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THE PETROLOGY OF UMNAK AND BOGOSLOF ISLANDS, ALASKA

BY

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spent in a geological reconnaissance of southwestern Umnak. Bogoslof Island was mapped on September 15 after completion of the field mapping on Umnak. During September, 1948, the writer, accompanied by H. A. Powers, spent several days on northeastern Umnak Island checking the geology of critical exposures.

The writer is greatly indebted to Dr. N. L. Bowen, formerly Distinguished Service Professor of Petrology at the University of Chicago, for the writer's original interest in petrology. During the Spring Quarter of 1948, while attending the University of Chicago, the writer received many helpful suggestions from Prof. Tom F. W. Barth on optical study and chemical analysis of the Umnak lavas. Ray E. Wilcox collected rock specimens on Umnak in 1945 while serving in the Army, and kindly made these available to the writer. During December, 1953, Prof. A. O. Woodford of Pomona College, California provided much-needed office space for assembling the manuscript and illustrations of the present dissertation.

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ABSTRACT

Umnak and Bogoslof Islands in the eastern part of the Aleutian volcanic arc have contrasting rock suites, though all are more or less typical of an orogenic belt. The oldest rocks on southwestern Umnak include a Tertiary (?) spilitic suite of folded keratophyre tuffs and flows with interbedded argillite. Altered lavas (epidotized, serpentinized, and potash feldspathized) rest with apparent angular unconformity on the keratophyres. A quartz diorite pluton with associated granophyre dikes has intruded the older rocks and is probably responsible for the potash feldspathization of the lavas. Late Tertiary or early Quaternary unaltered lavas also form part of the older terrain.

Beginning sometime during the Quaternary, two strato-volcanic cones of hypersthene andesite were built on a high eroded platform of older rocks on southwestern Umnak, while on northeastern Umnak a low basaltic shield volcano with a central caldera was built on a partly submerged platform. Though the older strato-volcanic cone has been deeply dissected by glaciers, volcanic activity has continued up into Recent time at both cones. Two violent eruptions occurred in Recent time: a caldera-forming eruption of the basaltic volcano occurred in early Recent time, and about 3,000 years ago a pumice-scoria

eruption issued from the younger strato-volcano of southwestern Umnak. Rhyolite domes were extruded on both northeastern and southwestern Umnak sometime before the culminating eruptions. Near the narrow part of Umnak a viscous quartz-bearing olivine andesite flow was extruded in latest Pleistocene or early Recent time. Post-caldera flows on northeastern Umnak include anorthite basalt, basalt, and basaltic andesite. The most recent eruption in 1945 consisted of an anorthite basalt flow, four miles long, in the caldera of northeastern Umnak.

The first recorded eruption of Bogoslof occurred in 1796 and consisted of a hornblende andesite dome (Castle Rock). Hornblende basalt rich in alkalis was extruded as a dome (Fire Island) during the 1883 eruption. Volcanic domes were extruded in 1906, 1907, 1910 and in 1927; of these only the 1927 dome, an undersaturated hornblende basalt, still remains.

Petrographic and chemical analyses were made of 35 rocks, of which 18 were for minor elements. Quaternary lavas on northeastern Umnak range from 46 to 73 percent silica, whereas southwestern Umnak lavas range from 54 to 77 percent silica. Bogoslof lavas range from 47 to 61 percent of silica. Of the minor elements, zirconium, boron, beryllium, barium, and lead increase with increasing silica, whereas chromium and nickel are not detectible in lavas of andesitic or more siliceous composition. Cobalt persists in the intermediate rocks, probably because of the similarity of its ionic radius with that of iron

and because of the ease with which the cobaltous ion is oxidized to cobaltic, analogous to iron.

The northeastern Umnak and the southwestern Umnak liquid lines of descent are contrasted by high iron and high alumina, respectively, differences expressed petrographically by hypersthene phenocrysts only in southwestern Umnak lavas. Calcic augite crystallizes with the hypersthene, and both are replaced during late stages of consolidation by ferriferous augite that grades commonly into ferrosugite. Curves established by compositions of aphyric lavas and porphyritic lavas groundmasses of northeastern Umnak indicate that these curves represent compositions on the liquid line of descent derived from fractional crystallization of basalt. The curves for lime and magnesia rise to 13 and 11 percent, respectively, at 49 percent of silica (olivine basalt groundmass); some solution of suspended crystals by liquid is inferred as they sank into hotter zones. The composition of the parental basalt magma of northeastern Umnak is between compositions of a plateau basalt magma and a tholeiitic basalt magma, though compositions of primary basalt are variable, particularly with respect to alumina, and may depend both on depth of origin and assimilation of alumina-rich argillites. The compositions of quartz-feldspar residual liquids of granitic composition show a close approach to experimentally investigated systems.

Incomplete melting of quartz diorite to yield an inter-

stitial liquid of lamprophyric composition is indicated by the groundmass of an analyzed hypersthene-bearing labradorite andesite, which is nearly identical in composition with an analyzed quartz diorite. The quartz-bearing olivine andesite is a hybrid lava, that resulted on mixing of quartz dioritic, gabbroic, and olivine-rich basaltic magma. The Bogoslof lavas have become progressively less silicious with time: the last eruption in 1927 was an undersaturated basalt with a small amount of normative nepheline.

