Geology of Buldir Island Aleutian Islands Alaska

By ROBERT R. COATS

MINERAL RESOURCES OF ALASKA, 1951

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The geography and geologic history of the island, with its flora, and the petrographic and chemical character of its volcanic rocks

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GEOLOGY OF BULDIR ISLAND, ALEUTIAN ISLANDS

By ROBERT R. COATS

ABSTRACT

Bnldir Island is a small volcanic island in the western Aleutians, about equidistant from Kiska and Shemya Islands. It is the westernmost of the Aleutian volcanoes that were active in late Quaternary or Recent time. The rocks of Buldir Island are attributed to eruptions from two volcanic centers. They differ in age, are separated by a considerable period of time during which the island underwent marine and subaerial erosion, and are separated in space by the steep sea cliff that is developed on the older structure. The rocks of the older volcano are chiefly olivine basalts and olivine-hypersthene basalts. The rocks of the younger volcano are hypersthene-bearing hornblende basalts and basaltic andesites. Chemical analyses of five of the rocks show that the rocks are similar to those of other circum-Pacific volcanoes. They are highly calcic and comparatively rich in magnesia. Norms and Niggli numbers have also been calculated. Normatively, the rocks are andose and tonalose : the Niggli magma-types range from gabbro-dioritic to peleeitic Spectrographic analyses show the contents of the rarer elements, which, in general, resemble those from other geochemical districts in the Aleutian Islands, but the contents of some of the elements differ from those found in rocks from Adak and Kanaga. The youthfulness of Buldir as a land mass is suggested by the fact that the number of species of flowering plants found there is somewhat less than on the neighboring islands.

INTRODUCTION

Buldir Island is geologically interesting because it is the westernmost outpost of Quaternary volcanism in the Aleutian Islands. It is geographically and ecologically interesting because it is the most isolated of the Aleutian Islands (fig. 1). In 1947, from July 19 to July 22, a Survey party, consisting of Will F. Thompson, Jr., field assistant, and the writer, worked on the island.

The work would not have been possible without the cooperation of Major John Davis, CAC, Port Commander, Adak, and of Lt. Aaron Isaacs, the captain of the FS 238, on which we traveled from Adak to Buldir and back to Kiska Island. Lt. Col. R. E. Ware, CE, Post Engineer, Adak, and Cmdr. J. M. Oseth, Commander NOB Adak, were of great assistance, and their cooperation is gratefully acknowledged, Valuable suggestions have been received from my colleagues in the Geological Survey, particularly H. A. Powers and W. S. Benninghoff.

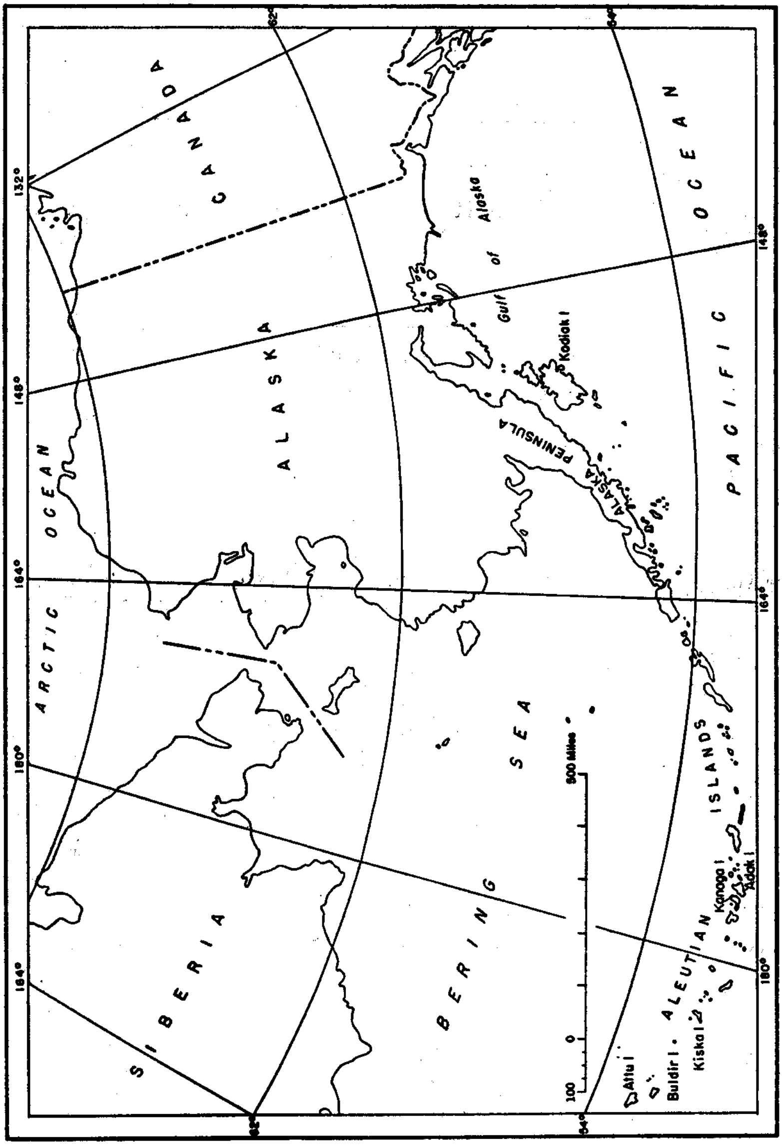


FIGURE 1.—Index map of Alaska, showing the position of Buldir Island.

HISTORY

Buldir Island was sighted by Vitus Bering on October 28,1741, and given the name "St. Stephen" (Collins, Clark, and Walker, 1945, p. 10). It appears never to have been inhabited by Aleuts. It played only a small part in World War II but its isolated position made it useful as a weather station. At least two airplanes, one Japanese and one American, unable to reach their bases, crash-landed on the island.

GEOGRAPHY

LOCATION AND SIZE

Buldir Island, 68 miles from Kiska Island and 78 miles from Shemya Island, lies between 50°21′ and 52°24′ N. latitude and between 175°57′ and 176°03′ E. longitude. It is about 3.8 miles long from east to west and 2.4 miles from north to south. It has an area of 6.64 square miles.

TOPOGRAPHY

The island (plate 1, fig. 2) is composed of two volcanic cones, the eruptive centers of which are about 1½ miles apart. The higher, older, and more dissected one I refer to as Buldir Volcano. It is slightly more than 2,000 ft high; the eruptive center is south of the middle of the island. The younger and less dissected cone, which I refer to as East Cape Volcano, rises 1,900 ft in a precipitous slope, steepened by the attack of the Bering Sea, from the eastern part of the northern shore. The cliffs of Buldir are forbidding; marine erosion is rapidly and steadily removing the island by peripheral attack.

The island is accessible from small boats only in favorable weather. The shores are everywhere steep, except for a sand beach at the mouth of a small valley near the northwest point. The beach is backed by a sand bluff, 15 to 20 ft high.

