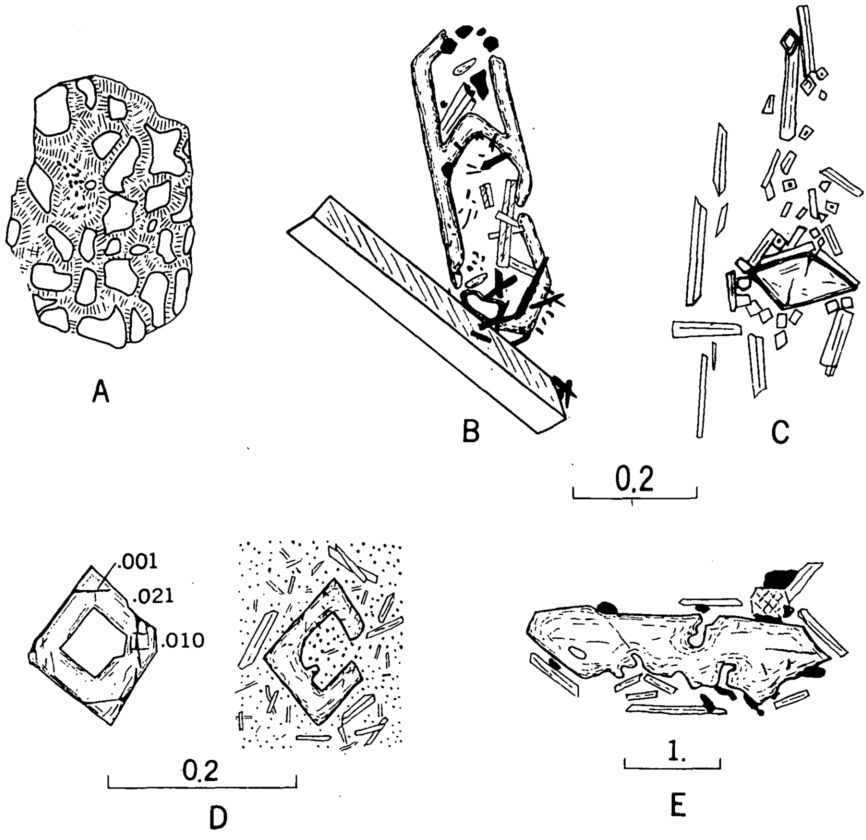

FIGURE 28.—Minerals in lavas. *A*, Serpentinized olivine from peridotite, Garden Cove, rock sample 1· Olivine, serpentine, and a small amount of magnetite. *B*, Olivine crystal in a state of resorption from plagioclase-hematite rock sample 18, top of road between village and Zapadni Bay, St. George Island. Olivine, plagioclase and hematite. *C*, Olivine phenocrysts and plagioclase laths illustrating preferred orientation in feldspathic basanite from rock sample 9 northeast shore of Otter Island. *D*, Hollow phenocrysts of olivine, plagioclase laths, and black pigments of magnetite in glass groundmass. Basanite rock sample 17 intrusive into Rush Hill, St. Paul Island. *E*, Resorbed olivine phenocryst in fluidal glass ground-mass). Basanite flow, Tolstoi Point, St. Paul Island. Scales in millimeters.

erally, dunites are found in the folded mountains. Here, on the concave side of the Aleutian arc, the peridotite may represent an upwelling of the substratum. Olivine nodules found in basanites on both St. George Island and St. Paul Island (p. 144) may represent fragments of this substratum.

Chemical and mineralogical composition of peridotite, Garden Cove, St. George Island

[Analyst, B. Bruun]

		Norm [1] (without water)		*Mode* [1]	
SiO_2	39. 83				
TiO_2	tr.	Ab	1. 2	Serpentine	70
Al_2O_3	1. 54	An	. 6	Olivine	26
Fe_2O_3	3. 70	C	1. 1	Magnetite	3
FeO	3. 77	Hy	23. 5		
MnO	. 12	Ol	70. 0		
MgO	41. 95	Mt	3. 7		
CaO	. 10				
Na_2O	. 12		100. 1		
K_2O	. 01				
P_2O_5	. 04				
H_2O+	8. 34				
H_2O-	. 62				
CO_2	tr.				
	100. 14				

[1] Throughout this paper the molecular norm and mode are used, correspondong to the "äquivalenten Molekularprozente" of Niggli (1936).

APLITE

Aplite is another rock that seems rather unrelated to any other rock type in the area. The mode of occurrence of this stock is shown in figure 29. It is intrusive into the peridotite and composite in character, has very fine-grained chilled margins, and a medium-grained, granular central portion. There is an appreciable difference in composition between the rock of the chilled margin and the central portion rock. The transition is gradual but seems to take place over a small distance (less than one yard); the width of the fine-grained margin is about 30 feet, the width of the total intrusion about 1,300 feet. In table 5, analysis 3 and 4, the chemical composition, norm, and mode of the two portions of the dike are listed.

The central portion is a holocrystalline, granular rock essentially consisting of plagioclase (strongly zoned oligoclase $n \cong 1.543$), in tabular subhedral crystals forming a sort of blocky mesh, with clear quartz filling the interstices between feldspars. Fresh red garnet is present in very small amounts ($n=1.790$). Sericite has replaced a good deal of the plagioclase, in many cases beginning with the inner zone leaving the rim relatively fresh. Chlorite occurs in elongate, unoriented shreds and in scaly masses between feldspars.

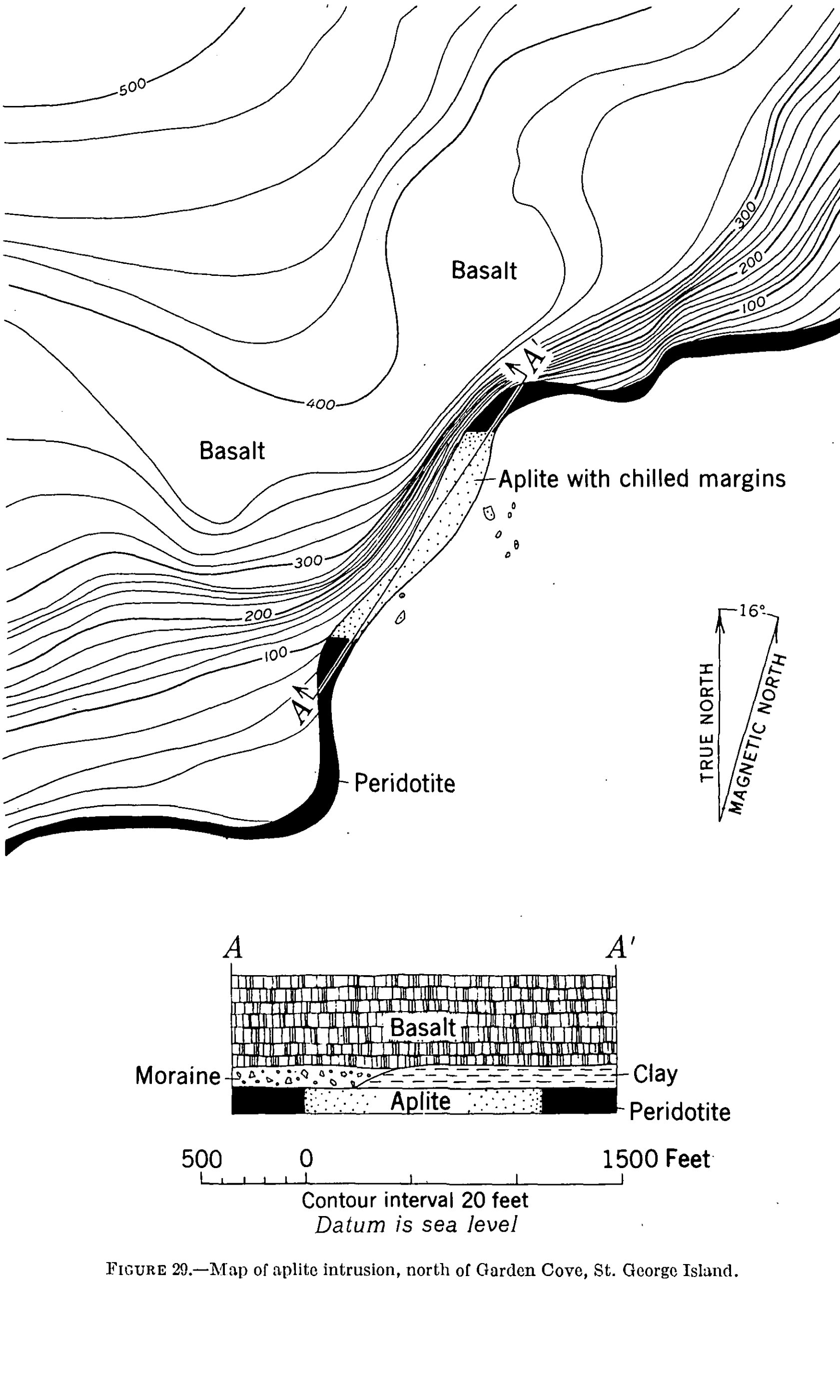

FIGURE 29.—Map of aplite intrusion, north of Garden Cove, St. George Island.

The marginal portions are made up of a very fine grained, almost dense rock with small, poorly defined phenocrysts of an albite-rich, nonperthitic alkali feldspar partly altered to sericite and quartz. The groundmass consists essentially of countless small, needlelike laths of albite-rich feldspar displaying a very definite subparallel orientation; they are altered and intergrown with quartz, sericite, chlorite, and a nameless yellowish powdery product probably iron staining. A very small amount of garnet is present.

A discussion of the mode of formation of this composite dike has been given in a previous paper in which the author (Barth, 1952) concluded that a difference in composition between the outer and inner portions of the dike could best be explained by a process of thermal diffusion as defined by Wahl (1946).

If the original magma was homogeneous the necessary diffusion to produce the two fractions is shown in table 1. The figures demonstrate that the necessary migration is, indeed, on a modest scale: in a reference volume containing more than 2,600 atoms a net diffusion of only 7 atoms each way suffices to bring about the observed compositional differences between the chilled-margin rock and the central rock.

The calculated composition of the original homogeneous magma as given in column 3 of table 1 corresponds to 1 part of the chilled-margin phase and 10 parts of the central-portion phase. It is not possible to determine the volume relations with certainty. The intrusion is about 1,300 feet wide, the marginal parts are about 33 feet wide. If the intrusion is circular the proportion of margin to core is 1: 10, but less if the intrusion has the shape of a plate. However, the accurate figure is of no consequence for the following discussion, and is therefore, somewhat arbitrarily, taken as 1: 10.

TABLE 1.—*Comparison of standard cells*

	1	2	3		1	2	3
Si	62.0	56.6	57.1	Na	8.6	7.1	7.3
Ti	--------	.1	.1	K	3.5	2.7	2.8
Al	15.8	18.4	18.2	P	.1	.4	.4
Fe [1]	1.3	3.2	3.0	H	7.2	11.2	10.8
Mg	.3	1.3	1.2				
Ca	.6	2.6	2.5	O	160.0	160.0	160.0

[1] Ferrous iron, ferric iron, and manganese are added together.

1. Chilled-margin rock; recalculated from column 4, table 5.
2. Central-portion rock; recalculated from column 3, table 5.
3. Calculated composition of the original homogeneous magma.