Sodium (spilitic) metasomatism of the oldest rocks preceded local more intense potassium metasomatism of both the oldest and slightly younger rocks.

The southwestern Umnak volcanic suite, which is closest to the Pacific basin, has an alkali-lime index of 64. Volcanic suites of Northeastern Umnak, Bogoslof, and the Pribilof Islands are progressively farther from the Pacific basin and also are progressively more alkaline. The two contrasting volcanic suites of Umnak are analogous to the hypersthene andesites of the High Cascades and the Columbia River basalts, except for the somewhat higher lime in Aleutian lavas.

INTRODUCTION

Geographic Features

Umnak and Bogoslof Islands are in the eastern part of the Aleutian Islands which form the northern border of the Pacific Ocean (Fig. 1). The Aleutian ridge, whose flat top is within 80 fathoms of the surface ranges from 23 to 35 miles wide in the vicinity of Umnak. The south slope of the Aleutian ridge passes into the Aleutian trench, an oceanic deep that parallels the Aleutian ridge throughout its length (Murray, 1945, p. 759). Umnak Island is situated on the Aleutian ridge. Bogoslof Island, 25 miles north of Umnak, is the top of a nearly submerged volcano that rises from depths of about 5,000 feet in the Bering Sea. Since 1927, the date of the last eruption, the part of the island above sea level is being reduced each year by marine erosion.

Umnak is a dumbbell-shaped island, 70 miles long and 675 square miles in area, and trends northeast (Pl. 1). Nikolski village, near the southwest end of the island is the only permanent settlement. Umnak Island has three major volcanic mountains: Okmok Volcano on northeastern Umnak and Mounts Recheschnoi and Vsevidof on southwestern Umnak. Okmok Volcano is a low shield volcano with a large central caldera, six miles in diameter, whereas Mounts Recheschnoi and Vsevidof are steep-sided cones

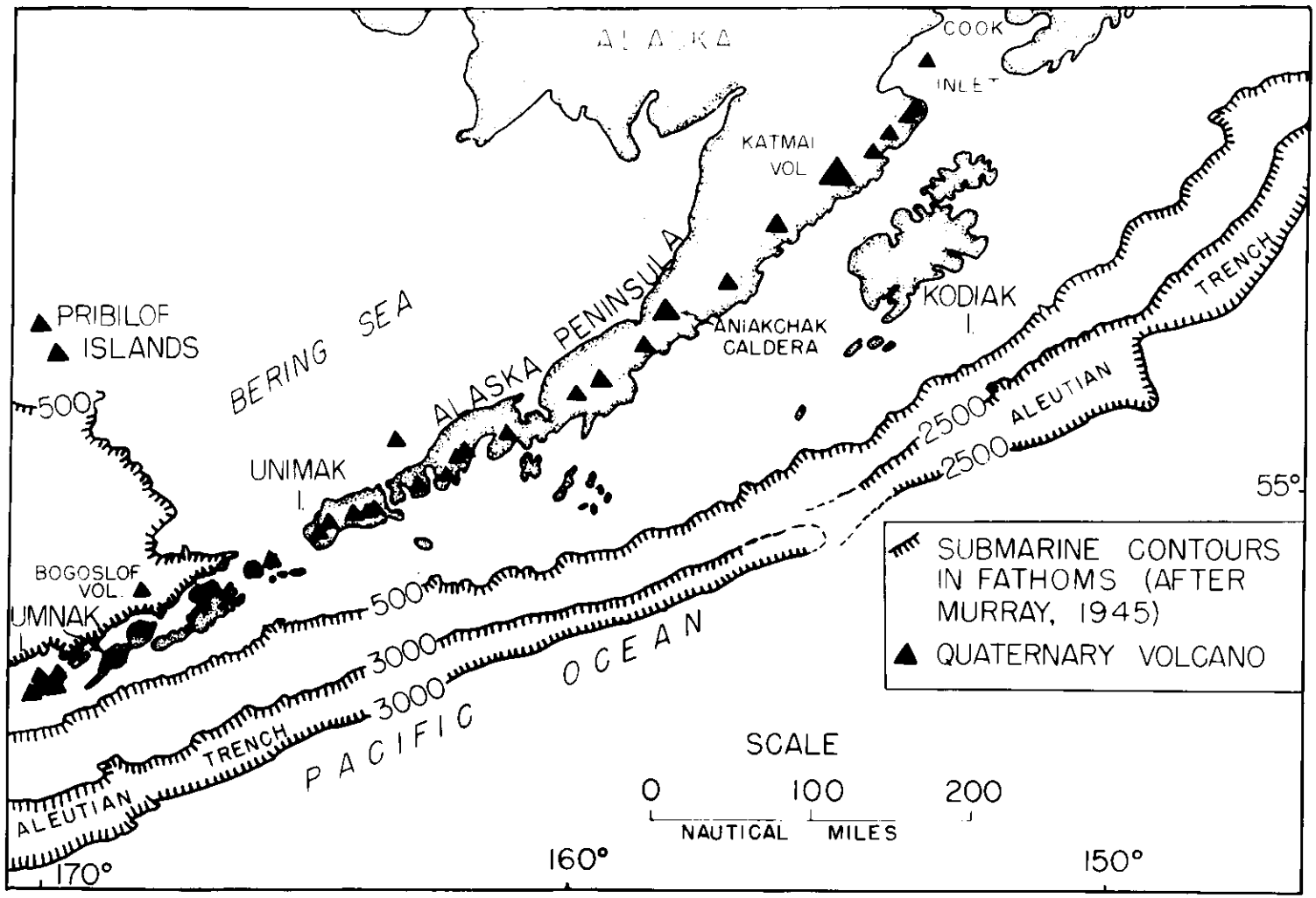

Figure 1.--Eastern part of Aleutian Volcanic Arc, showing positions of volcanoes and Aleutian Trench