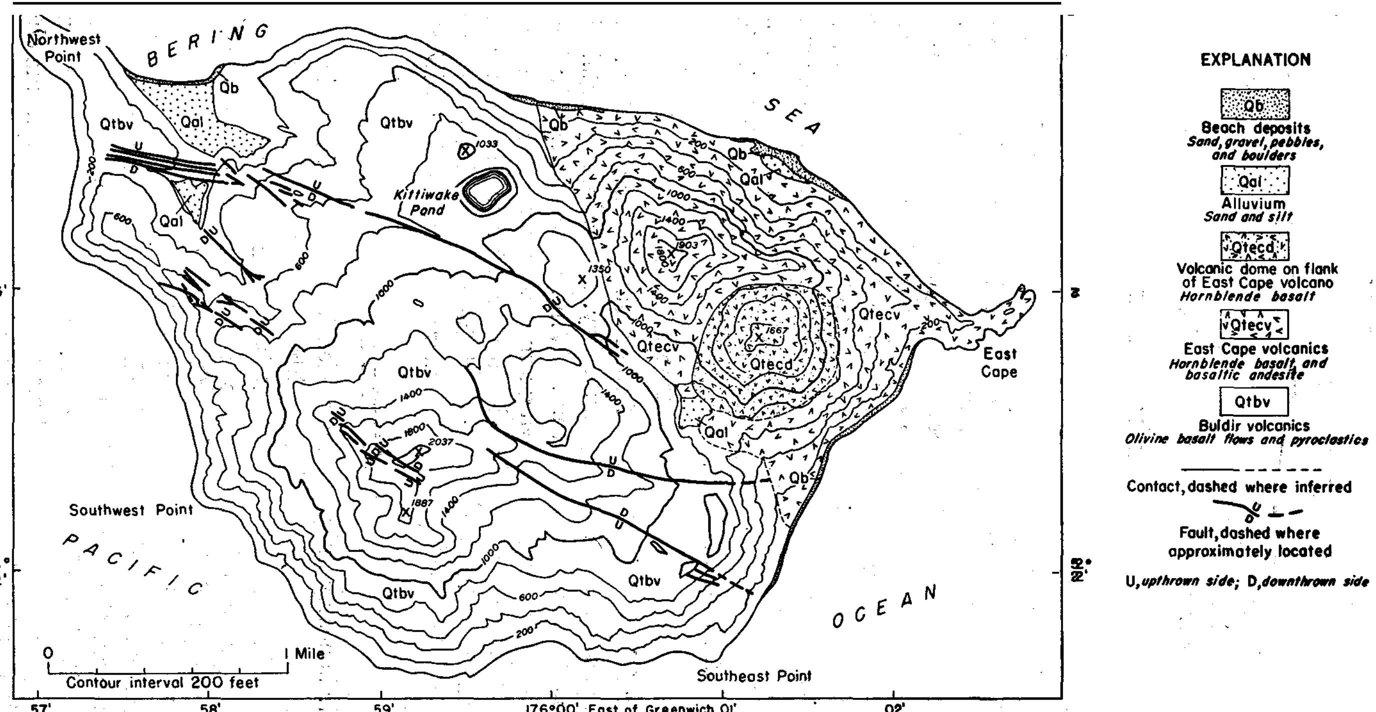
CLIMATE

Buldir Island, like the rest of the Aleutians, has a polar maritime climate, characterized by high humidity, fog, rain, and small diurnal and annual range in temperature. Wind velocities are considerable, and the topography causes much gustiness. Prevailing wind direction is probably from the southwest during the summer and from the north during the winter. The bottoms of the clouds seldom rise above an altitude of 300 to 400 ft in summer; winter weather probably is clearer.

ANIMAL LIFE

Buldir is nearly unique among Aleutian Islands of any size, in that it is one of the few on which the blue fox is not indigenous and has never been introduced. The result is a much denser bird population and the presence of some species not seen nesting elsewhere. Numerous geese, probably the lesser Canada goose, breed on the island. The underground burrows of the tufted puffin are very common on the steep slopes. A flock of Pacific kittiwakes appears to frequent the small lake on the island. Nearly all the sea birds common to the western Aleutians also nest here, and in great numbers—the numbers of birds flying about the island may actually afford welcome clues to its location during the frequent summer fogs.

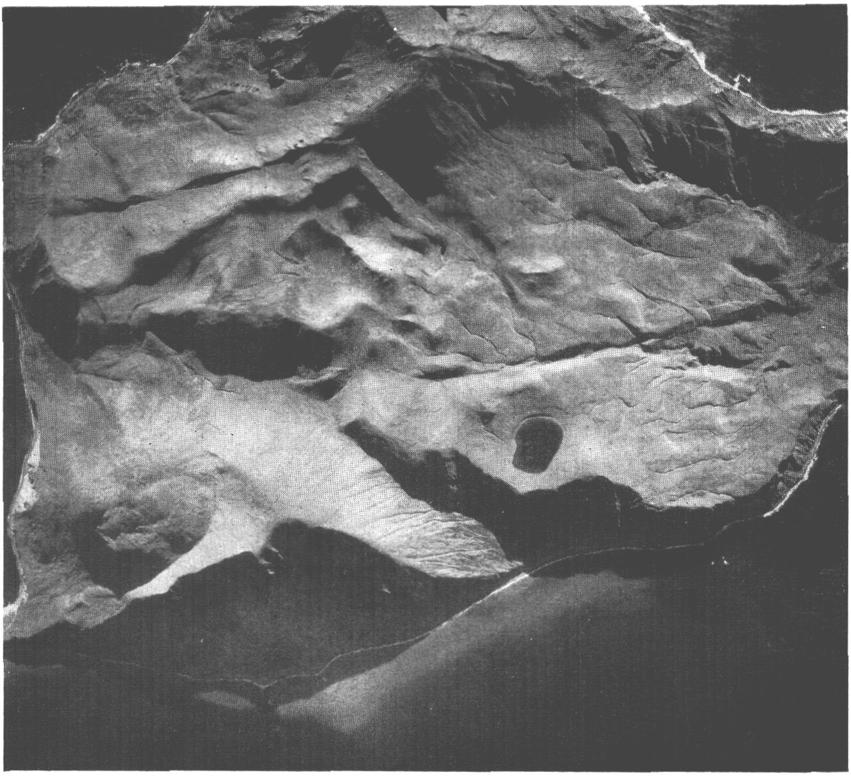
Some small rocky islands that occur a few thousands of feet off



Topography from map by Corps of Engineers, U. S. Army, 1943

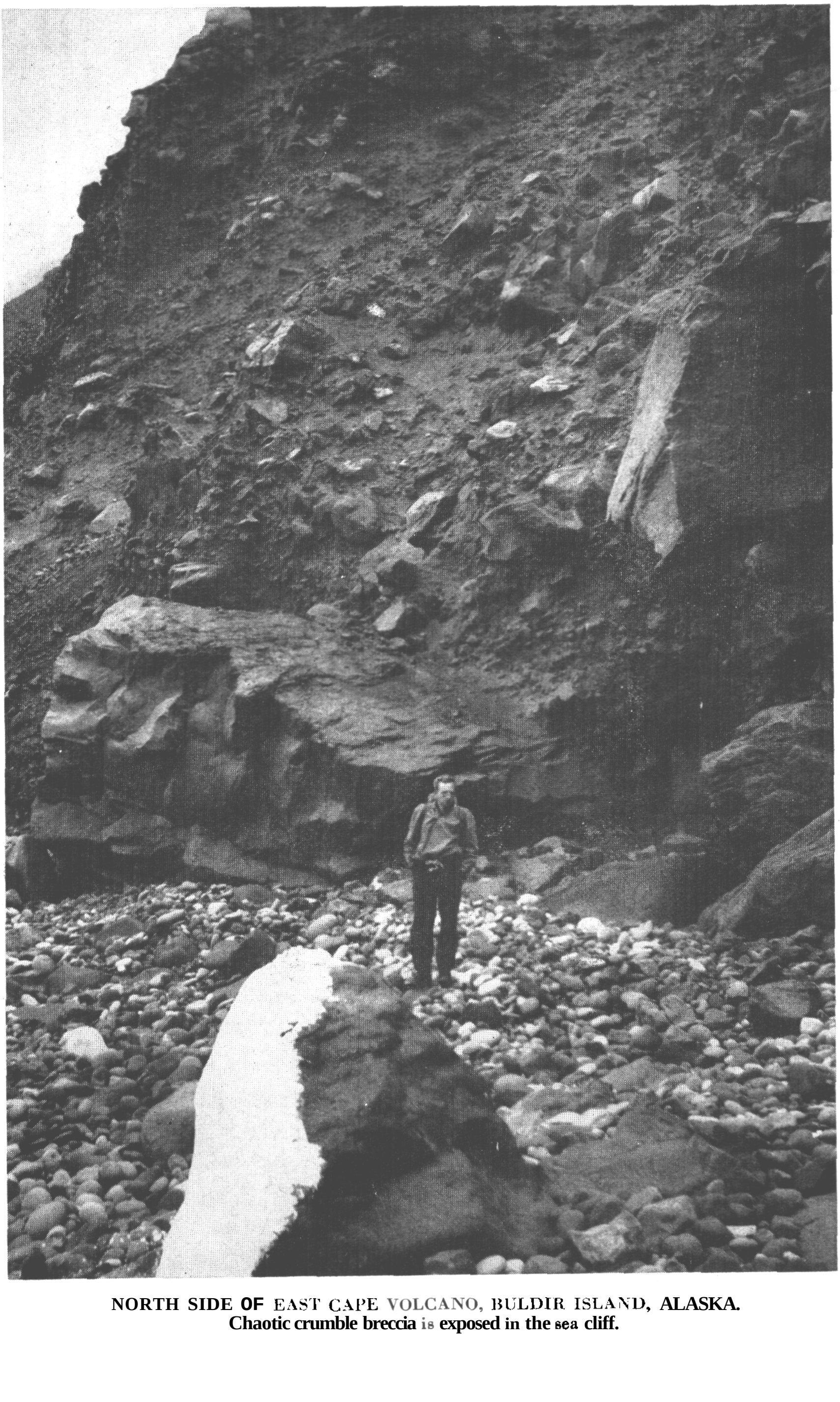
Geology by Robert R. Coats, 1947

FIGURE 2.—Geologic map of Buldir Island, Aleutian Islands, Alaska.



VERTICAL AERIAL PHOTOGRAPH OF HULDIR ISLAND, ALEUTIAN ISLANDS, ALASKA.

Top of photograph oriented toward west of south. Oblique lighting accents the topographic expression of faults. At left, block-covered surface of parasitic dome contrasts with little-dissected cover of East Cape Volcano.



NORTH SIDE OF EAST CAPE VOLCANO, BULDIR ISLAND, ALASKA.
Chaotic crumble breccia is exposed in the sea cliff.