If calculation of the cations is referred to a unit of 1,600 oxygens (a unit of 10 standard cells) the following cation migration must have taken place into the marginal part (round numbers):

5 Si
1 Na
1 K

---

7 cations

and into the central part:

2 Al
2 F
1 Mg
2 Ca
4 H

---

7 cations + 4 protons

Still unsolved is the problem of the relation of the original dike magma to the other rock magmas present in the Pribilof area. The dike is older than the lava flows and cannot therefore be derived from the lava. Nor can its chemical composition, according to the present theories, be derived from a magma similar to that of the Pribilof lava. A possible connection between this dike and the glassy material found at the Polovina Hill, St. Paul Island, is discussed on page 137.

LAVA

GENERAL FEATURES

Basanite is basaltic lava containing an appreciable quantity of nepheline. It is rather common in these rocks that nepheline and (or) plagioclase are not expressed as actual minerals but are hidden in the glass groundmass; following the usage of Washington (1930) we shall distinguish rocks with hidden nepheline in the glass as hyalobasanites. Lacroix (1928) has used the special names, basanitoid if nepheline is hidden, mandchourite if plagioclase is hidden, and limburgite if both plagioclase and nepheline are absent mineralogically. Pribilof type is here used if augite is hidden in the glass groundmass, whereas olivine and plagioclase represent the only minerals actually present in the rock.

The lava flows that cover the largest parts of the Pribilof area issued from fissures and are alkali subbasaltic in habit and composition. The four main types of lava show gradual transitions into each other.

1. Chrysophyric basalts: olivine and subordinate amounts of augite as phenocrysts, groundmass of olivine, augite, plagioclase, and magnetite. Very small amounts of glass are usually present.

2. Aphyric, well crystallized olivine basalts: olivine, augite, plagioclase, and magnetite.

3. Chrysophyric hyalobasanites: olivine and augite in subordinate amounts as phenocrysts, groundmass of olivine, augite, plagioclase, magnetite, and glass. This type is dominant on the islands.

4. Aphyric, olivine hyalobasanites: plagioclase, olivine, augite, and magnetite of fine grains in a glassy groundmass.

On St. Paul Islands all flows and sills examined are olivine hyalobasanite. The majority are porphyritic with much olivine and little augite as phenocrysts and a very fine grained groundmass of augite, plagioclase, olivine, magnetite, and glass. They contain about 10 percent normative nepheline. Another large group of lavas is represented by specimens in which olivine likewise shows a tendency to porphyroid texture, but the groundmass is so coarse as to obscure the porphyritic structure, that is, the grains of olivine, augite, and plagioclase are nearly equal in size. Only a little glass is present, and only small amounts of nepheline appear in the norm. A big lava flow between Bogoslof Hill and Lake Hill contains plagioclase as well as olivine and augite as phenocrysts.

On St. George Island again the majority of the lava flows and sills are olivine hyalobasanites containing predominant olivine and more sparsely augite phenocrysts in a groundmass of augite, plagioclase, olivine, magnetite, and glass. Normative nepheline attains 15 percent. Another group consists of aphyric, rather coarse-grained lavas in which the three chief minerals, olivine, augite, plagioclase, assume nearly equal dimensions, although the olivine still has a tendency to appear as phenocrysts. Glass is sparsely present, and the amount of normative nepheline is small. All these rocks are rather ferric, and have a color index higher than 50. One flow (top of the ridge northwest of Garden Cove) contains both plagioclase and olivine as phenocrysts, the groundmass is of the usual kind, and the rock is still rather mafic. One aphyric highly feldspathic, very fine grained flow (from Esogemunga) contains small grains of olivine and magnetite but no augite, in addition to plagioclase. Chemically it does not differ much from an ordinary olivine basalt. A related lava flow was observed at the northeast shore of Otter Island. Finally there is one flow of a rather ordinary olivine-free basalt on Gull Hill. It shows ophitic structure with plagioclase laths and grains of a pigeonitic augite.

MINERAL COMPONENTS

Olivine crystallized first in most magmas, forming conspicuous phenocrysts, in many places several millimeters long. The range of composition, determined by measuring the axial angle and the indices of refraction, is rather small: $Fo_{90}Fa_{10}$ to $Fo_{75}Fa_{25}$. Zoning is common.

In some rocks, olivine is thoroughly stained with red or "rusty" material, and in some fumed rocks, for example, sample 18, hematite has grown from olivine, which has become almost pure forsterite. Olivine phenocrysts are usually euhedral but show signs of strong resorption, pitting, and parting along cleavage planes. But conversion to pyroxene does not seem to take place. Probably olivine has no reaction relation to the pyroxene of the present magma. Peculiar "hollow" crystals have a tendency to form in many rocks (see fig. 28).

Pyroxene occurs in the groundmass of all lavas. Phenocrysts likewise occur, but in most rocks they are completely outnumbered by olivine phenocrysts. The composition corresponds to a titaniferous augite. The crystals in thin section are light-reddish brown with absorption alpha greater than gamma. The optical axes are highly dispersed, $r>v$, the angle being about (+) 2 $V=60°$, but may drop to 50°, extinction varies somewhat but is close to $\gamma \wedge c \cong 45°$, an average index of refraction is $\beta=1.70$. Zoning is conspicuous in most augites, hourglass structure is common. Pigeonitic pyroxenes have not been observed; the course of crystallization is from diopsidic to hedenbergitic, that is, all pyroxenes are calcic and therefore show no reaction relation to olivine. During most of the crystallization period, olivine and pyroxene separated together.

Plagioclase is rarely observed as phenocrysts. All over the Pribilof area the lava flows apparently were so mafic that olivine and part of the augite separated before any feldspar could crystallize. In the groundmass of most lava flows, plagioclase is present. It is always zoned, with composition ranging from An_{80} to An_{35}. More sodic plagioclase has not been observed.

Glass is present in many lava flows; it is colorless in thin sections. The refractive index is close to 1.54. Most lava is rather low in silica and high in alkalies, leading to the presence in the norm of an appreciable amount of nepheline and orthoclase; neither mineral is present in the glass base.

ANALYSES OF LAVAS

Sample 6. Columnar, dense flow of chrysophyric hyalobasanite, two-thirds of a mile south of Tolstoi Point, St. George Island (fig. 26). The phenocrysts are fresh, euhedral olivine crystals. The groundmass consists of a brownish glass in a state of devitrification containing small grains of olivine, augite, plagioclase, and magnetite. Many secondary growths of chalcedony and zeolite occur throughout the glass.

Mode		*Composition of the glass*	
Olivine	25	Or, Ab	6
Augite	20	An	12
Ores	5	Ne	12
Apatite	1	Di	2
Plagioclase (An_{70})	14	Ol	1
Glass	33		33
Chalcedony, zeolites and alteration products	2		
	100		

Sample 7. Large pebble of hyalobasanite from St. Paul Island, collected by Mr. Rauch and analyzed by M. G. Keyes (1930): Phenocrysts are yellow olivine (Fa_{20}) making up about 5 percent of the rock with an occasional phenocryst of black augite. The groundmass consists of thin laths of labradorite, irregular grains of brownish augite, and small rounded grains and some skeletons of ore. Considerable colorless glass is present which has a refractive index of $n=1.53$-1.54.

Sample 8. Dense flow of chrysophyric hyalobasanite, cropping out over a distance of several miles along the west shore (and under Einahnuhto Bluffs), St. Paul Island. The rock is gray with finely crystalline groundmass studded with clear, yellow phenocrysts of olivine from 1 mm to 10 mm across, some zoned, with a refractive index $\beta \cong 1.690$, $2\ V \cong 90°$, corresponding to about Fa_{20}. Very few phenocrysts are clinopyroxene; they are always zoned and usually pitted and intergrown with minerals of the groundmass. Positive $2\ V = 60°$; $\gamma \wedge c = 44°$, $\beta = 1.700$, corresponding to He_{40}. The glassy groundmass includes small grains of olivine and pyroxene. Small plagioclase laths form a mesh; indices of refraction lie in the range 1.555–1.565, indicating about An_{55}. The glass shows incipient crystallization, index $n=1.53$-1.54.

Mode			*Composition of the glass*	
Olivine	24	Phenocrysts	Or, Ab	7.0
Augite	4	Phenocrysts		
Olivine	5	Groundmass		
Augite	19	Groundmass	An	3.5
Ores, apatite	4	Groundmass	Ne	8.0
Plagioclase (An_{50})	23	Groundmass	Hy	1.5
Glass	20	Groundmass		20.0
	99			

Sample 9. Holocrystalline flow of aphyric basanite (pacificite defined as "feldspathic basalts, without nepheline and usually with olivine the analyses of which show the presence of . . . nepheline in the norm, although none of this appears in the rocks" by Barth in 1931, p. 401–402), northeast shore of Otter Island. The rock is very fine grained; rare microphenocrysts of plagioclase and pyroxene are seen. The groundmass shows sharp, small euhedral crystals of olivine, and very small crystals of pyroxene. The plagioclase laths average 0.02×0.0015 mm and show a vague preferred orientation. (See fig. 28.)

Mode		*Composition of the feldspars*	
Olivine	21	Or	9. 5
Diopsidic augite	10	Ab	26. 0
Ores, apatite	5	An	23. 5
Zoned feldspars	64	Ne	5. 0
	100		64. 0

The observed range of the feldspars is from An_{55} to An_{35}. Average composition is An_{40}. Nepheline could not be identified with the microscope.

Sample 10. Dense flow of phyric hyalobasanite, southeast point of Otter Island. Olivine augite, and plagioclase occur as phenocrysts. Augite is commonly twinned, $\gamma \wedge c = 43°$, (+) $2V = 50° - 55°$, $r > v$ distinct. The plagioclase crystals are also twinned, extinction angles correspond to An_{60}. In the groundmass the plagioclase ranges from An_{60} to An_{35}.

Mode			*Composition of the glass*	
Olivine	1	Phenocrysts	Or, Ab	6
Augite	1	Phenocrysts	An	3
Plagioclase (An_{60})	3	Phenocrysts	Ne	7
Olivine	8	Groundmass	Hy	2
Augite	24	Groundmass		18
Ore, apatite	5	Groundmass		
Plagioclase (An_{42})	40	Groundmass		
Glass	18	Groundmass		
	100			

Sample 11. Vesicular gray flow of olivine basalt, pacificite, northeast point of St. Paul Island. The rock is well crystallized with olivine and augite ranging in grain size from 0.1 to 1 mm, the lengths of the plagioclase laths range from one-third to 3 mm. Nepheline could not be identified with the microscope.

Mode		*Calculated composition of the feldspars*	
Olivine	15	Or	6. 5
Augite	21	Ab	28. 0
Ore, apatite	6	An	21. 0
Zoned feldspar (ranging from AN_{60} to An_{30})	58	Ne	2. 5
	100		58. 0

Sample 12. Vesicular, columnar flow or sill or aphyric olivine basalt, between Zapadni Bay and Red Bluffs, St. George Island. The rock consists of large, randomly oriented laths of plagioclase forming an irregular meshwork filled with olivine, augite, apatite, and magnetite, the latter being in large measure a reaction product of olivine; indeed, the olivine has the properties of pure forsterite, indicating that the fayalite component has been used up in the reaction.