that reach a maximum altitude of about 7,000 feet. In the narrow part of Umnak a rugged mountainous area east of Inanudak Bay has a maximum relief and altitude of about 2,600 feet. South of Mounts Recheschnoi and Vsevidof a rolling, lake-studded plain has a relief and altitude of only a few hundred feet.

The climate of the area is typical of the Aleutian Islands with considerable wind, rain, and fog. Temperatures range from about 46° to 71°F. during summer months on Umnak and are within a few degrees of freezing during the winter. Rainfall averages about 40 inches per year near sea level.

Previous Work and Historical Summary

Russian Period, 1741-1867

Umnak Island was first sighted in 1741 by Capt. Alexei Chirikof of the "St. Paul," a ship of Fleet-Captain Vitus Berings' expedition to North America (Collins, 1945, p. 9). The name, Umnak, was the native name (Baker, 1906, p. 650). No Russian investigations or settlements were made on Umnak during the latter part of the eighteenth century, although, Stephen Glottof and other Russian fur traders visited Umnak during this period (Baker, 1906, p. 36). William Coxe (1787, pp. 141-42 and 173-81) gives interesting accounts of the early Russian traders and the natives that inhabited Umnak.

Sail Rock (also called Ship Rock by some navigators) at the site of Bogoslof was first sighted by the Russians in 1768, but the name Bogoslof was not applied until 1796, when Castle

Rock or Old Bogoslof was extruded above the sea in the form of a viscous lava dome. The new island was named Joanna Bogoslova by the Russians after St. John, the apostle. (Merriam, 1902, pp. 291-94).

During the first half of the nineteenth century Umnak was mentioned in a few publications of Russian scientists and explorers. Otto von Kotzebue with the scientists, Eschscholtz and Chamisso landed on Umnak in 1816 or 1817. They were reported to have found tree trunks in the bottom of a lake, which was formed during an earthquake (Grewingk, 1850, p. 206), but this reported occurrence is believed to be in error. Father John Veniaminof, a Russian missionary and ethnologist, made trips to the Aleut villages on Umnak during his stay at Unalaska village from 1824 to 1834. Veniaminof has many references to Umnak in his Notes on the Islands of the Unalaska District, Book I. (St. Petersburg, 1840). Unfortunately for most readers, this publication is in Russian. Observations on both Umnak and Bogoslof Islands were summarized, by Constantin Grewingk in his compilation, Beitrage zur Kenntnis der orographischen und geognostischen Beschaffenheit der Nord-West Küste Amerikas mit den anleigeden Inseln, published in St. Petersburg in 1850. This work is still significant for the record of volcanic eruptions on the islands prior to 1840. Probably the first complete map of Umnak appeared in Tebenkoff's Atlas (1852) as an inset to plate XV. The map was sketched by Full-pilot Kuritzien and bears the year 1848. Most of the geographic names now on Umnak first appeared on this map in slightly

variant Aleut spelling or as Russian equivalents of the English names now used (e.g., C. Kotelnoi: Kettle Cape; C. Chornoi: Black Cape; etc.).

No significant Russian investigations are known to have taken place during the period 1850-1867, just prior to the time when Umnak and Bogoslof Islands along with the rest of Alaska changed from Russian to United States territory.

United States Territorial Period Since 1867

No survey or scientific work was done under United States' tenure until 1893, when the birth of a new volcano on Bogoslof Island attracted outside interest. Dall (1884 and 1885) and Diller (1884 and 1885) applied the names Grewingk and New Bogoslof, respectively to the new dome, the remnant of which is now known as Fire Island (Pl. I). G. P. Merrill (1885, pp. 31-33) contributed petrographic descriptions and two analyses of specimens from New Bogoslof. Members of the Harriman Alaska Expedition stopped at Bogoslof in 1899 and collected specimens from Castle Rock or Old Bogoslof. C. Hart Merriam (1902), a member of that expedition, published the first complete paper in English on the history of Bogoslof during the period 1768-1900. Marcus Baker's Geographic Dictionary of Alaska, second edition, published as Geological Survey Bulletin 299 (1906), is a treasure-trove of information, not only about origin of names but also about earlier workers and their publications, especially maps and charts.

Renewed volcanic activity at Bogoslof during 1906 and 1907 brought forth not only papers on Bogoslof but also the first account in English of Okmok volcano. T. A. Jaggar's (1909) paper has a history of Bogoslof and an account of his landing on Bogoslof on August 7, 1907. Bogoslof at this time also attracted an adventurer, Robert Dunn, to whom we owe the first account of Okmok Volcano and its caldera. Dunn's account of his visit to Bogoslof added nothing that Jaggar did not describe, but his paper (1908) gave Okmok Volcano ("The great Okmok crater") its present name, supposedly the native name for the caldera. Dunn also made the first recorded ascent of Mt. Vsevidof.