East Cape and Northwest Point are breeding grounds for Steller's sea lions. (These islands were not visited and are not shown on the map.)

VEGETATION

The distribution of plants in the Aleutian Islands depends to some extent on the geologic history. Apparently no list of the flora of Buldir Island has ever been published, and a fuller discussion than usual of the flora seems appropriate.

A small collection of plants was made, and the presence or absence of a few of the conspicuous and easily recognized species, well known from other Aleutian Islands was noted. The flora of Buldir contrasts strikingly with that of Attu and of Kiska Island.

Another small collection had been made on Buldir Island by Dr. O. J. Murie and Mr. J. H. Steenis of the U. S. Biological Survey (now the U. S. Fish and Wildlife Service) and identified by Dr. Eric Hultén, who kindly furnished the list of species (personal communication, 1948).

TABLE 1.—*Flora of Buldir Island*

	Murie and Steenis	Coats: Coll. [1]	Coats: Field ident. [2]
Athyrium felix-femina subsp. cyclosorum (Rupprecht) Carl Christenson (Ladyfern).[3]		x	
Lycopodium alpinum Linnaeus (Alpine clubmoss)	x		
Fritillaria camschatcensis (Linnaeus) Ker-Gawler (Indian rice-root).		x	
Platanthera hyperborea (Linnaeus) Lindley (Green orchid)		x	
Salix arctica var. ***obcordata*** (Andersson) Rydberg (Arctic willow).[4]		x	
Rumex sp. (Dock)			x
Claytonia cf. ***sibirica*** Linnaeus (Spring beauty)			x
Ranunculus sp. (Buttercup)		x	
Ranunculus acer frigidus Regel (Tall buttercup)	x		
Cochlearia officinalis subsp. ***oblongifolia*** (A. P. de Candolle) Hultén aff. (Scurvy weed).		x	
Saxifraga punctata var. ***insularis*** Hultén (Dotted saxifrage)	x	x	
Potentilla pacifica Howell (Cinquefoil)	x		
Geum calthifolium Meneies (Cowslip-leaved avens)	x		
Geum macrophyllum Willdenow (Large-leaved avens)		x	
Geranium erianthum A. P. de Candolle (Wild geranium)		x	
Empetrum nigrum Linnaeus (Crowberry)			x
Viola achyrophora Greene (Violet)		x	
Heracleum lanatum Michaux (Cowparsnip)			x
Cassiope lycopodiodes (Pallas) D. Don (Heather)	x		
Primula cuneifolia var. ***saxifragifolia*** (Lehman) Hultén (Primrose).	x	x	
Trientalis europaea arctica (Fischer) Hultén (Star flower)	x		
Veronica grandiflora Gaertner (Speedwell)		x	
Achillea borealis Bongniard (Northern yarrow)			x
Senecio pseudoarnica Lessing (Ragwort)			x

[1] Collection identified by Dr. E. H Walker, of the U. S. National Museum, except as noted.
[2] Identified by the writer in the field.
[3] Identified by Mr. C. V. Morton, of the U. S National Museum.
[4] Identified by Dr. C. R. Ball, of the U. S. National Museum.

Mr. W. S. Benninghoff of the Geological Survey has kindly submitted the following comments on the list:

By checking in the 8 volumes published thus far of Hultén's Flora of Alaska and Yukon, I have compiled the following notes on the species collected from or recognized on Buldir Island.

1. The following species have wide distributions on the Pacific Coast, in southern Alaska, and the Aleutians:

Athyrium felix-femina subsp. *cyclosorum.*
Lycopodium alpinum.
Fritillaria camschatcensis.
Salix crassijulis (? *S. arctica* in concept of Walker). Also Bering Sea *S. arctica* as recognized by Hultén occurs only on the Arctic Coast and Bering Sea shores and islands.
Claytonia sibirica.
Cochlearia officinalis subsp. *oblongifolia.*
Potentilla pacifica.
Geum macrophyllum.
Geum calthifolium.
Geranium erianthum.
Empetrum nigrum.
Heracleum lanatum.
Cassiope lycopodioides.
Primula cuneifolia saxifragifolia.
Trientalis europaea arctica.

2. The following subspecies do not have wide distribution over the general region:

Platanthera hyperborea. No previous records southwest of Matanuska, according to Hultén.
Ranunculus acer frigidus. Recorded only from Buldir and Alaid. A Eurasian species.
Saxifraga punctata insularis. Probably continuous distribution on Chain, but not found east of Unimak.
Viola achyrophora. Recorded from central Yukon region, Seward Peninsula, St. Lawrence Island, Pribilofs, but not from the Aleutians or the Pacific Coast. This may be a new record, or, more likely, Dr. Walker considered the specimen to be closer to *V. achyrophora* than to *V. epipesila repens* which, Hultén says is very closely related and occurs widely in southern Alaska, Kodiak, Popof Island, and Attu Island.

The above species that do not have wide distributions in the Chain are somewhat less valuable to your argument.

The foregoing list is far from complete; the cryptogams and grasses, which are known to be present, are inadequately represented in the collections.

The flora of Buldir Island is remarkable, however, more for the species missing from it than for the species included in it. It was predicted by Hultén (1937, p. 37) that certain Asiatic species, found on the Commander Islands and Attu, would also occur on Buldir Island. This prediction was apparently based on the luxuriant character of the vegetation, which Hultén says is recognizable from the sea, and permits recognition of the plant association, even without a visit to the island. The prediction does not appear to be confirmed by the facts. The flora of Buldir, so far as it has been studied, appears to be like that of the islands to the east, but with many species apparently missing. It was suggested by Thompson that the fertility due to the unusual concentration of bird life is responsible for the luxuriant vegetation. Table 2 includes the species known (Hultén, 1937) to occur on Kiska or Attu and looked for, but not found, on Buldir. It does not pretend to be exhaustive. All the species listed are relatively conspicuous and easily recognizable. Most of those characteristic of the eastern islands were in bloom on other islands at about the time of our trip to Buldir.

TABLE 2.—*Some plant species, recorded from nearby Aleutian Islands, not found on Buldir Island*

	Attu I.	Kiska I.
Iris setosa Pallas (Iris)	x	x
Orchis *aristata* Fischer (Orchid)	x	x
Platanthera dilatata (Pursh) Lindley (White bog orchid)	x	x
Trollius riederianus (Fischer and Meyer) (Globe flower)	-----	x
Aconitum maximum Pallas (Monkshood)	x	------
Anemone narcissiflora A. P. de Candolle (Windflower)	x	x
Aruncus sylvester Kosteletzky (Goatsbeard)	x	------
Sorbus sambucifolia (Chamisso and Schlechtendal) Roemer (Siberian mountain ash)[1]	x	------
Lupinus nootkatensis Donn (Lupine)	x	x
Mimulus guttatus A. P. de Candolle (Yellow monkey flower)[2]	-----	x
Cirsium kamtschaticum Ledebour (Kamtchatkan thistle)	x	------

[1] Hultén (1937, p. 220) reports identifying this species on Buldir through field glasses.
[2] Found on Shemya, according to G. B. [illegible] Schaak (personal communication, 1948).

The ig[illegible] of the plant distribution will be [illegible] in the section on [illegible] history [illegible]

Mr. [illegible] S. Benninghoff of [illegible] Survey has kindly offered the [illegible] on t[illegible] list:

[illegible]ck of some plant [illegible] recorded from nearby Aleutian [illegible] not found on Buldir Isl[illegible] [illegible] as follows:

1. T[illegible] following [illegible] have [illegible] continuous records all along the Chain, although there are several gaps ([illegible] district, Amlia Island, and Buldir) where lack of records may be due to lack of collecting:

Platanthera dilatata. [illegible] gaps in western p[illegible] of Chain.

Iris setosa.

O[illegible] aristata.

Anemone narcissiflora. [illegible] this plant would be [illegible] to ssp. [illegible] by [illegible] that is [illegible]mon along most of the Chain, although [illegible] other gaps occur in the western half.

Lupinus nootkatensis.

2. [illegible] that do not have continuous ranges in the Aleutians:

Trollius riederianus. The only station recorded in Hultén Flora (1937) is [illegible] so that the [illegible] of this [illegible] in the argument is somewhat i[illegible]paired.

Aruncus sylvester. Although common along the Pacific Coast and in southern Alaska, this species is recorded only from Nagai Island and Attu Island in the Aleutians.

Sorbus sambucifolia. This is an Asiatic species with its North American range limited to Buldir (identified by Hultén through binoculars), Alaid, Attu, and Agattu Islands.

Unfortunately I do not have at hand the reports (scattered in the literature). for checking *Veronica grandiflora, Achillea borealis, Senecio pseudoarnica, Mimulus guttatus,* and *Cirsium kamtschaticum.*

GEOLOGY

BULDIR VOLCANIC ROCKS

The rocks of Buldir Island may-be attributed to either of the two volcanic centers, Buldir Volcano or East Cape Volcano. The rocks of Buldir Volcano are probably of Quaternary age.