Mode	
Olivine (Fo_{10})	9
Augite	27
Ore, apatite, and decomposition products of olivine	12
Plagioclase (An_{46})	52
	100

Sample 13. Glassy olivine basalt, Pribilof type, a vesicular gray flow or sill of a glassy basaltoid rock from Esogemunga escarpment, St. George Island. The only crystalline silicates are olivine in small grains measuring about 0.05 mm across, and plagioclase in laths about 0.07 x 0.01 mm. They lie in a glassy, inhomogeneous matrix containing ore and apatite in distinct crystals, and various unidentified products of incipient crystallization. Such lavas are unusual, but a very similar variety has been described by Powers (1932, p. 275, 286, 290). The Pribilof type basaltoid lava flows have olivine, plagioclase, and glass as the only essential phases.

Mode		*Composition of the glass*		*Percent*
Olivine Fa_{24}	21	Q	1. 8	5
Plagioclase (An_{45})	36	Or	4. 0	45 (Or + Ab)
Ore, apatite, etc	8	Ab	12. 0	
Glass	35	An	7. 0	20
	100	Di	10. 8	30
			35. 6	100

In table 2 the cation percentages of the rock are listed to show the method by which the mode has been computed.

TABLE 2.—*Computation of mode, rock sample 13*

Computed mode		Cation percentages									
Modal mineral	Percent	Si	Ti	Al	Fe	Fe Mn	Mg	Ca	Na	K	P
Olivine, Fa_{24}	21.3	7.1	------	------	------	3.4	10.8	------	------	------	------
Ore, apatite	4.3	------	0.5	------	2.5	.5	------	0.5	------	------	0.3
Sphene	2.4	.8	.8	------	------	------	------	.8	------	------	------
Plagioclase, An_{45}	36.5	18.6	------	10.6	------	------	------	3.3	3.8	0.2	------
Glass	35.5	19.5	.1	5.9	------	2.5	.2	4.1	2.4	.8	------
Total	100.0	46.0	1.4	16.5	2.5	6.4	11.0	8.7	6.2	1.0	0.3

A comparison of this mode with the norm (table 6) brings out the following facts. The norm has a composition not uncommon to an ordinary olivine basalt with much more pyroxene than olivine. In the actual rock the observed amount of olivine is almost three times as large as that appearing in the norm; obviously the olivine has crystallized out in excess of its stoichiometric proportion; it has taken away from the melt a good deal of the ferromagnesian cations and has later failed to react with the melt which, therefore, has retained its silica to such an extent that quartz appears in the norm of the residual glass. The residual glass is also interesting in that in its composition it comes close to the artificial haplodioritic melts studied by Bowen (1915). If the normative potash and soda feldspar of the glass are added together and called albite, the projection point of the glass falls approximately on the cotectic curve of the haplodioritic system albite-anorthite-diopside, as was to be expected of a glass representing a residual melt.

Clearly the formation of a basalt of Pribilof type depends upon special physicochemical conditions during the rise and the effusion of the lava; in the usual cases the same lava would have produced a rather ordinary olivine basalt.

ANALYSES OF BASIC DIKES

The lava flows of the islands at many places are transsected by dikes with similar composition to that of the flows (see fig. 26 and analyses nos. 14–19, table 7). Sills are in most places indistinguishable from flows. But sills do exist (see fig. 31), and indeed, many of the apparent "flows" overlain by sediments may actually represent sills. A dike intrusive into a pyroclastic cone is pictured in figure 32 (p. 134).

Sample 14. Apophysis of limburgite at the seashore (fig. 30) 1 mile south of Garden Cove, St. George Island. On top of the basal peridotite is a thin, discontinuous layer of clay with boulders of peridotite. Right on top of it is a sheet of a semicrystalline, porphyritic hyalobasanite about 3 feet thick. It may be a flow, but the following observations make it reasonable to regard it as a sill: Figure 30 shows that

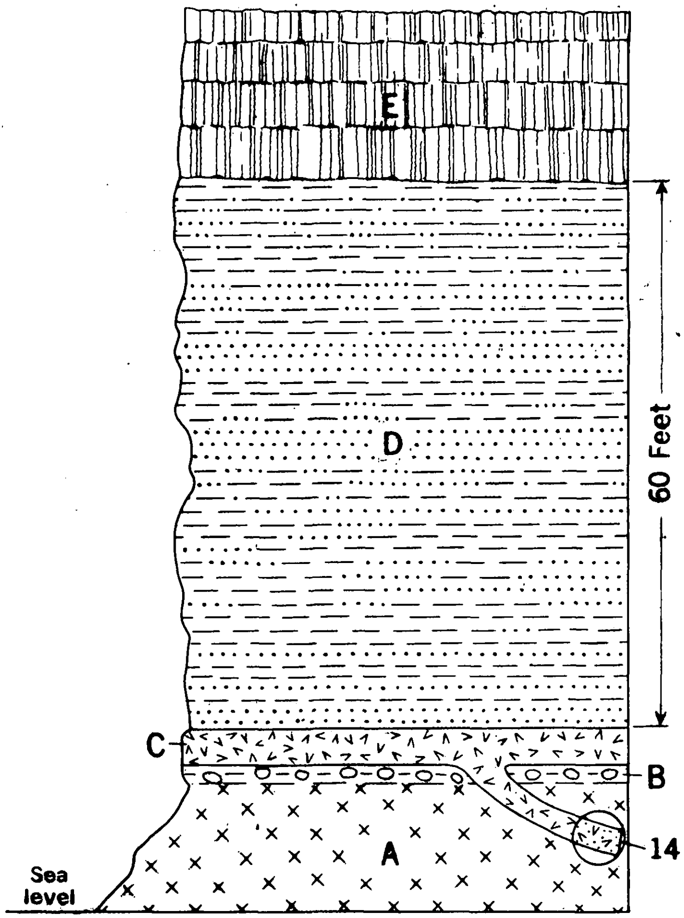

FIGURE 30.—Section at the seashore 1 mile south of Garden Cove, St. George Island. *A*, peridotite, *B*, thin layer of clay with boulders of peridotite; *C*, sill of hyalobasanite sending an apophysis down into the peridotite; at 14 the basanite has become limburgitic (analysis 14); *D*, sediments, 59 feet thick, consisting of clay, sand, and tuff with fragments of peridotite; crossbedding is conspicuous; *E*, lava flow with incorporated sedimentary material. At the top of this lava another series of sediment is deposited and again overridden by lava flows. Total height of the cliff is about 200 feet.

the basanite sends apophyses into the peridotite, indicating that the basanite is no flow but rather a sill intruded between the peridotite and the overlying sediment, and penetrating into fractures or cracks in the surface of the peridotite. In the apophyses the basanite becomes very dense and black but still remains slightly porphyritic. The thin sections reveal that it corresponds to a limburgite containing olivine, augite, and magnetite but practically no feldspar, as primary phases. Olivine shows 2 $V \cong 90°$, but is often distinctly zoned. Augite is reddish in color, shows hourglass structure and is highly zoned. Positive 2 V is around 60° with strong dispersion $r>v$; the directions of the extinctions are also highly dispersed, $\gamma \wedge c=45°$. It is a titaniferous augite. Zeolites are seen in cavities. Chemical analyses, norm and mode, are shown in table 4. A special description of the mechanism of crystallization in this dike is given on pages 141–143.

Sample 15. Dense dike of chrysophyric hyalobasanite, following a fault zone extending from the seashore 1 mile south of Tolstoi Point, southwestward toward Zapadni Bay, St. George Island (see fig. 26). In thin sections this dike rock is essentially similar to sections of lava flow sample 6, except that no secondary growths of zeolite or chalcedony were observed.

Mode		*Composition of the glass*	
Olivine	24	Or, Ab	7
Augite	20	An	11
Ores	5	Ne	11
Apatite	2	Di	2. 6
Plagioclase (An_{60})	16	Ol	0. 3
Glass	32		
			32. 0
	99		

Sample 16. Phyric hyalobasanite forming a dike spreading out to a sill (fig. 31), one-third of a mile, east of village, St. George. Phenocrysts of olivine and augite make up about 30 percent of the rock. The groundmass is fine grained with very small crystals of pyroxene, olivine, and magnetite in a meshwork of plagioclase laths and glass.

Mode			*Composition of the glass*	
Olivine	12	phenocrysts	Or, Ab	5
Augite	17	phenocrysts	An	5
Olivine	6	groundmass	Ne	11
Augite	10	groundmass	Di	1
Ore, apatite	6	groundmass		
Plagioclase (An_{55})	27	groundmass		22
Glass	22	groundmass		
	100			

Sample 17. Hyalobasanite injected under observation house at Einahnuhto Bluffs, St. Paul Island. (See fig. 32.) The rock has fluidal structure, is black and gray with small phenocrysts of plagioclase, about 0.5 x 0.01 mm, and peculiar "hollow" phenocrysts of olivine, from 0.1 to 0.5 mm across (see fig. 28). The groundmass is glassy with opaque pigments of magnetite and (or) ilmenite, and small grains of augite 0.01–0.02 mm in diameter and laths of plagioclase, about 0.5 mm long and 0.01 mm thick.

Mode			*Composition of the glass*	
Olivine (Fe_{90})	5	Phenocrysts	Or, Ab	12
Plagioclase (An_{70})	1	Phenocrysts	An	6
Olivine	6	Groundmass	Ne	13
Augite	25	Groundmass	Hy	2
Ore, apatite	5	Groundmass		
Plagioclase (An_{40})	25	Groundmass		33
Glass	33	Groundmass		
	100			

Sample 18. Ore basalt, forming a sill or dike on top of road between the village and Zapadni Bay, St. George Island. To the eye and under a low power lens the rock appears dark and almost dense because of its unusually high percentage of ore. It is very fine grained with some odd, small phenocrysts of plagioclase (optical constants corresponding to An_{60}), and a very few, small phenocrysts of olivine (fig. 28*B*) that are almost wholly resorbed and often obscured by tiny

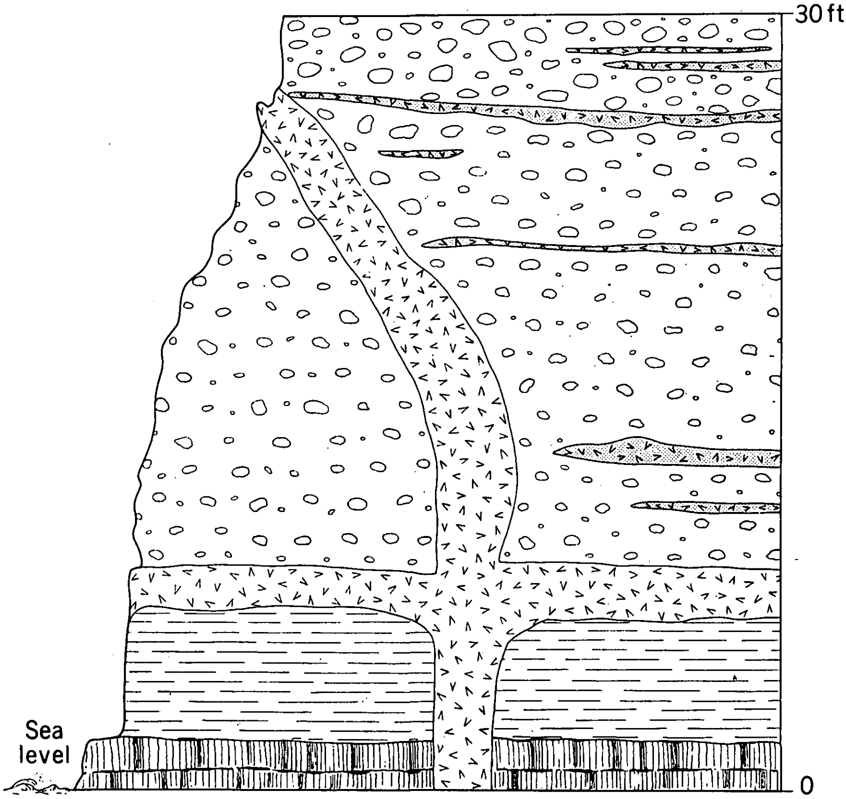

FIGURE 31.—Dike spreading out to form a sill. Section at the seashore one-third mile east of the village, St. George Island.