B. K. Emerson's contribution (1901, p. 30) on the geologic setting and petrography of the Harriman Alaska Expeditions' Bogoslof specimen later analyzed by Fenner (1926, p. 706) was essential to pin down Fenner's analysis as to exact locale. Sidney Powers' (1916) paper on Bogoslof gave an account of the 1910 eruption and the upraising of Tahoma Peak.

Waldemar Jochelson, an anthropologist, made excavations at ancient village sites on Umnak in connection with his studies on the origin of the Aleuts. The results of his archeological studies in the Aleutians, with descriptions of Umnak, were published in two Carnegie Institution monographs; number 367 (1925) and number 432 (1933). Hrdlicka (1945) also visited Umnak in connection with his anthropological studies of the Aleut.

During the 1930's a few geologic papers appeared, mostly

on changes of Bogoslof Island. T. A. Jaggar in the Volcano Letter (1930) gave an account of the 1926-27 Bogoslof activity, and two years later (1932) reported the 1931 eruption of cone A, northeastern Umnak Island. Lukens (1936) gave a description of Bogoslof Island as it was in 1935, when Bogoslof and the surrounding hydrography was mapped by the Coast and Geodetic Survey. Also based on this mapping, a paper by Paul A. Smith (1937) described the submarine canyons near Bogoslof. The master canyon or submarine drainage described by Smith appears on Plate I, just north of Bogoslof Island.

During World War II from 1942 to 1945 Okmok caldera became generally known to military personnel stationed at Umnak Airbase. Dean Freiday (1945, pp. 453-54) described Okmok caldera by means of illustrations and speculated on its origin. Ray E. Wilcox (1945 and 1946), while serving in the Army at Umnak Airbase prepared file reports on the 1945 activity of cone A. Howel Williams (1945) also observed the 1945 eruption of cone A during July and advised the Alaskan Defense Command that Umnak Airbase was not threatened.

Byers, Hopkins, Wier, and Fisher prepared part 3 of Alaskan Volcano Investigations Report No. 2 (1947) a progress report on volcano investigations on northeastern Umnak begun in 1946. This report was for limited distribution only within the U. S. Government. Byers and Brannock (1949) described volcanic activity on Umnak Island during the period 1946-48.

GENERAL GEOLOGIC SETTING

Umnak and Bogoslof Islands are a small segment of the Aleutian volcanic arc, which rises above the Aleutian ridge (see Fig. 1). The Aleutian ridge (Studds, 1950, p. 787) is geanticlinal and is bordered on the south by a downbuckle or tectogene (Hess, 1948, pp. 417-418), known as the Aleutian trench (Murray, 1945, pl. 3). The Aleutian ridge is expressed as a double island arc nearer the North American continent (Umbgrove, 1947, p. 189), where older, folded sediments squeezed out of earlier tectogenes have been incorporated into the present geanticlinal ridge. Umnak and Bogoslof Islands, however, are situated where the Aleutian volcanic arc is essentially a single arc, parallel to the Aleutian trench and where sediment from adjacent islands of the arc is insufficient to fill the trench (Menard and Dietz, 1951, pp. 1263-1286).

Umnak and Bogoslof Islands are geologically divisible into three contrasting parts; namely, northeastern Umnak Island, southwestern Umnak Island, and Bogoslof Island. Only southwestern Umnak (Pl. I) contains the oldest rocks, an albitized sedimentary and igneous complex of diverse geologic ages ranging from possibly late Paleozoic to middle Tertiary. A middle or late Tertiary(?) basement volcanic complex underlies many of the Quaternary volcanoes on both northeastern and southwestern Umnak. Dioritic

plutonic rocks were found only on southwestern Umnak. Northeastern Umnak is arbitrarily separated from southwestern Umnak at the narrowest part of the island where only the basement volcanic complex is present. Differences in the petrography, composition, and physiographic expression of the Quaternary volcanic rocks are evident between northeastern Umnak and southwestern Umnak. The historic volcanic rocks of Bogoslof Island differ in age and composition from those of both northeastern or southwestern Umnak.

Rocks of Northeastern Umnak Island

Pre-caldera Rocks

The major episodes in the volcanic history of northeastern Umnak are recorded at Okmok Volcano, whose caldera-forming eruption makes it convenient to subdivide the volcanic rocks into three major categories; namely, pre-caldera rocks, pyroclastic rocks of the caldera-forming eruption, and post-caldera rocks. The oldest rocks, which antedate Okmok Volcano, are the Tertiary basement volcanic complex (unit 1, Fig. 2), largely hydrothermally altered and potash feldspathized, silicified volcanic rocks that occupy the rugged terrane in the narrow part of Umnak and isolated small areas along the southern shore. The oldest Quaternary pre-caldera rocks are the basaltic rocks comprising the bulk of Okmok Volcano (unit 2, Fig. 2) and the Idak Plateau. They consist of mafic basalt flows, palagonitized pyroclastic rocks, aphyric basalt flows, and plagioclase basalt flows, rich in