The highest summit of the island, 2,037 ft in altitude, is apparently part of the rim of an old summit tuff cone of Buldir Volcano. It is probable that the crater of the cone was about half a mile in diameter, and that the center of the old crater was about half a mile north of the southernmost point of the island. The steeper tuff cone, about 600 ft high, surmounts a composite cone of relatively gentle slopes. Fragmental material is dominant in the composite cone. The lavas of the cone are mostly pale gray, dense, holocrystalline olivine basalts. The flows are generally thin, averaging less than 10 ft.

A lower and presumably parasitic cone (Hill 1350) rose to the northeast of the main cone; and its activity was probably at least partly coeval with that of the main cone. The small pond at 720 ft altitude, which I call Kittiwake Pond, is believed not to occupy the main crater of this parasitic volcano, but rather a small maar blasted out of the western side of the cone. The prevalence of westward-dipping beds where the pyroclastics of this cone are exposed in the cliff northeast of the pond, and the relatively gentle westward slope, together with the lack of any corresponding eastward-dipping beds or eastward-sloping surface, *suggest strongly* that the greater part of the parasitic cone has been removed. The general trend of the scarp separating Buldir Volcano from East Cape Volcano and its resemblance to the existing sea cliffs around the perimeter of the island suggest that the removal took place by marine erosion. The possibility that it was in part down-faulted seems negated by the discordance in trend between the scarp and the recognized faults on the island.

EAST CAPE VOLCANIC ROCKS

The other volcanic center which has contributed largely to the construction of Buldir Island is called the East Cape Volcano, and the rocks erupted by it are also considered of Quaternary age.

The southwestern part of the island, formed by the Buldir Volcano, with its parasitic cone, is separated from the northeastern part by two valleys, trending in opposite directions, and heading in a pass at an altitude of 1,100 ft. The southwestern walls of the two valleys form one continuous scarp, and are regarded as parts of the same sea cliff, eroded prior to the eruption of the rocks of East Cape Volcano.

East Cape Volcano consists of two parts, the older and higher cone to the north, and a smaller volcanic dome on the southeastern flank. The highest remaining part of the main cone is apparently near the principal eruptive center. Little essential pyroclastic material was erupted during the formation of this cone. The central part is occupied by what appears to be a plug dome, of medium gray, hypersthene-bearing hornblende basalt, grading into an andesite, similar in appearance and mineral composition except for the presence of slightly more sodic feldspar. Much of the present cone is mantled by a crumble breccia derived from the plug dome (pl. 2). East Cape is apparently a lava flow now nearly removed by erosion.

The most recent manifestation of eruptive activity on the island is the dome, 1,667 ft in altitude, a flank eruption of East Cape Volcano, The formation of this dome was preceded by one or more explosive eruptions that blasted a lateral crater in the southeast flank of East Cape Volcano, and built a partial cone southeast of the principal summit. The extrusion of the dome deformed the pyroclastic beds of the parasitic cone, where these were caught between the dome and the old sea cliff of Buldir Volcano to the southwest of the dome. The dome is a medium gray, hypersthene-bearing hornblende basalt.

SEDIMENTARY ROCKS

ALLUVIUM

Because of the mountainous nature of the island, alluvium has accumulated and has been preserved only in a few protected spots. The largest area of alluvium forms the flat at the northwest end of the island. Where exposed in the sea cliff, it is composed of sand and gravel, reworked cinders, and ash. The alluvial surface now ends in a sea cliff 15 to 20 ft high, which must be retreating rather rapidly to permit the maintenance of the vertical face of the cliff. At the time of its deposition this body of alluvium probably was protected from the sea by parts of Buldir Volcano and the northeastern parasite cone.

Some high-level bodies of alluvium fill undrained primary depressions resulting from irregular volcanic deposition. Near the northeast end of the island a small body of alluvium has accumulated behind a bar, formed from debris moved eastward alongshore from a large rockslide off the steep cliffs of East Cape Volcano.

BEACH DEPOSITS

The beaches of Buldir Island, because of its exposed situation, are predominantly narrow and composed of coarse material, ranging in size from boulders to cobbles. A sand beach half a mile east of Northwest Point is unique on Buldir and owes its survival to the continuous supply of fine material resulting from the rapid erosion of the fine alluvium of the small valley south of the beach.

STRUCTURAL GEOLOGY

Little or no evidence of warping of the rocks of the island was seen, but the island is transected by numerous Recent faults, which displace the present topographic surface by considerable amounts. The mean trend of these faults is about N. 67° W., almost parallel to the trend (N. 73° W.) of the Aleutian Ridge from Buldir I. to Shemya I.

There appears to be no systematic arrangement of upthrown and downthrown sides, but this observation is based on the displacement of recognizable land forms, rather than on the recognition of geologic displacements. Most of the faults are steeply dipping, and apparently normal. The throw, judging again by displacement of the land forms, ranges from about 6 ft, in the case of the longest fault shown, to an estimated maximum of 250 ft, on the fault that appears to terminate near the small pond, half a mile north-northeast of the highest point on the island. The marked topographic expression of these faults is well shown on the vertical aerial photograph (pl. 1). Sag ponds and other undrained depressions are common, and in many places talus cones have not been able to override the upthrown, downhill side of a fault. The trace of most faults, however, becomes obscure or disappears on the sea cliffs, suggesting that the faulting is less active than marine erosion. All fault scarps seen on the ground were turfed over at low altitudes where plant growth is vigorous.

The origin of these faults is obscure. Recent faults, tangential to a volcanic center, have been described from Adak Island (Coats, 1947, p. 84), but the Adak faults uniformly have the downthrown side nearest the eruptive center about which they are oriented and the regional structural features have no effect on their orientation. It is believed that the faults on Buldir are tensional structures, due to stretching over the crest of a rising geanticline, the Aleutian Ridge. Much larger scale faulting of a volcano situated on an active anticline has been described in Java (van Bemmelen, 1938).

GEOLOGIC HISTORY

The oldest event in the known geologic history of Buldir Island was the building up of Buldir Volcano. The main center, and probable source of the oldest eruptions, was slightly south of the present highest point of the island; later centers were successively farther northeast. The largest and latest of these minor centers (of which Hill 1350 is the highest remnant) was built up by both extrusion of lava and explosive eruption of liquid and solid material. Activity varied from strombolian to vulcanian in type. Toward the end of the life of this volcano, a small crater, now occupied by Kittiwake Pond, was blasted out of its western flank.

A period of quiescence followed. Marine erosion cut away the flanks of the main volcano and its major parasitic cone (of which Hill 1350 is the highest point remaining). After the parasitic cone had disappeared beneath the encroaching sea, a new eruption built another cone, the East Cape Volcano, largely by explosive activity, culminated by the extrusion of two domes of hypersthene-bearing hornblende basalt, one in the summit crater, the other in a secondary crater blasted out of the southeast flank. The eruption of the latter dome represents the latest eruptive activity on the island.

The subsequent geologic history of the island has been one of erosion, with minor deposition in protected basins. Numerous faults that find surface expression suggest that it must have been rocked by many earthquakes in the recent past, and perhaps one of these was responsible, as Thompson suggested, for the rockslide on the northeast shore, now nearly removed by the sea.

In the discussion thus far, only the relative ages of the several rock bodies have been considered. No fossils that might permit dating the geologic events were discovered on Buldir Island. We are forced to fall back on comparisons with events in better known areas, and on reasoning from lines of evidence other than geologic.

The most recent dome on Buldir Island is comparable in degree of subaerial erosion with some of the volcanic domes on Adak Island that are regarded as Pleistocene or pre-Pleistocene. It must be remembered, however, that volcanic domes, because of their high permeability and consequent lack of surface runoff, are able to survive unmodified for periods of time during which composite cones have been deeply denuded. Similar effects on cinder cones have been noted by Cotton (1944, p. 150) and von Engeln (1942, p. 608). It may be expected that a dome, having a deeply fissured carapace, will be modified to some extent by mechanical disintegration and block fall, the effects of which will be scarcely distinguishable from the after-effects of the act of intrusion itself. The high permeability will minimize solifluction as an agent of reduction, and the coarseness of the blocks will reduce the effects of snow to a minimum. Hence, degree of erosional attack is not a very sensitive measure of relative age of volcanic domes.

The effects of marine erosion on Buldir Island may be compared with its effects on Castle Rock, or Old Bogoslof, one of the Bogoslof group, which has lost, since 1796, most of its original area of about two square miles. Factors which may invalidate a direct comparison of the two volcanoes are: The unknown effect of explosive episodes in both volcanoes, differences in sizes of blocks which must be removed by wave action, and differences in height of the subaerial sea cliff. Nevertheless, it seems reasonable to believe that the age of East Cape Volcano may be on the order of a few thousand years.