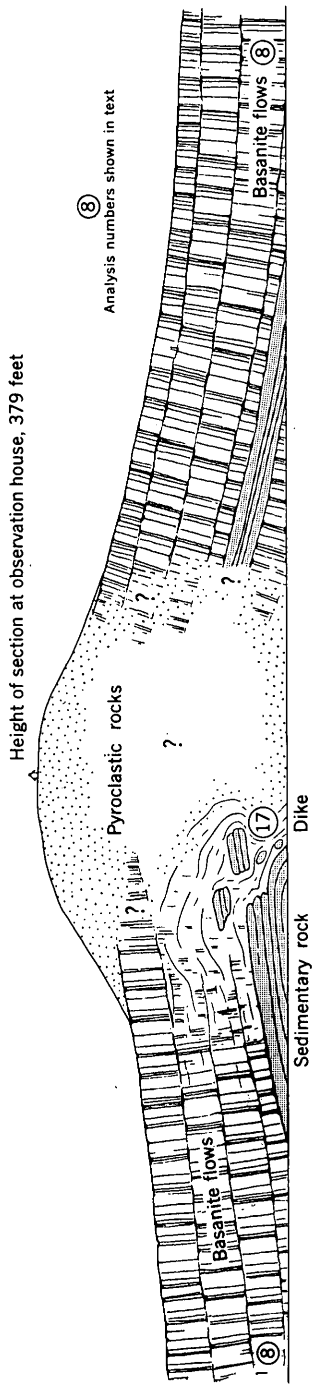

FIGURE 32.—Section through Einahnuhto Bluffs, west coast of St. Paul Island.

grains of ore (hematite?) which have grown along closely spaced cleavage planes. Some olivines have been effectively replaced by ore. The profusion of ore gives the rock its distinctive character.

Mode

Olivine (pure forsterite)	3. 0
Augite (diopsidic)	17. 4
Ore (2.0 ilmenite+7.6 hematite)	9. 6
Apatite	1. 0
Plagioclase (An_{34})	69. 0
	100. 0

It is reasonable to assume that the iron necessary for the production of the ore minerals was in part taken from the original olivine and augite during the stewing of the rock in hot vapors and other volcanic gases, deuteric or otherwise. The separation of finely granular ore is, according to Macdonald (1944), common in reheated (?) olivine phenocrysts in blocks thrown out of Halemaumau crater, Kilauea.

Dr. H. S. Yoder of the Geophysical Laboratory has informed me that L. O. Nicolaysen made some hydrothermal tests on fayalite under oxidizing conditions. He found that fayalite is destroyed at all temperatures investigated (250°–970° C and 100 atmospheres). Above approximately 350° C he gets magnetite plus quartz, and below hematite plus quartz. This gives an idea about the temperature at which the alteration of the present rock has taken place.

Sample 19. Olivine basalt, at Fox Castle, St. George Island. Fox Castle is a huge pile of loose lava blocks forming a "castle" which seems to represent the top of a dike or neck that has penetrated the tuffs in the Esogemunga fissure. The rock is well crystallized with conspicuously zoned laths of plagioclase, 1–2 mm long. According to their extinction angle the average composition is around An_{55}. Intersertally are olivine, pyroxene, and some ore in grains of 0.1 to 0.5 mm.

Mode

Olivine	11
Pyroxene	10
Ilmenite, hematite (?)	5
Sphene (?)	3
Apatite	2
Plagioclase	69
	100

Average modal composition of the plagioclases

Or	12. 5
Ab	38. 4
An	16. 8
Ne	1. 3
	69. 0

PYROCLASTIC DEPOSITS

Most of the pyroclastic material is basaltic. It is usually found as loose pebbles forming mounds or filling the interspace between two lava flows. The sedimentary beds likewise contain much pyroclastic matter. There is always much glass in this material, and an occasional pebble is made up entirely of glass. It is a black basaltic glass, highly vesicular, almost spongy, in thin sections brownish and transparent. Index of refraction is n=1.66, but it is inhomogeneous. This index is similar to that of the sideromelane of Iceland (olivine basaltic glass). The crystalline phases are olivine, which evidently always was the first to crystallize, and a fine-grained mixture of plagioclase, pyroxene, and magnetite. The rather predominant role of magnetite in these rocks is remarkable. It seems to have been introduced by pneumatolytic (or hydrothermal) activity.

There is no doubt that gas action represents one of the major factors in the formation of the pyroclastic material: Explosion pipes,

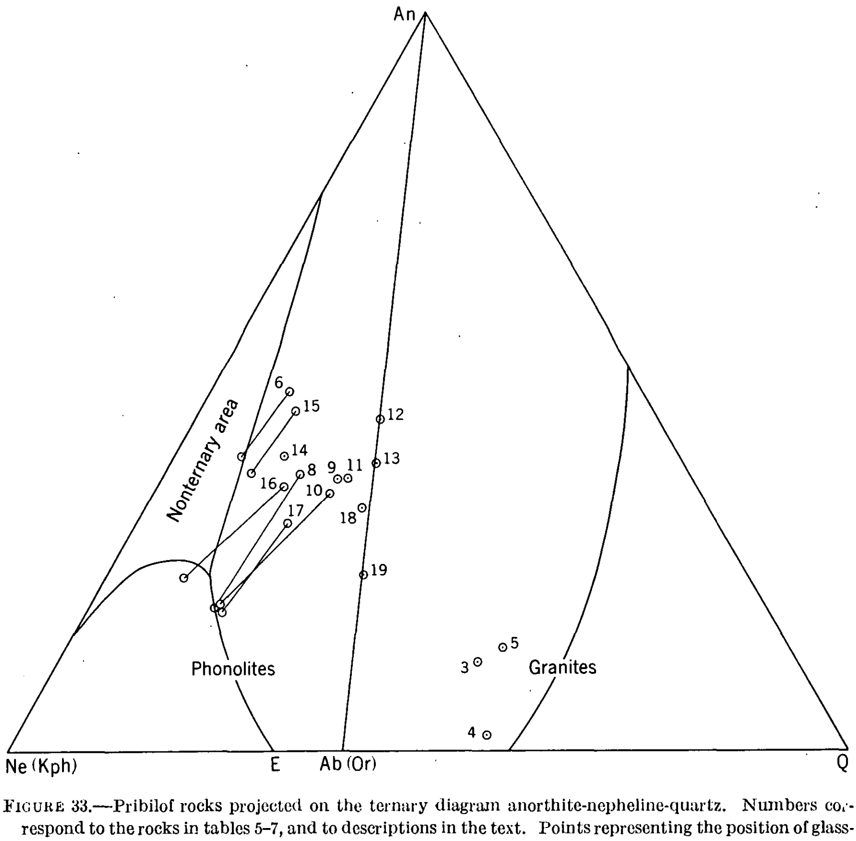

FIGURE 33.—Pribilof rocks projected on the ternary diagram anorthite-nepheline-quartz. Numbers correspond to the rocks in tables 5–7, and to descriptions in the text. Points representing the position of glass-bearing rocks are connected with corresponding glasses by lines. Cotectic lines (so far unpublished) were determined by Dr. J. F. Schairer of the Geophysical Laboratory.

chimneys through which vapor and gases found egress, also served as conduits for glassy and solid ejectamenta. The mineral composition indicates that these ejectamenta were derived from subbasaltic magma and subbasaltic rocks. The explosion craters now visible are evidently younger than the lava flows. But this does not mean that the explosive activity was limited to the last phase of the building up of the islands. The existence of layers of pyroclastic material between the lava flows, and the presence of unmistakable pyroclastic material in the sedimentary beds testify to the importance of this kind of explosive activity throughout the volcanic history of the area.

If ever a residual liquid was formed from the magma of this area, one would expect it to be associated with the gases and volatile constituents. Vestiges of such a liquid should therefore be found among the pyroclastic deposits. A thorough search was made for many days with negative results: most of the large pyroclastic cones seem to be built up entirely of subbasaltic material. But, eventually, high on the east slope of Polovina Hill, St. Paul Island, a small amount of whitish, pumiceous material was found and collected. Under the microscope it was shown to be completely glassy with an index $n=1.54$. A chemical analysis for it is listed in the following table. The rock is, therefore,

Rhyolitic glass, Polivina Hill, St. Paul Island

[n=1.54]

SiO_2	69. 09
TiO_2	. 43
Al_2O_3	14. 90
Fe_2O_3	1. 53
FeO	1. 69
MnO	. 07
MgO	1. 00
CaO	2. 97
Na_2O	4. 18
K_2O	2. 37
P_2O_5	. 33
H_2O^+	1. 31
H_2O^-	. 23
CO_2	. 00
	100. 10

Norm	
Q	25. 8
Or	13. 8
Ab	36. 7
An	12. 0
C	1. 0
Hy	3. 6
Mt	1. 5
Il	. 8
Ap	. 8
H_2O	4. 0
	100. 0

a rhyolitic glass (a glassy rock of similar chemical composition has been described under the name of cantalite in 1921 by von Leonhard) which, indeed, can be looked upon as a residual liquid but not residual in relation to the common basanitic magma of this area, that is, it cannot be derived from a basanitic magma by simple fractional crystallization; it seems to belong to an entirely different magma suite. It shows a striking chemical similarity to the magma of the aplite stock of St. George Island (fig. 33). However, the aplite is older than the lava flows, and the rhyolitic glass is younger. It occurs in negligible quantity as compared with the other rocks making up less than 10^{-12} part of the lavas of St. Paul. The pyroclastic pipes are therefore chimneys of egress for gaseous, liquid, and solid material from the practically pure basanitic sublava. The tuff vent at Esogemunga did eject feldspar crystals, however, whose composition relates them to the rhyolitic glass (see p. 140).

In one place, at Einahnuhto Bluffs on the west coast of St. Paul Island an imposing sea cliff, 379 feet high, plunges precipitously into the sea, thus cutting a vertical section through the peripheral parts of the Rush Hill cone of pyroclastic material. The following sequence of events can be read out of the sketch in figure 32: Lava flows were extruded, one on top of the other, interrupted by periods of sedimentation; during this time the area was close to sea level. Towards the end of the eruptive period, incarcerated volcanic gases built up a tremendous pressure underneath. The roof of solid lava was lifted approximately 100 meters, and the adjacent flows tilted up for a distance of about 1¼ miles from the central bulge. Then, with rupture of the restraint imposed, paroxysmal explosion of the gases occurred. The liquid lava in the pipe, highly charged with gases that through the release of pressure suddenly came out of solution, was inflated and became spongy; then it quickly congealed as it was flung out of the throat.