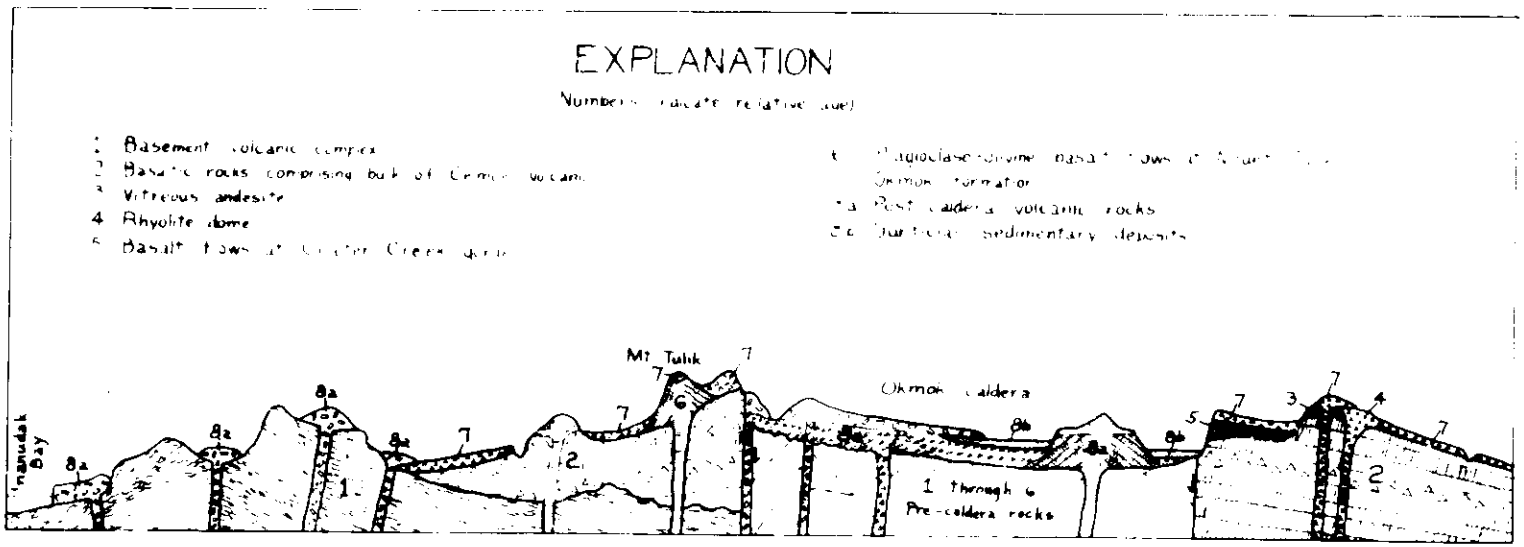

Figure 2.--Generalized diagrammatic section of principal rock units of northeastern Umnak

anorthite phenocrysts. At least 35 cubic miles of these basaltic rocks are inferred above sea level. The major fraction is composed of aphyric and plagioclase basalt flows; mafic basalt flows, including anorthite-rich mafic flows, and palagonitized pyroclastic rocks compose a minor fraction.

Vitreous andesite dikes, pipes, plugs, and short stubby flows (unit 3, Fig. 2) intrude or overlie the older basaltic rocks of Mount Okmok and Mount Idak areas and are exposed especially well in the walls of Okmok caldera and in Crater Creek gorge. Sparse phenocrysts of labradorite-andesine and iron-rich olivine (hyalosiderite to ferrohortonolite) are distributed in hyalopilitic groundmasses that are magnetite-charged in the less silicic representatives of the suite.

The rhyolite dome (unit 4, Fig. 2) on the northwest side of Okmok caldera rests on older basaltic lavas of Mount Okmok and contains both obsidian and felsitic phases. Olivine-bearing basaltic andesite xenoliths associated with the rhyolite obsidian are probably the source of many xenocrysts of calcic labradorite and olivine in the rhyolite.

The basalt flows exposed in Crater Creek gorge (unit 5, Fig. 2) extend around the north wall of Okmok caldera. They are similar petrographically to the aphyric and porphyritic basalt flows of the older basaltic rocks of Mount Okmok. The maximum exposed thickness, comprising about 15 flows, is 500 feet. They rest on palagonitized pyroclastic rocks, and their younger age is also inferred from their low topographic position with respect

to the older basaltic rocks. The basalts at Crater Creek gorge appear to have flowed through an erosional gap or sector graben involving the older basaltic rocks and do not appear to have been glaciated. Hence these flows are probably latest Wisconsin or early Recent in age.

The plagioclase-olivine basalt flows of Mount Tulik (unit 6, Fig. 2) form a lava pile on the southeastern slope of Okmok Volcano. The flows rest on older basaltic rocks of Mount Okmok and are in turn overlain by ash of the Okmok formation. Mount Tulik has been but slightly eroded and has not been extensively glaciated; hence a Late Pleistocene or early Recent age seems probable.