The differences between the floras of Buldir and its nearest neighbors, Kiska and the Near Islands, are suggestive as to the relative ages of these islands. Unfortunately, other factors besides the relative ages of the several land masses involved must also be considered. Among these are relative area, climatic conditions, suitability of soil, bird and animal life. The observed fact is that a number of Aleutian plant species, including some of those most widely distributed on other islands, in both directions from Buldir, are missing from that island.

It is conceivable that an island of very small area might have a very restricted flora, for either of two reasons: It is too small a target for the migrating plant to hit by chance, or the limited area affords no suitable site for the plant to become established. Both of these reasons boil down to one—the small chance that the seeds of any given plant will land on a site suitable for establishment and reproduction. On the other hand, the influence of area must be less for some means of dispersal, such as migrating land birds, than for others, such as wind. Too little is known about the method of dispersal of the Aleutian plants to permit any conclusive statement. The effect of area on the chance of settlement should be greater for the relatively rare plants, but some of the plants not present are among the commonest Aleutian plants.

Climatic conditions, soil, bird and animal life should have been relatively uniform in Kiska, Buldir, and the Near Islands during the last few thousand years, with any advantage on the side of Buldir, because of its lower altitude and absence of strong chilling effect of large areas above the snow line. At present, the distribution of bird and animal life among the islands differs considerably, but many of these differences are due to the coming of the white man, and can have had little or no effect on the distribution of the plants.

Buldir Island is approximately half as far from Attu as Attu is from the Commander Islands, and about as far from Kiska as it is from the nearest of the Near Islands. If Buldir, as a land mass, were as old as Attu, it would be expected that the flora of Buldir would be like that of Attu, but somewhat less Asiatic in aspect, as suggested by Hultén. If it were as old as Kiska, it would be expected that it would have nearly every species common to both Attu and Kiska and perhaps share with Attu some not found on Kiska. If Buldir

Island were younger than either Attu or Kiska, it might be expected to have a restricted number of species, as compared with either of those islands. This last indeed appears to be the case; the evidence of the flora, insofar as it has been studied, bears out the impression conveyed by the physiographically youthful constructional volcanic slopes of Buldir Island. The evidence of the flora also suggests that Buldir Island is a wholly young island, and not the last remnant of a larger and older island, owing its preservation to the recency of volcanic activity at this center. It might be suggested that Buldir Island is older than the flora would indicate, but that an earlier flora may have been destroyed either by volcanic eruption or by glaciation. Such complete destruction is believed to have taken place at Krakatau (Docters Van Leeuwen, 1929, p. 60). There is, however, no evidence of a paroxysmal eruption of a violence sufficient to destroy all the vegetation; and there is no evidence that, the island was ever glaciated.

PETROGRAPHY

BULDIR VOLCANIC ROCKS

All the rocks of Buldir Island are basalts and basaltic andesites. Textures have been studied in thin section and compositions of minerals determined from refractive indices in immersion oils. In general, the rocks of Buldir Volcano are olivine basalts and olivine-hypersthene basalts. A rock from the main cone (47AC27) is a holocrystalline purplish, somewhat porous rock, with a maximum grain size of 1.5 mm. It consists of about 70 percent plagioclase, from An_{70} to An,, in composition, with a median of about An,,; about 5 percent olivine (Fa_{15}), 20 percent augite, 3 percent magnetite, and 2 percent of pseudomorphs of magnetite and augite after hornblende. The texture is intergranular and essentially seriate, as no well-defined break in range of grain sizes is present. The smaller grains of augite, ranging in size from 0.1 to 0.04 mm, are, together with magnetite, interstitial to the somewhat lath-like crystals of plagioclase. The olivine shows a slight color zoning, the outer part having a higher index and slightly darker color, presumably reflecting a higher content of iron.

An early flow (47AC31) from the northerly parasitic cone of Buldir Volcano is purplish gray, dense, and porphyritic, with a maximum grain size of 2 mm. Of the total volume, 35 percent is plagioclase phenocrysts, zoned, ranging in size from 2 to 0.5 mm, with a median composition of An,,. Three percent is olivine with a composition about Fa_{24}. Two percent is made up of augite and magnetite in the form of pseudomorphs after hornblende, and about 1 percent is hypersthene with a composition of about $En_{60}Fs_{40}$, judging from the negative 2V of about 60°. Some hypersthene crystals have augite jackets.

The groundmass, about 60 percent of the total volume, includes about 50 percent plagioclase, 3 percent hypersthene, 6 percent augite, and occasional prisms of cloudy apatite. The texture of the groundmass is also intergranular; between the plagioclase laths, ranging in length from 0.2 to 0.07 mm and in width from 0.02 to 0.08 mm, there are pyroxene granules from 0.04 to 0.01 mm in size and slightly smaller granules of magnetite.

Interstratified with lava flows on the sea cliff northeast of Kittiwake Pond, at an altitude of 760 ft, are layers of essential basaltic lapilli, consisting of hyalophyric olivine basalt. The rock includes 50 percent of labradorite phenocrysts, 10 percent of olivine, 5 percent of augite, 3 percent of pseudomorphs of augite and magnetite after hornblende, 2 percent of hypersthene, 2 percent of magnetite grains, and 28 percent of brown glass with a mean refractive index of 1.537. The glass is probably andesitic (George, 1924). The groundmass is exceedingly fine-grained, and consists of unoriented prisms of augite and laths of plagioclase, with small grains of magnetite, and interstitial glass.

A later flow (47AC26), forming the small hill (Hill 1350) south of Kittiwake Pond, is a pale gray, porous holocrystalline olivine andesite, about 77 percent plagioclase, which ranges in composition from An_{20} to An_{70} and averages about An_{45}. Clinopyroxene grains, 0.1 to 0.5 mm ($Di_{60}He_{40}$), make up 15 percent of the rock; olivine grains (Fa,,,), ranging in size from 0.2 to 2 mm, about 5 percent; and magnetite grains, 0.1 to 0.5 mm in size, about 3 percent. A trace of hypersthene is present. The seriate texture is essentially determined by the presence of stout subparallel laths of plagioclase with interstitial granules of clinopyroxene and magnetite.

EAST CAPE VOLCANIC ROCKS

The rocks of East Cape Volcano include hypersthene-bearing hornblende basalts and basaltic andesites. All are dense, medium gray rocks, with 80 to 90 percent of plagioclase, ranging in composition from An_{50} to An_{70}; 10 to 15 percent of hornblende, which is brown, with a deep black resorption border and a low extinction angle; and about 1 percent of hypersthene (47AC28 is typical). Two percent of magnetite and a small amount of apatite, in cloudy prisms ranging in size from 0.2 to 0.02 mm, are also present. The groundmass is a very fine-grained unorientated aggregate of prisms of oxyhornblende, augite, laths of plagioclase, and grains of magnetite, with a little interstitial orthoclase.

Significant information about the basement rocks of this part of the Aleutian ridge is given by a small xenolith of hypersthene granulite, with a well-defined layering, and lineation apparently parallel thereto.

The bed with the better lineation consists of relatively long prisms of hypersthene and more equant plagioclase, riddled with inclusions of orthoclase. The other bed has a similar composition, but it has no pronounced directional texture and contains a small circular mass of slightly differing composition in which greenish-brown biotite and orthoclase are notable. Apparently this accidental xenolith is a product of the granulite facies and represents a region of high grade regional metamorphism. The plagioclase crystals of the xenolith continued to grow where they were in contact with the magma but show rapid zoning to less calcic composition; the only hypersthene grain in contact with the lava seems to have been converted to brownish hornblende.

Some blocks of volcanic rock have been reheated locally, after solidification, by gases diffusing into them from narrow cracks. Megascopically, the alteration is shown by reddening; microscopically, by a darkening of the hornblende, a decrease in its extinction angle, and production of pleochroism in the apatite, which becomes noticeably yellow for the fast ray. Similar changes in hornblende in the Marysville Buttes intrusive were attributed by Williams (1929, p. 192) to reheating. The material erupted by the Marysville Volcano was less extensively oxidized than that just described. Williams demonstrated by experiment that the temperature could not have been higher than about 600C under oxidizing conditions, or about 800C under neutral conditions. It may be inferred that the deeper penetration into joint blocks of the oxidation, manifested by the reddening and dehydration of the hornblendes, is due to the longer period during which the rocks of the central dome of the East Cape Volcano were exposed to heated gases. The extremely unsorted, chaotic, and unstratified character of the material making up the sea cliffs on the north side of the mountain suggests that these breccias were produced by crumbling of a lava dome, perhaps disrupted in part by weak steam explosions (pl. 2).