Thus was formed the bulk of the pyroclastic material that broke up the overlying solid lava, penetrated laterally and disrupted the adjacent lava flows and sedimentary beds, and eventually was deposited in great amounts around the orifice of the pipe, forming an impressive cone of cinders and pyroclastic material, attaining an altitude of 650 feet on top of the tilted lava flows. Following the explosive discharge of gases and pyroclastic material, normal lava from below entered the lower end of the pipe and was forced upward. This lava was liquid except for intratelluric crystals of olivine, which had a peculiar hollow habit (fig. 28). The lava flowed upward as a viscous liquid insinuating itself between fragments of solid lava, sediments, and pyroclastic material. It is now seen as an intrusive dike, markedly fluidal in structure, that seems to merge with the older, disrupted lava flows at the top end of the dike. Petrographically the dike is a chrysophyric hyalobasanite, and chemically it is identical to the average olivine-rich basanite of the area. See analysis 17, table 7, and the petrographic description, page 132.

SOME PETROGENETIC PROBLEMS

TUFFS

The tuff deposits at St. George Island are rather unique. The sources of the huge accumulation of the material seem to be close at hand: as seen from figure 34, the Esogemunga escarpment is interpreted as the rim of a large fissure or vent filled with tuffs composed of compacted pyroclastic fragments and indurated volcanic material. A chemical analysis is entered in table 3, and analyses of large cleavage pieces of homogeneous feldspar contained in the tuff are given in the following table.

TABLE 3.—*Chemical data on tuff, 1 mile east of Suskaralogh Point, St. George Island*

[Analyst, B. Bruun]

		Norm		*Cation percentages*	*Average lava*	*Tuff*
SiO_2	35. 47	Q	1. 4	Si	42. 8	39. 5
TiO_2	2. 52	Or	9. 0	Ti	1. 5	2. 1
Al_2O_3	15. 12	Ab	4. 0	Al	16. 7⟶	19. 8
Fe_2O_3	7. 61	An	27. 5	Fe	9. 0	9. 4
FeO	2. 98	C	6. 2	Mg	12. 5	19. 3
MnO	. 21	En	38. 6	Ca	9. 4⟶	6. 6
MgO	11. 67	Mt	2. 7	Na	6. 2⟶	. 8
CaO	5. 57	Il	4. 2	K	1. 5	1. 8
Na_2O	. 37	Hm	4. 6	P	. 4	. 7
K_2O	1. 27	Ap	1. 8			
P_2O_5	. 78				100. 0	100. 0
H^2O^+	7. 84					
H^2O^-	8. 71			$+H_2O$	1. 5⟶	29. 1
CO_2	. 00					
Cl	. 00					
	100. 12					

The association of alkali feldspars with basalts is unusual, but similar feldspar fragments have been found by Mahony (1926) at or near volcanic vents belonging to the so-called Newer and Older Basalt of Victoria, Australia. Homogeneous alkali feldspar with high soda content has been described from Pantelleria by Förstner (1884) who showed it to be polymorpheous, changing from triclinic to monoclinic symmetry on heating. Apparently no one checked his observations, and they have been neglected in the interpretation of the alkali feldspar relations until Laves (1952) showed that the St. George feldspar pieces behaved similarly, possessing triclinic symmetry at ordinary temperature, inverting to monoclinic at around 500° C.

Analyses of crystals of feldspars from tuff

[Corresponding to Or_{17}, Ab_{80}, and An_3. Crystal 1 and 2 analyzed spectrographically by O. Joensuu, crystal 3 analyzed chemically by B. Bruun]

	Crystal 1	Crystal 2		Crystal 3
		Rim	Core	
CaO	0. 9	0. 43	0. 45	--------
Na_2O	8. 6	8. 9	9. 1	9. 00
K_2O	4. 1	3. 0	2. 8	2. 66

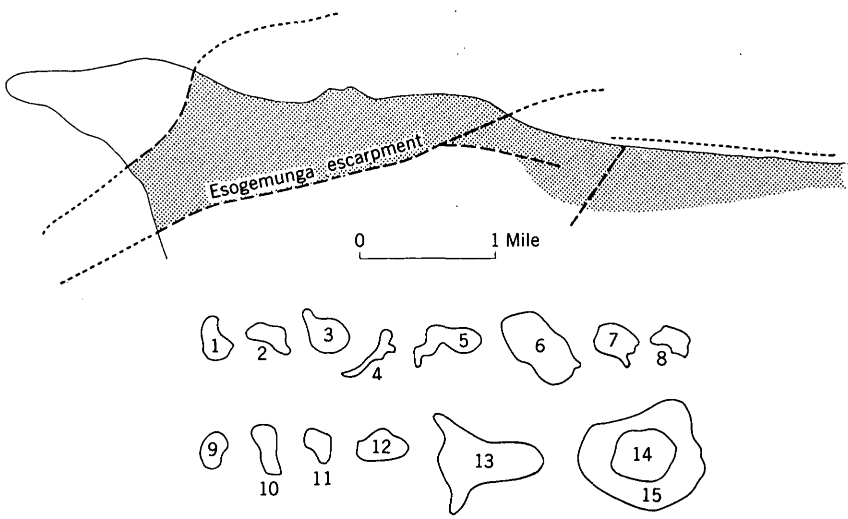

FIGURE 34.—The tuff conduit at Esogemunga, St. George Island (diagonally hatched) compared with tuff necks from Kimberley, South Africa (1–8) and from Schwaben, Germany (9–15). 1, Bulfontein; 2, Wesselton; 3, Kaffyfontein; 4, Ottos-Kopje; 5, Du Toitspan; 6, Premier; 7, Jagersfontein; 8, De Beers; 9, Grafenberg; 10, Florian; 11, Metzinger-Weinberg; 12, Neuhauser; 13, Jusi; 14, Limburg; 15, Randecker Maar. (1–15 after H. Cloos, 1941).

It is possible that the tuffaceous material has been somewhat altered by weathering and leaching. This is best seen in the norm: there is an excess of alumina and ferric iron, and a corresponding deficiency in lime and soda. Table 3 gives a direct comparison between the cation content of the tuff and that of an average lava flow (from last column of table 6), and brings out rather clearly these chemical relations.

Hans Cloos (1941) in his masterly treatise on the origin of tuff vents has demonstrated that volcanic tuffs form in consequence of an amalgamation of volcanic material from below and crustal material from above. This idea has been applied by Lehmann (1952) to explain the origin of the keratophyre tuffs of Sauerland. He introduces the word mictite to designate a tuff-magma-migmatite. The beginning of the process is a tectonic fissuring of the crust extending down to "magmatic" regions. Using the initial fissures, gas and tuffaceous material flow upward, sometimes resulting in an explosive blowout, sometimes effecting a quiet "tuffization" of the surrounding rocks.

In the Pribilof area such tectonic fissures evidently reached down into a region of olivine basanitic magma: first the fissures gave vent to the volatile material of "tuffization" followed by the ascending magma itself which in subsequent eruptions flooded the surroundings of the fissures, thus concealing the vestiges of the initial tuffaceous discharges. Only the Esogemunga fissure of St. George Island escaped destruction and remained in testimony of an early stage in the history of development of those great fissure eruptions so characteristic of many basaltic provinces (the plateau type, Hawaiian type, and others). Worthy of special notice is the fact that the Esogemunga fissure apparently represents the biggest tuff conduit on record.

Tuffs are, of course, widely distributed in many volcanic areas (Ross, 1951), but tuff conduits of this size have never been described before. The tuff pipes at Kimberley, Scwaben, and other places, are associated with volcanoes of the central vent type, and therefore of much smaller dimensions than the Esogemunga fissure (fig. 34).

LIMBURGITE

The limburgite dike (sample 14, p. 130) presents an interesting petrological problem.

The chemical data, as given in table 4, in combination with the study of thin sections suggest the following history of crystallization.

Let us assume an original melt of the composition of the rock. If ore and apatite are neglected, and potash is added to sodium, we obtain the following simplified composition of the original melt:

Ab	16	50 percent
An	20	
Ne	14	
Di	27	50 percent
Ol	23	

Studies of thin sections show that from this melt the ferromagnesian minerals (olivine and augite) crystallized first, and, indeed, continued to crystallize until the mother liquor became very feldspathic, the end product being a rock with olivine and augite as sole crystalline phases, and a feldspathic glass. This means that the Bowen reaction series of the ferromagnesian minerals was well advanced before the feldspathic-feldspathoidal series started. It is well known that rock melts rarely show eutectic crystallization. Rather there are two or more leading mineral reaction series, each crystallizing out semi-independently of the other. It is possible, therefore, in order to survey the crystallization processes of the present melt, to discuss separately the ferromagnesian types of mineral series (olivine and diopside), and the feldspathic mineral series (anorthite, albite, and nepheline). Bowen has pointed out that between the two types of series there is a suggestion of a eutectic relation, for members of one series lower the "melting" temperature of the members of the other series. Let us therefore, look at the original melt as consisting of a neutral solvent of feldspathic composition from which the ferromagnesian minerals precipitated.

The composition of the ferromagnesian fraction is 46 percent olivine and 54 percent diopside. In a dry melt of this composition (Bowen, 1914) crystallization will start with separation of olivine (at around 1,650° C.), and olivine will continue to separate until the melt becomes eutectic in composition at 13 percent olivine and 87 percent diopside at 1,387° C. These conditions will be notified by the feldspathic solvent and by the presence of volatiles, mostly H_2O; the content of H_2O will be taken, rather arbitrarily, as 4 percent, and the corresponding depression of the temperature of crystallization will be about 200° C.

The diagram in figure 35, helps to describe the crystallization process: one side of the diagram represents olivine and diopside together (melting at 1,650° C), the other side represents a mixture of albite, anorthite, and nepheline, the melting point of which can be estimated to be about 1,200° C. Between them, and close to the feldspathic side, is a (pseudo) eutectic, the temperature of which is about 50° lower. Referred to the actual rock melt containing 4 percent H_2O and other foreign ions the whole diagram will be displaced about 200° lower than that referring to dry melts. In the diagram, x represents the composition of the rock. Under intratelluric conditions and slow cooling, olivine started to separate at 1,175° C. At 1,025° C both olivine and diopside together began to crystallize out of the melt. But approximately at this stage the intrusion took place causing a rapid cooling with consequent rapid precipitation of a mixture of diopside and olivine (as now shown in the groundmass of the rock). Thus the pseudoeutectic point at 950° C was approached. But here the melt became very viscous and the cooling became very rapid because the magma penetrated into the cracks of the cold peridotite, so the actual pseudoeutectic crystallization never materialized; instead the anchieutectic liquid congealed as glass.