Pyroclastic Rocks Deposited by the Caldera-forming Eruption of Okmok Volcano

The Okmok formation (unit 7, Fig. 2), the product of the caldera-forming eruption of Okmok Volcano, forms a widespread blanket of bedded and unbedded pyroclastic debris over most of the outer slopes of Okmok Volcano and the lava plateau north of Mount Idak. A few thin basalt flows are interbedded with the pyroclastic rocks. A maximum thickness of 400 feet is exposed in the type section of the formation in the north wall of Okmok caldera. About 7 cubic miles of Okmok formation is present on northeastern Umnak. The formation rests on all the earlier rocks and is overlain only by a few basaltic lava flows and alluvium. Two welded beds of andesitic agglomerate are found in the lower half of the formation, though the upper welded bed of

the caldera wall appears correlative with the lower welded bed of the arcuate ridge north of Okmok caldera. The upper welded bed of this arcuate ridge is basaltic in composition. In most exposures only one welded bed can be recognized. A thin rhyodacitic ash bed is present beneath the lower welded bed of the arcuate ridge north of Okmok caldera and has been exposed in a few places on the flanks of Okmok Volcano. The two welded beds grade laterally and vertically into dark andesitic scoriaceous agglomerate and bomb beds. The partly palagonitized agglomerate bed on the outer flanks of Okmok Volcano may be gradational with one of the welded agglomerate, though exposures are by no means continuous. The upper part of the Okmok formation that is above the welded agglomerate and palagonitized beds consists of loosely consolidated ash, scoria, bombs, and lithic fragments and reaches a maximum thickness of 230 feet in the north wall of Okmok caldera.

The welded andesitic beds of the Okmok formation contain sparse andesine-labradorite and augite microphenocrysts with fairly common basaltic xenoliths and associated bytownite, olivine, and diopsidic augite xenocrysts. Some basaltic xenoliths can be seen that were apparently in the process of disintegration when the welded bed was chilled. The partly palagonitized beds contain light glass shards with unpalagonitized cores along with many angular xenoliths and broken crystal fragments in a dense cellular cryptocrystalline aggregate of palagonitized glass and comminuted crystal fragments. Most of the unpalagoni-

tized glass has a refractive index of 1.565, but one specimen contained pumiceous fragments having an index of 1.525.

The pyroclastic deposits comprising the Okmok formation originated during the caldera-forming eruption of Okmok Volcano, because these deposits have not been recognized within the calderas. The welded agglomerate beds probably originated as molten lava showers near source vents in the vicinity of Okmok caldera, for the welded agglomerates can be seen to grade into bomb beds. The partly palagonitized beds and the massive scoria beds farther out on the flanks of the volcano present more of a problem; probably they were deposited by nuées ardentes. The age of the Okmok formation and Okmok caldera is almost certainly Recent as the Okmok formation is incised by only narrow V-shaped gullies, and Okmok caldera itself is a very youthful feature.

Post-caldera Rocks

Post-caldera volcanic rocks (unit Qa, Fig. 2) are confined largely to Okmok caldera. The early eruptives within Okmok caldera after the caldera-forming eruption include (1) early post-caldera pyroclastic rocks, in part palagonitic, (2) bedded volcanic sediments that are gradational with the pyroclastic rocks, and (3) plagioclase basalt flows of cones C and D (Pl. I). The early post-caldera pyroclastic rocks are probably in part the irregular surface of the Okmok formation produced upon collapse of the caldera, because plagioclase basalt flows of cones C and D rest on these pyroclastic rocks, yet were extruded while

the newly formed caldera was still filling with water, prior to overflow. Part of the early post-caldera pyroclastic rocks were erupted under a caldera lake, which left wave-cut terraces and depositional surfaces at an altitude of 1,560 feet. This level marks the maximum stillstand of the lake and was maintained by the outlet on the resistant upper surface of the basalt flows at Crater Creek gorge.

The volcanic sediments (unit Qb, Fig. 2) include lake silts, sands, and minor bedded, coarse alluvium that was graded to the surface of the lake. Volcanic sediments become finer toward the northeast part of the caldera, farther from the centers of eruption. Large angular blocks, probably in part ice-rafted, are not uncommon in the lake beds. The volcanic sediments continued to accumulate in the northeast part of Okmok caldera until the final disappearance of the lake, only a few centuries ago.

Later flows from cones in Okmok caldera (part of unit Qa, Fig. 2) were extruded on a dry surface after the caldera lake had receded from the immediate area of volcanism. These flows include the basalt flow from cone F (Pl. I), basalt flows from cone E--some of which are probably contemporaneous with the caldera lake, basaltic andesite flows from cone B, pre-1945 basalt flows from cone A, 1945 anorthite basalt flows from cone A, and minor basaltic flows from wall vents in Okmok caldera. All these basaltic rocks are petrographically similar to pre-caldera rocks. Many of the later post-caldera vents are localized along the caldera

ring fissure. The later post-caldera flows, with the exception of older basalt flows from cone E, have probably been extruded within the last several hundred years; those flows from cones A and B may have been extruded during historic time in the eastern Aleutians, or since the middle of the eighteenth century.

Post-caldera basalt flows outside Okmok caldera comprise aphyric flows on the lava plateau north of Mount Idak and anorthite basalt flows in the rugged mountainous area east of Inanudak Bay (Pl. I). The anorthite basalt flows east of Inanudak Bay are of special interest because they contain as much as 30 per cent of anorthite phenocrysts.

Surficial deposits (not subdivided on Plate I) include glacial till, talus and alluvium, and beach and dune sand. Small patches of glacial till within Okmok caldera probably were deposited by cliff glaciers. A small glacier still occupies the southern part of Okmok caldera (Pl. I).