The dome on the flank of East Cape Volcano (47AC30) is also a hypersthene-bearing hornblende basalt, pale gray, porous in structure, with a faint lineation due to the orientation of the hornblende prisms. About four-fifths of the coarser part of the rock consists of plagioclase grains from 0.02 to 0.6 mm in size, with an average composition of An_{55}. Hornblende, about 10 percent by volume, is greenish brown, and the needles are from 0.02 to 2 mm long. The hypersthene prisms, which form about 3 percent of the rock, are from 0.02 to 0.4 mm in length. Magnetite grains make up about 2 percent and augite about 1 percent of the rock. Traces of apatite, olivine (Fa_{18}), and glass ($n=1.515$) are present. A small amount of analcime(?) appears to replace both glass and plagioclase. The groundmass, which forms

by

about 20 percent of the whole rock, consists of unoriented augite needles, averaging about 0.0002 by 0.02 mm in size, plagioclase crystals, 0.01 by 0.02 mm, and magnetite granules, in glass.

CHEMISTRY

Five of the specimens collected from Buldir Island have been analyzed in the laboratories of the Geological Survey, and the results of the analyses are shown in table 3. Also included in that table are the norms, calculated by the use of von Philipsborn's tables (von Philipsborn, 1933), the Niggli values (Niggli, 1923, pp. 60–62), and the Niggli magma-type (Burri and Niggli, 1945, pp. 31–32).

The specimen numbers at the head of the colums correspond to those given in the petrographic descriptions.

The analyses confirm the results of the petrographic descriptions, and show that the rocks of Buldir are normal basalts and basaltic andesites, like those of other circum-Pacific volcanoes. The range of chemical variation seems to be small at Buldir Island. It is notable that the latest rock to be erupted is one of the most silicic, and the viscosity of the erupted material is high, although the rock is less silicic than rocks from similar domes at other circum-Pacific volcanoes. It is possible that this eruption signals the end of the eruptive history from the magma chamber beneath Buldir, which is not only the most westerly in the line of Quaternary Aleutian volcanoes, but also one of the smallest. Perhaps the magma chamber in which the differentiation took place was never as large as those beneath some of the volcanoes farther east.

TABLE 3.—*Chemical composition and parameters of volcanic-rock specimens from Buldir Island, Aleutian Islands, Alaska*

A. Chemical analyses for major constituents

[A. C. Vlisidis, analyst; flame-photometer analyses of alkalies by W. W. Brannock]

	47AC27	47AC26	47AC31	47AC28	47AC30
SiO_2	52.27	52.28	55.33	60.44	60.73
Al_2O_3	17.08	17.69	17.22	18.02	16.67
Fe_2O_3	3.38	2.35	2.61	2.08	2.96
FeO	4.38	4.84	3.98	2.52	2.58
MgO	7.70	7.32	6.38	2.98	3.49
CaO	9.08	9.03	8.03	6.86	6.88
Na_2O	3.52	3.51	3.78	4.04	3.69
K_2O	.80	.88	1.15	1.34	1.10
H_2O-	.12	.28	.12	.08	.10
H_2O+	.52	.88	.48	.30	.44
TiO_2	.88	.80	.76	.60	.68
P_2O_5	.20	.22	.27	.19	.29
MnO	.12	.13	.14	.11	.13
Cl	.06	.05	.23	.72	.10
F	.02	.04	.01	.02	.02
	100.13	100.30	100.49	100.30	99.86
O=Cl	.01	.01	.05	.16	.02
O=F	.01	.02	----------	.01	.01
Corrected total	100.11	100.27	100.44	100.13	99.83
Specific gravity 30°/4° (powder)	2.88	2.87	2.75	2.75	2.68

TABLE 3.—Continued

B. Spectrochemical analyses [1] for minor constituents

[K. J. Murata, analyst]

	47AC27	47AC26	47AC31	47AC28	47AC30
Cu	0.004	0.004	0.004	0.003	0.003
Ni	.009	.01	.009	.001	.002
Co	.002	.002	.002	.001	.001
Cr	.02	.02	.01	.002	.004
V	.009	.008	.007	.007	.006
Zr	.004	.004	.005	.004	.006
Ga	.001	.0008	.0009	.0009	.001
Ba	.02	.02	.02	.03	.03
Sr	.04	.04	.04	.05	.06

C. CIPW Norms.

[See von Phfllipsborn, 1933, for tables used in calculations]

Quartz	0.06	----------	2.83	16.52	17.16
Orthoclase	4.73	5.18	6.79	7.90	6.52
Albite	29.36	29.31	31.04	28.84	30.46
Anorthite	28.67	30.09	27.12	29.93	25.79
Fluorite	.06	----------	----------	----------	----------
Halite	.1	.as	.23	1.19	.16
Wollastonite	6.34	5.47	4.65	1.25	2.79
Enstatite	19.17	16.53	15.88	7.42	8.69
Ferrosilite	4.02	5.33	4.16	2.14	1.41
Forsterite	----------	1.19	----------	----------	----------
Fayalite	----------	.41	----------	----------	----------
Magnetite	4.91	3.41	3.80	3.01	4.29
Ilmenite	1.67	1.52	1.44	1.14	1.29
Apatite	.47	.54	.64	.44	.67
	99.50	99.12	98.58	99.78	99.23
Classification:					
Class, Order	II,5	II,5	II,5	II,4	II,4
Rang, Subrang	3 (4), 4 (5)	3 (4), 4 (5)	3″, 4″	3″, 4″	3″, 4
Name	Andose	Andose	Andose	Tonalose	Tondose

D. Niggli Values

Numbers: [2]					
al	24.2	25.5	26.6	34.3	31.5
fm	43.0	41.2	39.2	26.6	31.1
c	23.4	23.6	22.6	23.7	23.6
alk	9.4	9.7	11.6	15.5	13.8
	100.0	100.0	100.0	100.0	100.0
si	126.	128.	145.5	195.4	196.
qz	−11.6	−10.8	−.9	33.4	40.8
k	.132	.141	.165	.179	.191
mg	.645	.E48	.635	.54	.537
c/alk	2.49	2.44	1.96	1.54	1.72
Magma types [3]	Normal gabbro-dioritic	Orbitic	Lampro-dioritic	Peléeitic	Peléeitic

[1] Elements looked for, but not found: La, B, Pb, Be, ;, Pt, Pd, Bi, As, Sb, Tl, Mo, Zn, Cd, Ge, In.
[2] See Niggli, 1923, pp. 60–62
[3] See Burri and Niggli, 1945, pp. 31–32.

DIFFERENTIATION OF THE ANALYZED ROCKS

The small number of analyzed rocks makes it difficult to arrive at any conclusions regarding the course of rock differentiation shown by the rocks of Buldir.

The analyses, when plotted against silica percentage in the usual manner, show both resemblances to and differences from rocks from the better-known centers of Adak and Kanaga Island (Coats, R. R., 1952).

The alkali-lime index, obtained by extrapolation of the lines for calcium and the sum of the alkalis beyond the region of the analyses, is about 64½, which is comparable to and perhaps slightly more than that for the Adak and Kanaga rocks. The highly calcic nature of this part of the province is conspicuous (Peacock, 1931, p. 54). The calcium curve is flatter than that for Adak and Kanaga; the curve of the iron oxides is flatter and, in general, below that for Adak and Kanaga; and the curve for magnesium is above and much steeper than that for Adak and Kanaga. The curve for sodium is similar to that for Adak and Kanaga; and that for potassium is nearly parallel to and only slightly lower than the curve for Adak and Kanaga. Mineralogically, these differences suggest that in the Buldir rocks magnesium minerals, particularly olivine, have been concentrated at the basic end, and that calcic plagioclase is present in all the members; in other words, differentiation has taken place chiefly by removal of ferromagnesian minerals.

A type of diagram which shows the relation of rocks by plotting MgO, FeO, and alkalis as the three variables has recently been used with success by Poldervaart (1949, pp. 177–188) to show the contrasts in trends of differentiation between the calc-alkaline series and the basaltic series which show iron enrichment. Because of the common and inconstant degree of oxidation of the iron in volcanic rocks, it seems best to modify Poldervaart's diagram by adding to the FeO the amount of FeO corresponding to the Fe_2O_3 found by analysis. This does not distort significantly the relation between the analyzed rocks. In such a diagram the points which represent the average basalt, andesite, dacite, and rhyolite of Daly fall on a fairly smooth curve which is convex toward the iron corner, and trends toward a point on the iron-alkali side about 15 percent of the way from the alkali corner to the iron corner. In a series where iron enrichment has taken place, the plotted points fall on a line above the calc-alkaline curve and more sharply convex toward the iron corner. The analyses of the Buldir rocks all fall below the calc-alkaline curve. The position of the points representing the Buldir rocks is shown on figure 3, together with four points representing the Daly averages (Daly, 1933). The reason that the plotted points for the Buldir rocks fall below the calc-alkaline line is the high magnesia and the low iron content of the analyzed rocks.

When the Niggli numbers are calculated from the analyses, however, and plotted in a section of the Niggli tetrahedron, this contrast is concealed by the combination of iron with magnesia in fm, and the points are grouped very closely. In the diagram, figure 4, the dotted line encloses the positions of 17 analyses of rocks from Adak and Kanaga Islands. The relatively small degree of variation is well shown by the small field occupied by all the plotted points.