A feature of special interest of the present study is the demonstration of the pseudoeutectic point (actually a cotectic field) between olivine and diopside on the one side and undersaturated feldspathic mixtures on the other being located close to the feldspathic compo-

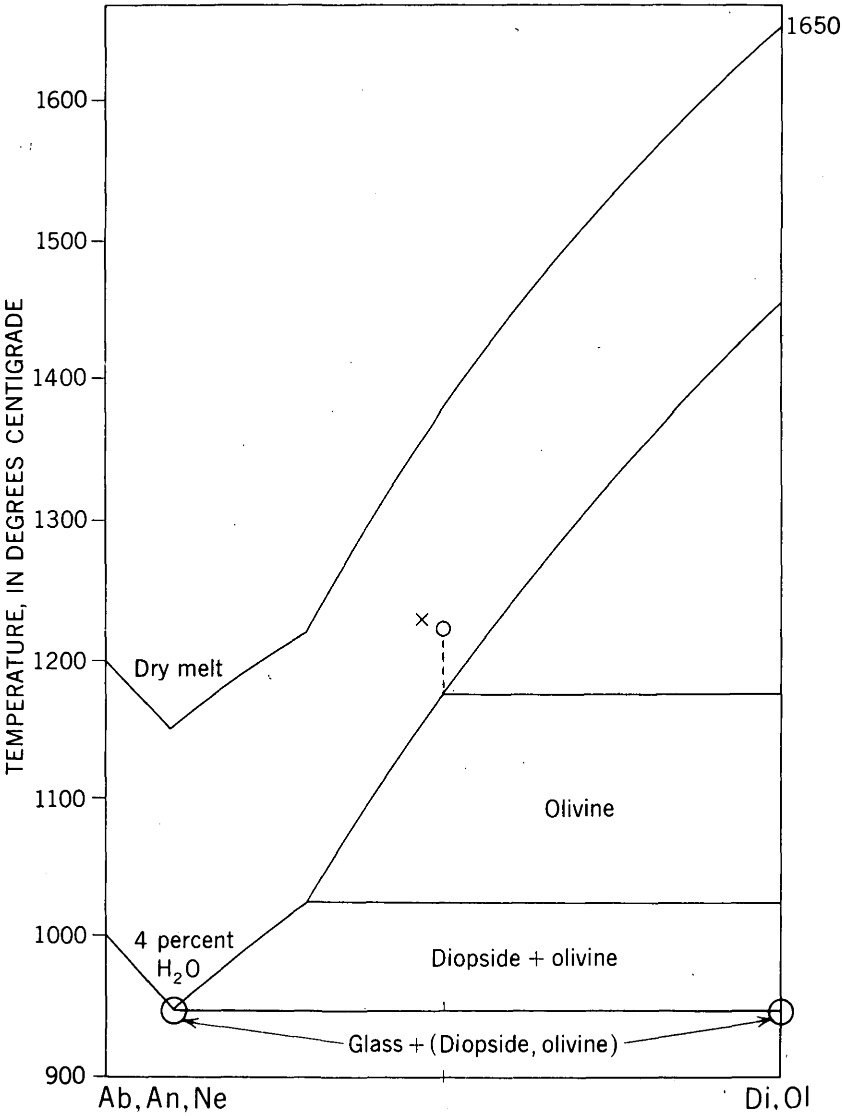

FIGURE 35.—Diagram illustrating the crystallization of a polynary melt containing diopside and olivine as ferromagnesian constituents, and albite, anorthite, and nepheline as "feldspathic" constituents.

nents. Experiments at the Geophysical Laboratory have demonstrated that artificial feldspathic liquids show this relation.

It is interesting to see, from table 7 and figure 33, that the limburgites differ very little, chemically, from the basanites. Consequently it is the cooling history, rather than the chemical composition of the magma that produces a limburgite.

TABLE 4.—*Comparison of three samples of limburgite*

	14	*B*	*C*
SiO_2	40. 30	43. 46	44. 32
TiO_2	3. 25	2. 21	1. 18
Al_2O_3	13. 14	15. 34	12. 51
Fe_2O_3	5. 34	1. 46	3. 68
FeO	7. 62	8. 17	5. 27
MnO	. 20	. 16	, 20
MgO	11. 24	12. 60	13. 98
CaO	10. 33	11. 39	10. 82
Na_2O	3. 40	2. 61	3. 15
K_2O	. 80	. 69	. 80
P_2O_5	. 86	. 48	. 57
$H_2O\pm$	1. 68	. 59	2. 71
H_2O-	2. 24	. 41	1. 04
CO_2	none		
	100. 40	99. 63	100. 23
Norm			
Or	4. 5	4. 0	5. 0
Ab	10. 0	8. 5	13. 0
An	17. 8	28. 0	17. 5
Ne	12. 0	9. 0	9. 0
Di	21. 2	20. 0	26. 0
Ol	17. 9	24. 0	22. 5
Mt	5. 4	1. 5	3. 9
Il	4. 4	3. 2	1. 6
Ap	1. 8	1. 0	1. 3
H_2O	5. 0	[1]	[1]

Mode of sample 14

Phenocrysts:	
Olivine	10
Augite	2
Crystalline groundmass:	
Olivine	4
Augite	25
Ore	5
Apatite	2
Serpentine, chlorite, iron hydroxides	6
Glass (including zeolite)	46
	100

Composition of glass for sample 14

Or	4. 5
Ab	8. 5
An	12. 0
Ne	12. 0
Ol	3. 0
Di	1. 0
H_2O	4. 0
	45. 0
Zeolite	1. 0
	46. 0

[1] The norms of samples B and C have been calculated to a water-free base.

14. Limburgite, 1 mile south of Garden Cove, St. George Island, Pribilof Islands. Analyses. B. Bruun.
B. Limburgite, Nonopapa Landing, The Leeward Islands, Washington and Keyes (1926).
C. Limburgite, Ryudo, Meisen district, Korea, Lacroix (1928).

OLIVINE NODULES

Several olivine nodules about an inch in diameter were observed in basanite lava flows of St. George Island and a larger nodule, 3 inches across, was observed in pyroclastic material forming a layer in an intercalated sedimentary bed at Tolstoi Point, St. Paul Island. For almost a hundred years, olivine-rich inclusions in basaltic rocks have attracted the attention of petrologists. In his famous monograph on the inclusions in volcanic rocks, Lacroix (1893, p. 484) writes:

"Ces nodules sont plus abondants parmi les produite de projection que dans les roches massives . . . ils ont été si souvent décrits qu'il reste peu de chose à en dire au point de vue minéralogique."

Since Lacroix's time the nodules again have been described; among others Chudoba and Frechen (1941) have studied the mineralogy, Ernst (1935) and Turner (1942) have made a special study of the petrofabric, and recently Ross, Foster and Myers (1954) have given complete chemical and mineralogical data on the various minerals. All have wanted to find out if the nodules represent mineral segregates from the magma, or foreign inclusions.

The present investigation brings little that is new, but the following data are offered for consideration.

In the present nodules, olivine dominates (about 70 percent) with enstatite second (about 30 percent). Less than one percent spinel is present.

Olivine shows (+) 2 $V=89°$, $\beta=1.682$, corresponding to Fa_{14}.

Enstatite shows (+) 2 $V=85°$, $\beta=1.672$, corresponding to Fs_{12}.

Spinel shows index of refraction, $n=1.762$; edge of the unit cube, $a_o=8.12$ A, corresponding to 70 $MgAl_2O_4$, 26 $FeAl_2O_4$,4 Fe_3O_4. The distribution of iron among these minerals is interesting. In harmony with the observations of Ramberg and de Vore (1951), iron enters into olivine and enstatite in approximately equal proportions. Iron usually prefers pyroxene to olivine, but observations show that iron nevertheless distributes itself with approximately equal coefficients between the magnesian olivines and orthopyroxenes. In spinel the Fe:Mg proportion is much higher than in the silicates, in harmony with the fact that oxygen ions in most oxides are more readily polarized than in the silicates. The distribution of iron in spinel, olivine, and enstatite supports the a priori conclusion that all three minerals were in equilibrium with a common magma. But this conclusion makes it hard to see, generally speaking, how the distribution relations of the chemical elements may contribute anything to the genetic history of the rock. If equilibrium was attained it means that all elements will distribute themselves in the "right" proportions within olivine, enstatite, spinel, and magma, regardless of the provenance and original composition of the mineral phases. We may go further along this line of thought: spinel phenocrysts (not inclusions) have been observed in some of the lavas. They are particularly conspicuous in an olivine-rich, mafic basanitic lava (at top 570, one-half mile west of Staraya Artil Rookery, St. George Island). The lack of any evidence of assimilation of aluminous material by any of the lavas makes it reasonable to assume that spinel here developed as a primary phase during the crystallization. Olaf Andersen (1915) has shown that in certain parts of forsterite-anorthite-enstatite melts, spinel will appear as a primary phase on crystallization. Osborn and Tait (1952) have extended the studies to include diopside and finds in the ternary system forsterite-anorthite-diopside a rather large field of spinel. The olivine-plagioclase-rich lava may come sufficiently close to this composition to yield primary spinel. This spinel, a phase of crystallization formed in equilibrium with the magma, shows index of refraction, $n=1.761$, and the length of the edge of the unit cube, $a_o=8,12$ A. These constants are practically the same as those in the spinel of the nodule.

The chemistry of spinels in basic lavas is not well known. Thomas (1922) has published a description with analysis of a spinel derived from assimilation of aluminous sediments by Tertiary lavas of Mull. The chemical composition (in percent) is $MgAl_2O_4$,40; $FeAl_2O_4$,50; Fe_3O_4,4; Al_2O_3,6. The high iron content reflects the fact that the lava of Mull (a tholeiite) is more ferriferous than the basanite of Pribilof. It indicates that equilibrium was reached with the lava (so much iron could scarcely reside in the clay sediment) and supports the view that the composition is governed by reactions with the magma.

The general conclusion of the study of the spinels from the Pribilof Islands is that the composition of the mineral phase (in the olivine-rich inclusions) and the distribution of the elements in them will not contribute to the genetic history of the nodules.

According to a suggestion by Tomkeieff (1952), phenocrysts of olivine, pyroxene, and spinel will sink easier in the relatively fluid basanite magma than in ordinary basaltic magma, and at some depth consolidate in the form of peridotite, fragments of which become olivine nodules. This explains why nodules are more frequent in basanites than in common basalts.

PETROCHEMISTRY

ANALYSES OF THE ROCKS

All analyses of the rocks from the Pribilof area are listed in tables 5, 6, and 7. Unique in its relation is the peridotite (sample 1, p. 119) The aplite stock also stands apart (samples 3 and 4), as does the rhyolitic glass (sample 5) which, however, seems to represent a residual liquid, perhaps related to some of the mineral fragments of alkali feldspar (analyzed on p. 140) found in the tuff (sample 2).

Analyses of eight of the extensive lava flows, and of six of the numerous basic dikes in St. Paul, St. George, and Otter Islands are compiled in tables 6 and 7. The dikes are by and large very similar, chemically, to the flows; together they form a typical assemblage of olivine basaltic-basanitic rocks, clearly unusual in this part of the world.

The Pribilof Islands are made up almost wholly of lava flows. Consequently the average composition of the rocks of the islands would be represented approximately by the average composition of all lava flows. Table 6 shows that rock sample 7 has an unusually high content of titania; also, alumina is rather low as compared to the high alkali content, thereby anorthite becomes low in the norm. For these reasons and because the sample may not represent a flow, this analysis has been omitted from the average. The last column of table 6 shows the average composition of the lava flows as computed from samples 6, 8, 9, 10, 11, 12, and 13. In the norm system the lava obtains the symbol III, 6, 2, 4 and the name monchiquose (but not far from limburgose).