Rocks of Southwestern Umnak Island

Basement Rocks

Southwestern Umnak Island (Pl. I) contains a greater variety of rocks than northeastern Umnak. The oldest rocks (unit Tvs, Fig. 3) are an ancient series of albitized sedimentary and igneous rocks, including folded tuff and argillite beds, keratophyres, albite diabase, and albite diorite. Part of the keratophyres are nearly horizontal and may be much younger than the folded beds. This rock complex forms the bedrock over all

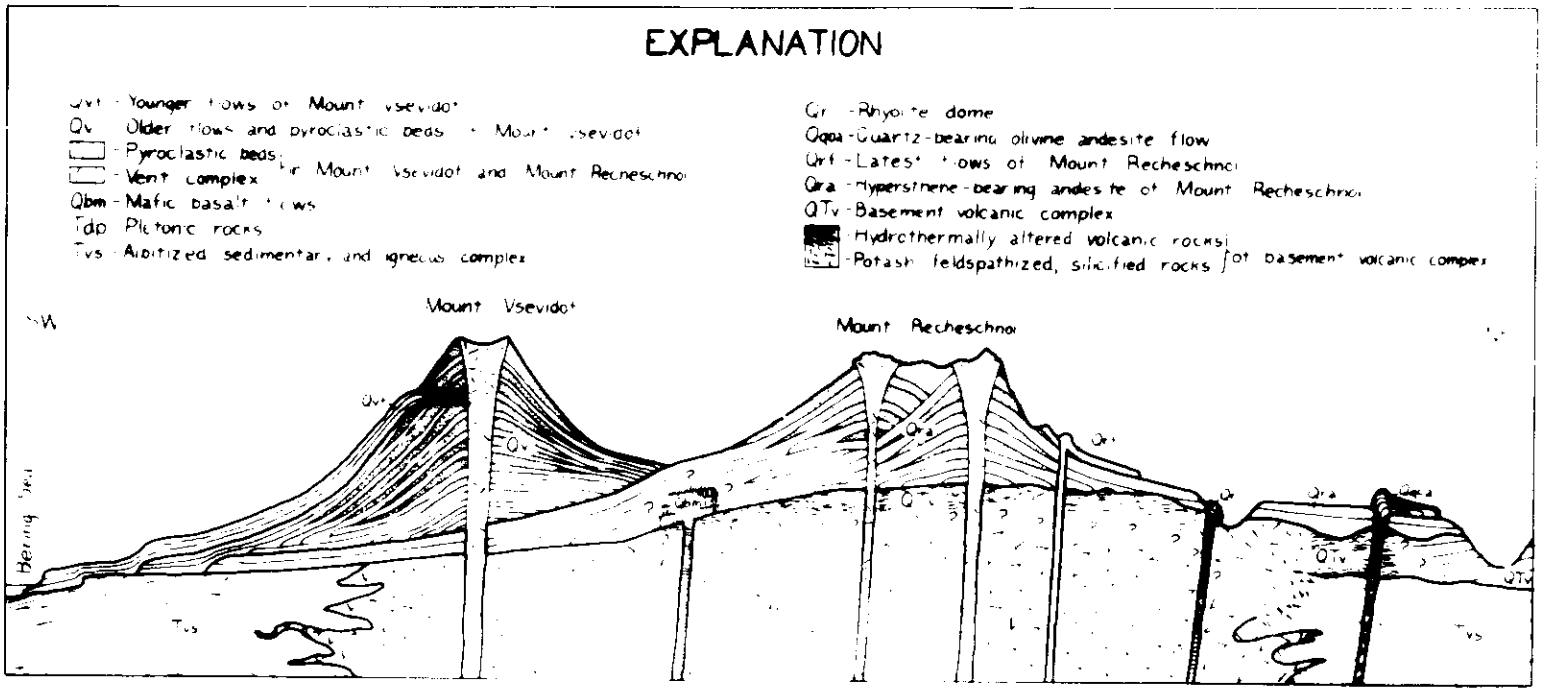

Figure 3.--Generalized [illegible]

the southern part of southwestern Umnak and extends under younger rocks to the north. These rocks are intruded by the quartz diorite and are overlain by hydrothermally altered volcanic rocks, whose alteration was caused following the emplacement of the plutonic rocks. The albitized sedimentary and igneous complex has been folded along northwest axes, transverse to the trend of the Aleutian arc. The available evidence suggests that the albitized sedimentary and igneous complex was albitized sometime after the original emplacement of the rocks but before the hydrothermal alteration and probably before the emplacement of the plutonic rocks. The age of the bedded argillite and tuff may be as old as late Paleozoic (Coats, 1950), p. 46) or as young as Tertiary, if Tertiary fossils reported from near Nikolski (Capps, 1934, p. 144) actually came from this sequence.