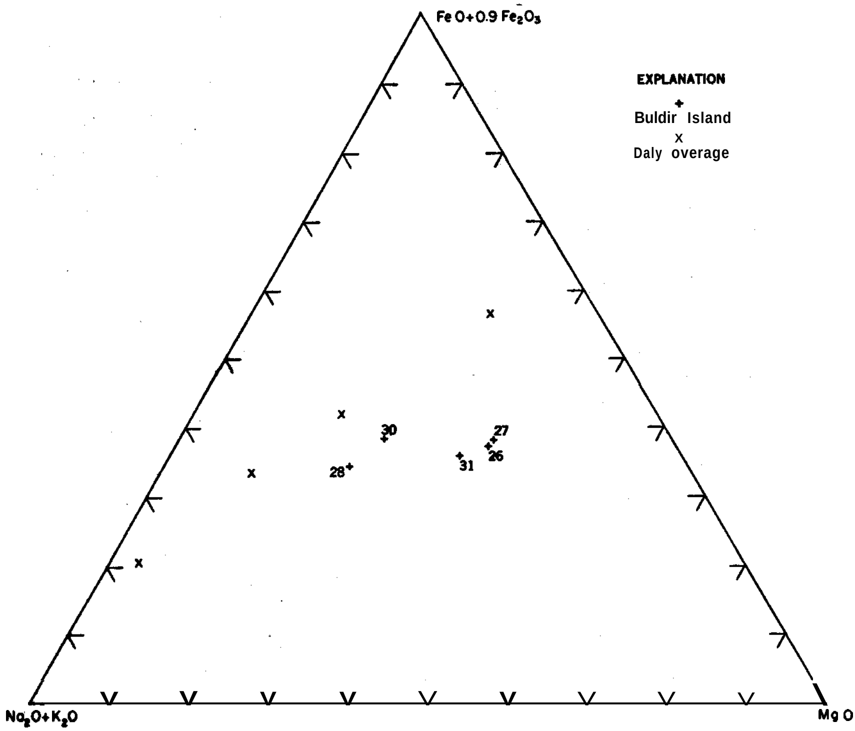


FIGURE 8.—Relation of magnesia (MgO), iron (FeO), and alkalies (Na_2O+K_2O) in volcanic rocks from Buldir Island.

THE RARER CONSTITUENTS

The results of spectrographic analyses of the analyzed rocks are also shown in table 3, together with a list of the elements looked for by the spectrographer, but not found. The limits of sensitivity of the spectrographic method that was used, for some of the elements in the latter category, are shown below (K. J. Murata, personal communication).

	Percent		*Percent*
La	0.002	Bi	0.002
B	.001	As	.1
Pb	.001	Sb	.05
Be	.0001	Sn	.002
Ag	.0001	Ge	.003
Zn	.03	In	.003
Cd	.01	Tl	.01
Pt	.003	Mo	.001
Pd	.001		

A comparison of the results for these rocks with those for the rather similar volcanic rocks from Adak and Kanaga Islands reveals certain significant similarities and differences. In general, the elements found in the Buldir rocks were present consistently also in the rocks

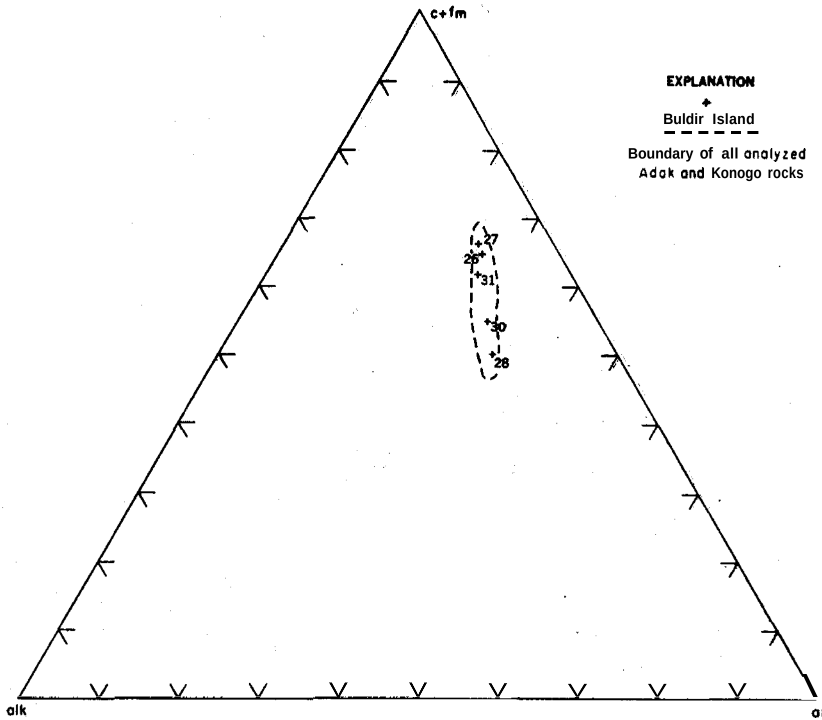


FIGURE 4.—Relations of al, alk, and c+fm in volcanic rocks from Buldir Islands, plotted in a section of the Niggli tetrahedron that includes the al-alk edge.

from Adak and Kanaga, in which, however, occur others not present at Buldir. In a study of the Adak and Kanaga rocks (R. R. Coats, 1952) significant differences between the two islands were found in the ratios of the rarer constituents to one another and to the more common constituents for which they are able to proxy in the space lattices of the several rock-making minerals. This is also true of the Buldir rocks, as compared with those from Adak and Kanaga Islands.

The ratio of strontium to barium, as shown in the earlier study, is consistently higher in the rocks of Adak than in those of Kanaga, being independent of the silica percentage. In the rocks of Buldir Island, this ratio is generally lower than in those of Adak and higher than those of Kanaga, as is shown by their plotted positions in figure 5.

This relation probably reflects original differences in concentration of strontium in the magma rather than differences in the amount of barium. Barium varies here, as in many rock series, in a nearly constant ratio to potassium, which it replaces in potash feldspar diadochically—a relationship defined by Rankama and Sahama (1950, p. 121) as follows: "Two atoms or ions occurring in a mineral are

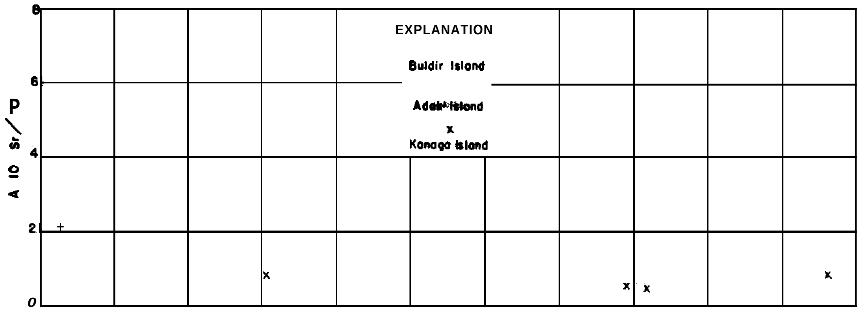


FIGURE 5.—Relation of the strontium-barium ratio to the silica percentage in volcanic rocks from Buldir, Adak, and Kanaga Islands.

called diadochic if they are capable of replacing each other in the structure of the mineral, each occupying the other's position." The barium-potassium ratio (see fig. 6) is nearly uniform in the rocks of the three islands; in all of them it is approximately 0.025.

NICKEL, COBALT, CHROMIUM, AND VANADIUM

Nickel, cobalt, chromium, and vanadium are commonly concentrated in ferromagnesian minerals. Nickel and cobalt substitute diadochically for magnesium and are consequently concentrated in the magnesium-rich minerals. Over a narrow range of differentation it may be possible to calculate a ratio of concentration of the rare element

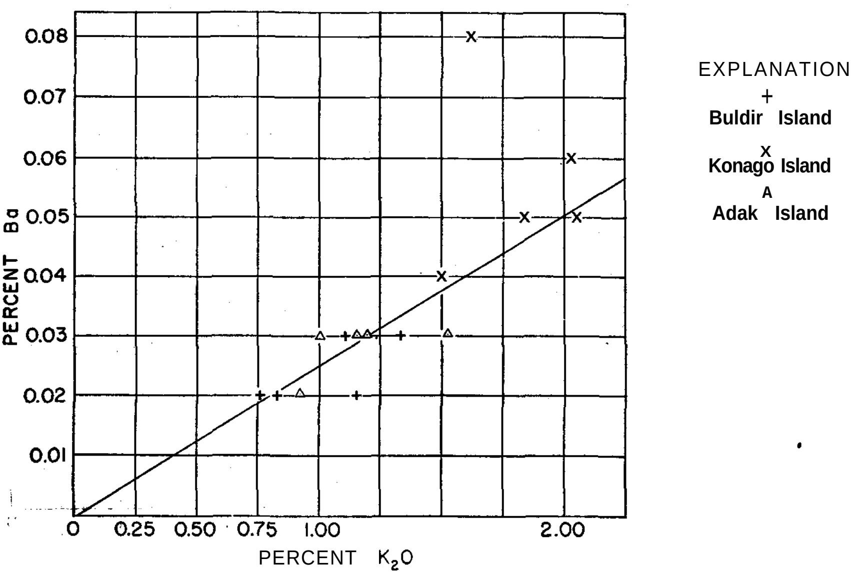


FIGURE 6.—Relation of barium content to that of potassium (as K_2O) in volcanic rocks from Buldir, Adak, and Kanaga Islands.