The Niggli values are as follows:

al	27. 3	si=	140
fm	29. 4	qz=	−10
c	30. 7	k=	0. 20
alk	12. 6	mg=	0. 68

The lava flows belong to the essexite gabbroid group of magmas (Niggli, 1936).

TABLE 5.—*Analyses of rocks from the Pribilof Islands*

[All analyses by B. Brunn]

	1	2	3	4	5
SiO_2	39. 83	35. 47	64. 35	71. 89	69. 09
TiO_2	trace	2. 52	. 23	trace	. 43
Al_2O_3	1. 54	15. 12	17. 76	15. 64	14. 90
Fe_2O_3	3. 70	7. 61	. 56	. 78	1. 53
FeO	3. 77	2. 98	3. 91	1. 13	1. 69
MnO	. 12	. 21	. 15	. 03	. 07
MgO	41. 95	11. 67	. 96	. 24	1. 00
CaO	. 10	5. 57	2. 79	. 62	2. 97
Na_2O	. 12	. 37	4. 18	5. 16	4. 18
K_2O	. 01	1. 27	2. 39	3. 18	2. 37
P_2O_5	. 04	. 78	. 50	. 08	. 33
H_2O+	8. 34	7. 84	1. 86	1. 26	1. 31
H_2O-	. 62	8. 71	. 41	. 39	. 23
	100. 14	100. 12	100. 05	100. 40	100. 10

1. Peridotite, St. George Island, see p. 119.
2. Tuff, St. George Island, see p. 139.
3. Core of aplite, St. George Island, see p. 121.
4. Margin of aplite, St. George Island, see p. 121.
5. Rhyolitic glass, St. Paul Island, see p. 137.

TABLE 6.—*Analyses of lava flows of the Pribilof Islands*

[The numbers correspond to those in the description in the text, p. 126-130. Analyses 6 and 8 by B. Bruun; 7, by Keyes (1930); 9-13 by rapid methods, S. M. Berthold]

	6	7[1]	8	9	10	11	12	13	Average of 7 flows[1]
SiO_2	41.70	44.21	44.37	47.0	47.0	47.2	46.7	49.4	46.12
TiO_2	1.25	4.78	2.19	2.8	2.8	2.3	2.1	2.0	2.21
Al_2O_3	14.68	14.28	12.74	17.2	16.6	15.4	15.0	15.1	15.22
Fe_2O_3	3.38	2.35	2.15	4.3	3.9	4.8	7.6	3.5	4.22
FeO	8.97	9.91	9.42	7.0	7.4	6.8	4.8	7.9	7.46
MnO	.18	.13	.18	.2	.2	.2	.2	.2	.19
MgO	12.62	7.34	14.71	5.1	4.9	8.1	10.1	7.9	9.04
CaO	9.93	8.92	9.30	9.8	9.9	9.8	8.9	8.7	9.46
Na_2O	2.95	4.70	3.00	4.0	4.1	3.8	2.8	3.4	3.43
K_2O	1.22	2.51	1.41	1.6	1.6	1.1	1.0	.9	1.26
P_2O_5	.67	.79	.71	.51	.50	.38	.33	.34	.49
H_2O+	1.15	.19	.20						.51
H_2O-	1.10	.02	.05	-------	-------	-------	-------	-------	.39
	99.80	100.13	100.14	99.5	98.9	99.9	99.5	99.3	100.00

Norm

	6	7[1]	8	9	10	11	12	13	Average of 7 flows[1]
Or	7.0	12.8	8.0	9.5	9.5	6.5	6.0	5.0	7.5
Ab	4.0	9.4	10.0	24.5	24.5	25.5	25.0	31.0	22.8
An	22.5	10.3	16.5	24.3	22.5	22.0	25.5	23.3	22.5
Ne	12.9	16.5	9.6	7.2	7.8	5.1	-------	-------	4.9
Hy	-------	-------	-------	-------	-------	-------	9.6	10.8	-------
Di	17.6	22.6	18.8	17.6	19.6	19.2	13.6	14.0	16.8
Ol	26.0	11.7	29.1	7.4	6.8	12.5	9.0	8.1	16.9
Mt	3.4	3.5	2.3	4.5	4.2	5.1	7.2	4.2	4.5
Il	2.0	9.1	3.8	4.0	4.0	3.2	3.0	2.8	3.0
Hm	-------	-------	-------	-------	-------	-------	.5	-------	-------
Ap	1.2	2.0	1.4	1.0	1.0	.8	.6	.8	1.1
H_2O	3.5	-------	.6	-------	-------	-------	-------	-------	-------

[1] Analysis for sample 7 omitted from average because the sample may not be representative.

TABLE 7.—*Analyses of dikes from the Pribilof Islands*

[The numbers correspond to those in the descriptions in the text, p. 130-135. Analyses 14 and 15 by Bruun, 16-19 by rapid methods, S. M. Berthold]

	14	15	16	17	18	19
SiO_2	40.30	42.44	44.1	45.6	48.5	49.6
TiO_2	3.25	1.70	2.4	2.8	2.6	2.9
Al_2O_3	13.14	14.78	14.0	16.4	17.3	15.5
Fe_2O_3	5.34	3.08	3.4	3.4	10.8	4.9
FeO	7.62	9.40	8.0	7.7	1.1	6.9
MnO	.20	.20	.2	.2	.2	.2
MgO	11.24	11.95	9.8	6.6	4.4	3.5
CaO	10.33	10.15	10.8	9.4	8.5	7.8
Na_2O	3.40	3.01	3.7	4.4	4.2	4.4
K_2O	.80	1.41	1.2	2.0	1.7	2.0
P_2O_5	.86	.77	.64	.64	.50	.78
H_2O+	1.68	.79				
H_2O-	2.24	.39	-------	-------	-------	-------
	100.40	100.02	98.3	99.1	99.8	98.4

Norm

	14	15	16	17	18	19
Or	4.5	8.0	7.5	12.0	10.0	12.5
Ab	10.0	6.0	11.0	15.5	37.0	40.5
An	17.8	22.0	17.7	19.0	23.5	16.7
Ne	12.0	12.0	13.2	14.4	.9	-------
Di	21.2	17.6	26.0	19.2	9.6	14.4
Ol	17.9	24.3	15.8	11.0	5.7	5.1
Mt	5.4	3.1	4.0	3.6	-------	5.2
Il	4.4	3.0	3.4	4.0	2.0	4.0
Hm	-------	-------	-------	-------	7.6	-------
Ap	1.8	1.6	1.3	1.3	1.0	1.6
H_2O	5.0	2.4	-------	-------	-------	-------
Ti	-------	-------	-------	-------	2.7	-------

Figure 36 is an ordinary variation diagram showing CaO and (Na_2O+K_2O) plotted against silica; the alkalic character of the present rock suite is obvious, but the alkali-lime index cannot be determined accurately, as only members of low silica content are known. For the same reason the trend of the differentiation cannot be defined adequately by a mere tabulation of the various rock analyses. But there is another way in which the trend of the fractional crystalliza-

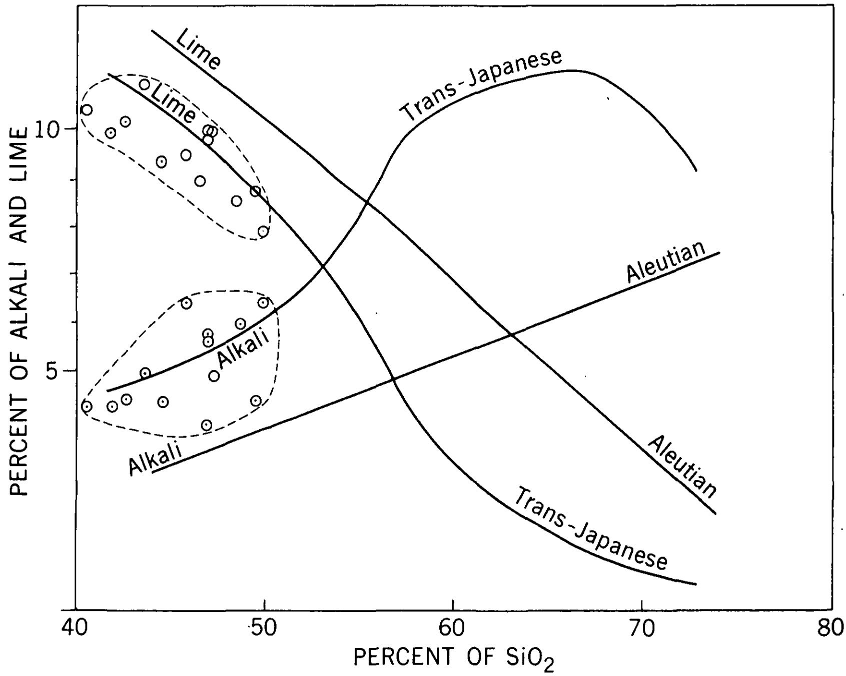

FIGURE 36.—Diagram showing the variation in alkali and lime with increasing silica for Aleutian lavas and for the Trans-Japanese alkalic rocks. The projection points of 13 Pribilof lava flows are plotted.

tion is revealed: in each rock certain minerals (mainly olivine, some diopside-augite, and calcic plagioclase) have crystallised first, leaving a residual liquid that in many rocks has congealed as glass. From each rock analysis in combination with optical determinations of the mineral phases it is possible to calculate the composition of this residue (see p. 127). The results of these calculations show that if soda and potash are combined the composition of the residual glass can be expressed, approximately, in terms of quartz, anorthite, and nepheline. Figure 17 contains the projection points of the rocks and their constituent glasses. It demonstrates that the trend of differentiation was in all rocks "down" the fusion surface. The differentiation trends toward the cotectic curve separating the field of the feldspars from the field of the nephelines. The glass fraction of the rocks thus shows the composition of a phonolite, and if this fraction had had the chance to be separated from the antecedent minerals, it would have formed lava of the composition of a phonolite. In spite of a careful search for such lava in the islands, none were found; the only indication of a residual lava is a rhyolitic glass occurring in a few pieces of white pumice at Polovina Hill, St. Paul Island (fig. 33 sample 5, see also p. 137). As seen from figure 33 the rhyolite is quite unrelated, chemically, to the expected but still hidden phonolites of this province.

ORIGIN OF THE ALKALIC ROCK SUITE

The effusive rocks in the Alaskan-Aleutian range of Tertiary to Recent age are in the main andesitic in composition, although basaltic phases on the one hand and rhyolitic on the other are also represented: the rock suite is typically calc-alkalic; (Byers;[1] Coats, 1950; 1952; Snyder [2]). Inferior analyses have been cited as evidence that the rocks of Bogoslof Island (straight west of Unalaska) are alkalic. A modern restudy of these rocks by F. M. Byers has shown that such is not the case.

St. Matthew, Hall, and Pinnacle Islands lie about 250 miles north of the Pribilof area. According to P. S. Smith (1939) they are composed almost exclusively of Tertiary to Recent volcanic rocks of andesite character. Again on Nunivak and Nelson Islands much of the bedrock is basaltic lava which seems indistinguishable from the basaltic rocks along the lower Yukon, at St. Michael and in Seward Peninsula (pl. 2).