to the common one, which can then be used for the comparison of rocks representing the same stage of differentiation from two different provinces or subprovinces. These relationships are most readily seen when the content of nickel and of cobalt are plotted against the magnesium content. This has been done in figure 78. The cobalt content of the Buldir rocks is comparable, within the limits of error

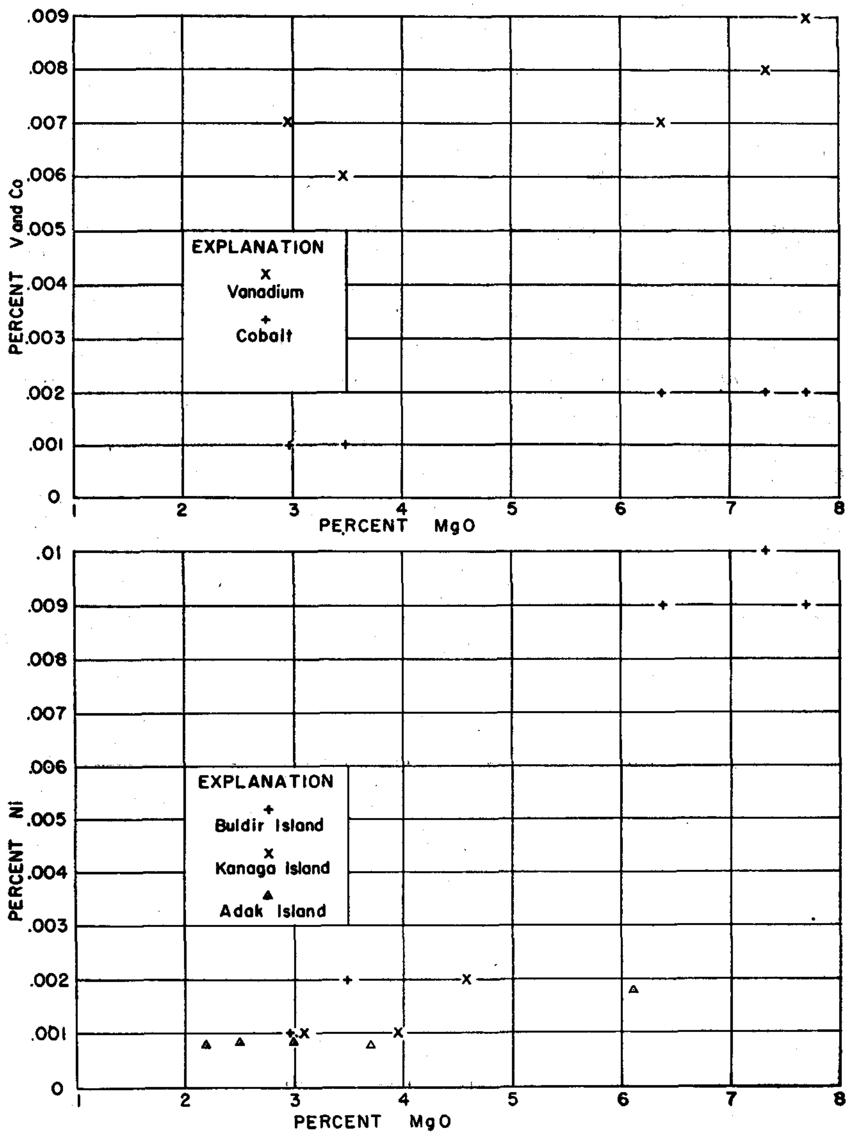


FIGURE 7.—*A*. Relation of cobalt and vanadium to magnesia in volcanic rocks from Buldir Island. *B*. Relation of nickel to magnesia in volcanic rocks from Buldir, Adak, and Kanaga Islands.

of determination, with that of rocks of similar magnesium content from Adak and Kanaga Islands. The vanadium content does not show any clear dependence on magnesium in the rocks from any of these islands, but the total content seems to be about half as great in the Buldir rocks as in those from Adak and Kanaga Islands.

The amount of nickel relative to that of magnesium, however, seems to be much greater in the Buldir rocks than in those from

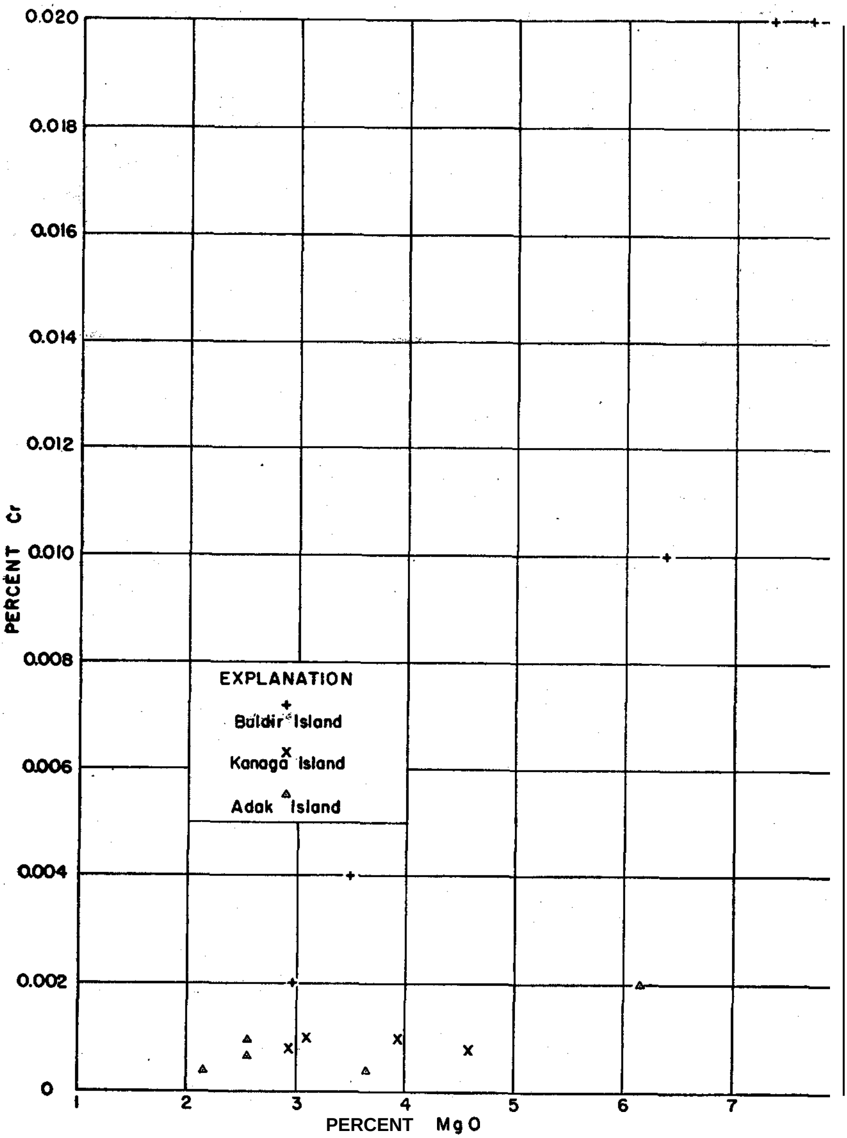


FIGURE 8.—Relation of chromium to magnesia in volcanic rocks from Buldir, Adak, and Kanaga Islands.

Adak and Kanaga. This contrast is shown by figure 7*B*, where the results show that the nickel content of the Buldir rocks not only is higher, but it increases more rapidly with increasing content of magnesium than in the Adak and Kanaga rocks. This richness in nickel is in part a reflection of the higher magnesium content of the Buldir rocks; and both may result from enrichment in the early formed magnesium-rich ferromagnesians, which Vogt (1923, p. 326) showed to be richer in nickel than the later-formed ones.

The amount of chromium is also much higher in the rocks from Buldir Island than in those from either Adak or Kanaga, as is shown by figure 8. The maximum found is 0.2 percent, whereas the highest in the rocks from the other islands is only one-tenth as great. The nature of the minerals that carry the chromium is not known; because of the resemblance of the curve to that for nickel, it is possible that chromium may, as suggested by Rankama and Sahama (1950, p. 622) be present as a diadochic replacement of magnesium in the ferromagnesian minerals. There is a suggestion that both chromium and nickel are more abundant in the rocks of Buldir Island than in those of Adak and Kanaga Islands.

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