But on the St. Lawrence Island, far north in the Bering Sea, about 150 miles southwest of Nome, volcanic rocks of post-Cretaceous age and of alkalic character form a considerable part of the island. These rocks have been sampled by the Geological Survey, and the following description of them has been sent to me by Dr. Louis L. Ray:

The alkaline nature of the rocks is indicated by:

a) Recognition of analcime, nepheline, or sodalite in more than 25 percent of the basalts collected. For specimens from the central part of the island (Kookoolgit Mountains) the proportion is considerably higher with slightly less than half the specimens being somewhat alkalic and with information on the remainder being inadequate for conclusive determination.

b) Although megascopic determination of the feldspars cannot be definite, specimens from the Ongovewhat River area probably contain 47 percent orthoclase and 47 percent albite.

c) Inclusions and injections within the basalts were described as syenite with minor nepheline content.

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[1] Byers, F. M., 1955, The Petrology of Umnak and Bogoslof Islands: Ph. D. thesis, Univ. Chicago (in preparation).

[2] Snyder, G. L., 1952, Some considerations of Aleutian lava with special emphasis on those of Little Sitkin Island: mimeographed and on file in the library of the University of Chicago.

Thus we see that in the northern part of the Bering Sea on St. Lawrence Island and in the southern part on the Pribilof Islands alkalic rock suites occur; and, according to Washington, who also quotes Zygmuntonska, soda rhyolite occurs on the Komandorskiye Ostrova, off the coast of Kamchatka; nepheline syenite and comendite have been found at East Cape, Siberia, where monzonite and rhyolite also occur (Washington, 1902).

Isostatic compensation prevails in most parts of the earth, but several very interesting exceptions have been demonstrated by gravity measurements conducted at sea by Vening-Meinesz (1934): a mass deficiency prevails along the foredeeps of the arcuate orogenic island chains (that is, parallel to the convex side of the island arcs of, for example, the Malay Archipelago, the arcs of the Antilles, of the Aleutians, and other arcs). There is a relation therefore, between island festoons, oceanic deeps, and mass deficiency. This deficiency attains a magnitude of more than 200 milligals. A rock blanket 5,600 feet thick, of density 2.7 and with indefinite horizontal extension would be required to compensate for this deficiency; and if concentrated along a band, the thickness must be still greater. At the same time a mass excess builds up on the inner (concave) side of the arc. Obviously strong tangential forces are thus produced, releasing themselves in horizontal mass movements of large dimensions. Great crustal instability will ensue, and spread far into the hinterlands of the orogenic areas.

The tectonic environment is now recognized as an active factor in the evolution of magmas. Vertical faulting of nonorogenic areas are the accepted prerequisites for the formation of alkalic rock suites. Tomkeieff (1949) has pointed out that igneous rocks with marked, or even strong alkalic character, have developed in the hinterland of many circum-Pacific arcs: for example, the Australian Cainozoic igneous rocks in the hinterland of the New Guinea–New Zealand arc; the rocks of the inner side of the Java–Sumatra arc; the "Trans–Japanese alkaline province" comprising the Sea of Japan, Korea, eastern China and Mongolia. In all these places the alkalic rocks are also associated with vertical faulting.

Consequently, it seems to be a rule that alkalic rock suites develop in the hinterlands of the folded arcuate mountains, probably always associated with vertical movements. The alkalic rocks of the Pribilof mound were, therefore, to be expected, and find their counterparts in other regions of similar geologic relations.

The visible amount of alkalic rocks on the inner (concave) side of the Alaskan–Aleutian arc is small because the area is mostly under the sea. But it is quite possible that the whole Pribilof area between (3,000 and 4,000 square miles), being a region of crustal instability, has produced extensive flows of markedly alkalic lavas now at the floor of the shallow Bering Sea.

To test this we should try to find out what is underneath the Pribilof Islands. The geographic position on the continental shelf indicates a continental basement. However, no obvious traces of continental rocks exist, and no interaction (assimilation relations) between lava and sialic rocks can be inferred. Quite to the contrary, the alkalic, strongly basic character of the lavas is indicative of primary basaltic substratum that reached the surface without any contamination (Barth, 1940). The existence of a peridotite basement in St. George Island, although quite possibly of local extent, is a similar indication. The only evidence in favor of "continental" rocks underneath is an aplite stock of granitic composition in St. George Island (p. 121) and the presence of a small amount of rhyolitic glass in St. Paul Island (p. 137). Also, large loose crystals of anorthoclase in the tuff deposits west of Staraya Artil in St. George Island similarly indicative of a continental basement (p. 139). Whence came these crystals? They are volcanic ejectamenta, but certainly not derived from any of the lavas known in the Pribilof area. The only magma compatible with the composition of the anorthoclase would be syenitic or granitic (granodioritic) in composition. They may have the same origin as the rhyolite glass.

GEOLOGIC ANALYSIS

The Bering Sea is a triangular basin between Alaska and Siberia bounded to the south by the Aleutian Island arc (pl. 21). The greater depths are in the southwestern part, where a maximum of 2,240 fathoms (4,070 m) is attained 43 miles northeast of Attu. The northeastern part of the basin is conspicuously flat and shallow. It is commonly referred to as the Bering Sea shelf and is nowhere deeper than 100 fathoms. Say Buffington, Carsola and Dietz (1950):

> Straight line traverse over distances as great as 5° of latitude (343 nautical miles) have resulted in traces which are almost completely smooth at relatively constant depth. Slight roughnesses which occur occasionally in an otherwise perfectly smooth trace are attributed to locally stony bottom. Over long distances the bottom gradients are typically less than 1 foot per mile (a slope angle of considerably less than 1 minute). The straight line traverse between the Pribilof Islands and St. Lawrence Island showed a net rise of 25 fathoms in 343 nautical miles. This gradient of 0.43 feet per mile is not to be found on any land surface of comparable extent and is more nearly approached by the gradients of very old and slow-flowing rivers. The break-in-slope at the southern edge of the Bering Sea shelf occurs at a depth of about 85 fathoms, a depth which is constant within a few fathoms at least 150 miles of the length of the break. This depth is about 20 fathoms greater than the 65-fathom depth typical of continental shelf breaks throughout the world. It is believed that the Bering Sea break, like other breaks on continental margins, marks an old shore-line of a lowered sea-level or, more exactly, that it is a wave-abraded feature cut within the breaker zone of the lowered sea level.

CRUSTAL MOVEMENTS

Close to the edge of this remarkably flat and monotonous shelf lie the Pribilof Islands (pl. 21). St. Paul Island rests on a broad submarine mound; St. George Island rises more abruptly from the sea, but east and northeast of it is another broad platform with broken water shoaling from 3 to 8 fathoms. It is believed that these conspicuous variances in the monotony of the shelf call for a special explanation. They represent accompaniments to the igneous activity that is manifest in the extensive fragments of Recent lava flows now dominating the bulk of the islands. Consequently, these marginal parts of the shelf, covering an area of almost 4,000 square miles, must have been subject to crustal movements, faulting, and block elevation attendant on the Recent lava effusions. The oldest lava flowed over a glaciated surface on which marine shells are found in their original position (*Saxicava*, *Mya*, *Astarte*, and others, see p. 117) thus proving that the area was close to sea level at the beginning of the volcanic activity. During the later stages of the lava formation the intercalated fossiliferous sedimentary beds, in places conspicuously crossbedded, indicate shallow water. There can be no doubt, therefore, that during all this time the area oscillated around sea level, and that the crater fissures as well as the extensive, flat-lying, lava flows were formed close to sea level. On the other hand, the great thickness, of some of the sediments (p. 118) strongly indicates high local relief probably caused by faulting and block elevation.

This area of crustal instability will be referred to as the Pribilof mound. It is now mostly submerged, only the islands themselves, or 2 percent, being above sea level.

Most geologists agree that a eustatic lowering of sea level occurred during the Pleistocene. The drop is variously estimated from 300 to 392 feet (50 to 66 fathoms). This range is supposed to be related to the present depth of the break in slope between the continental shelf and the continental slope, which in the Bering Sea happens to be 85 fathoms. In any event; a drop of only 50 fathoms would be enough to make dry land of most of the Bering shelf, with the Pribilof area emerging as an elevated plateau. (See pl. 21.)

The building up of the Pribilof area can certainly be dated as Pleistocene. It developed as a raised tableland with the highest parts attaining, and, at that time locally exceeding an altitude of 1,300 feet, abruptly plunging into the ocean to the southwest, gently sloping into the remarkably flat and low-lying hinterland of the north and east.

GLACIATION

No traces of glaciation are evident on the present surface, but, as stated in the description of St. George Island (p. 110), the basement periodotite was eroded and leveled by glaciation before the effusion of the basaltic lavas. Various types of glacial sediments were also deposited, partly directly on top of the peridotite, partly in alternation with lavas. These sediments are very thick. The general impression is that the glaciation was extensive in both space and time and a ready inference is that it corresponds to a continental glaciation in Alaska. However, according to the best information (A. L. Horberg, personal communication, and Capps, 1931), it is hardly possible that Alaska at any time during the Pleistocene was glaciated to such an extent that the ice could spread westward over the present Bering Sea and reach the Pribilof Islands. Rather, it seems that in the western parts of Alaska only the higher mountain ranges were glaciated. In the lowlands no permanent cover of snow or ice existed. Or, is it possible that a cover of ice rested motionless over the Bering shelf and eventually melted without leaving any vestiges?

How is it possible, then, to account for the glaciation of the peridotite of St. George Island? High elevation might seem to be the answer. This is contradicted, however, by the fact that fossil marine shells lie directly on the glaciated surface; the first lava outpours evidently rode over lowlands and the shallow sea floor. The presence of similar fossil shells in the intercalated sediments higher up in the basalt profile indicates that the area was close to sea level during most of the subsequent volcanic activity. This conclusion needs some modification: parts of the area must have reached higher altitudes, for only in this way is it possible to explain the great thickness of some of the sediments, for example at Otter Island. Consequently, high local relief existed, which in all probability was produced by faulting and block elevation.

This supports the view that the Pribilof area during the Pleistocene was subject to large vertical movements. It may have maintained a high average elevation in early Pleistocene for example—in Günz and Mindel, subdivisions in European usage—and during this time it became heavily glaciated. Thereafter a general foundering of the area took place in combination with fissuring and outpouring of lava. During all the subsequent volcanic history it remained in a low position, oscillating around sea level.[3]

The only other way to account for the glaciation of the peridotite would be by pack ice. This means that the glaciation took place in late Pleistocene, after the eustatically lowered sea level again had risen and inundated the shallow Bering Sea on which the pack ice would have to float. The still younger lava sequence and the deposition of thick sediments between the lava flows would thus be just a few

[3] A submarine eruption in this area is recorded as having taken place in 1815 (Ross, 1951) and Landgrebe (1855) states that flames have been seen to rise from the sea northeast of the Pribilof Islands. However, in spite of these assertions any present volcanic activity must be regarded as doubtful.

thousand years old. In view of the strong erosion of the peridotite surface and the great thicknesses of some of the subsequent sediments including glacial till, indicating local high reliefs in very recent time, this explanation does not seem probable.

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