The plutonic rocks (unit Tdp, Fig. 3) are largely diorite and quartz diorite with minor quartz monzonite and granophyre dikes. The plutonic rocks crop out beneath younger volcanic rocks along the northern coast of southwestern Umnak and south of Mount Recheschnoi (Pl. I). The quartz diorite has been potash feldspathized and epidotized adjacent to the granophyre dikes. The plutonic rocks intrude the albitized sedimentary rocks and probably the hydrothermally altered volcanic rocks, which are unundated. They are overlain by unaltered late Tertiary or early Quaternary lavas. Intrusive rocks that have similar geologic relations on Kodiak Island, Alaska (Capps, 1937, p. 111), have been dated as very late Cretaceous or very early Tertiary; possibly

the plutonic rocks observed not only on Umnak but elsewhere in the eastern Aleutian Islands may be correlative with the plutonic rocks of Kodiak. However, plutonic rocks in the Oregon-Washington Cascades intrude mid-Tertiary chloritized, epidotized volcanic rocks and are overlain by unaltered, undeformed lavas, including those of the High Cascade volcanic cones. The Cascade plutonic rocks are commonly regarded as Miocene (Callaghan and Buddington, 1938, p. 21; Coombs, 1936, p. 170). If the albitized argillite-tuff sequence of Umnak should prove to be Tertiary (Capps, 1934, p. 144), the plutonic assemblage of Umnak must also be Tertiary, inasmuch as it could hardly be as young as Quaternary.

Older volcanic rocks (unit QTv, Fig. 3) of the basement volcanic complex, including hydrothermally altered rocks and intensely altered potash feldspathized, silicified rocks similar to those on northeastern Umnak, are also exposed in the northeast part of southwestern Umnak. The older volcanic rocks were probably intruded by the quartz diorite judging from intrusive relationships between diorite and similar altered volcanic rocks on nearby Unalaska Island. Included with the altered volcanic rocks of the basement volcanic complex are unaltered basic lavas, which could not be mapped separately in the time available but which are definitely older than the lavas of the Quaternary volcanic cone of Mount Recheschnoi. These unaltered lavas of the basement volcanic complex could be as young as early Quaternary.

Quaternary Volcanic Rocks

One eroded mountain of mafic basalt flows (unit Qbm, Fig. 3) is on the northwest slope of Mount Recheschnoi and forms Kshaliuk Point headland (Pl. I). Whether these lavas are older, younger, or possibly intertongue with lavas of Mount Recheschnoi could not be determined in the field, but they are probably Quaternary in age. These flows are the only basalts known on southwestern Umnak and it may be significant that they are on the northwest side, farthest removed from the Aleutian trench.

The older hypersthene-bearing andesite of Mount Recheschnoi (unit Qra, Fig. 3) includes lava flows, which are dominant, with minor pyroclastic flows. About 18 cubic miles of hypersthene-bearing andesite have been extruded from Mount Recheschnoi vents. The cone has been deeply incised by glaciers (Pl. I) and rests on an erosional surface carved across the albitized rocks, plutonic rocks and the older volcanic rocks. The dominant petrographic type is a hypersthene-bearing plagioclase-rich andesite with nearly 30 percent of corroded andesine-labradorite phenocrysts enclosed by a shell of An_{55}, equivalent in composition to the groundmass plagioclase. Hypersthene-bearing (nearly) aphyric andesite with sparse phenocrysts similar in composition to the highly porphyritic hypersthene-bearing andesites and hypersthene-bearing andesitic tuff-breccia are interlayered with the more porphyritic flows. The extensive glaciation of the cone of Mount Recheschnoi indicates that it is older than the most recent glaci-

ation of the Pleistocene. Though the dating of the oldest flows is somewhat in doubt, it seems reasonable to assume that the Recheschnoi cone is largely Pleistocene in age.

The latest flows of Mount Recheschnoi (unit Qrf, Fig. 3) consists of three lava flows and an earlier mudflow(?) that came down earlier glacial valleys cut in older hypersthene-bearing andesite of Mount Recheschnoi. The mudflow(?) appears to have been glaciated and underlies glacial till. The lava flows consist of hypersthene-bearing plagioclase andesite similar to the underlying older andesite. The mudflow (?) contains thin clayey orange-pink seams that are isotropic (index, 1.54) in thin section. Slippage has occurred along many of the seams so that they almost certainly originated at a late stage in the consolidation of the rock. The mudflow(?) also contains large angular lithic blocks up to 10 feet in diameter. Both the mudflow(?) and the andesite flow on the southern side of Mount Recheschnoi have been cliffed by a recent high stand of the sea, possibly the high stand associated with the post-Wisconsin thermal maximum. If this dating is correct, the younger hypersthene-bearing andesite flows of Mount Recheschnoi are prethermal maximum: possibly latest Pleistocene or early Recent in age. A peculiar debris ridge, resembling a glacial moraine, borders one of the andesite flows and may have resulted by contact of the lava flow with a glacier.

The quartz-bearing olivine andesite flow (unit Qqoa, Fig. 3) covers about a square mile in northeasternmost southwestern

Umnak (see Pl. I). The flow contains large concentric ripples, indicating that the flow was highly viscous when extruded. The thickness of the flow ranges from 200 to 300 feet. The front of the flow has been eroded back by as much as 800 feet, as indicated by breaching of the ripples. The flow rests on the glaciated surface of older hypersthene-bearing andesite flows of Mount Recheschnoi. The quartz-bearing olivine andesite contains about 1 per cent of anhedral quartz grains up to 0.5 mm encased by clinopyroxene laths oriented radially to the quartz. Olivine phenocrysts (Fo_{86}) comprise $7\frac{1}{2}$ percent of the rock and are jacketed by similar clinopyroxene laths. The plagioclase phenocrysts are largely corroded andesine phenocrysts encased by a thin shell of An_{60}, equivalent in composition to the groundmass plagioclase. Sparse areas charged with clinopyroxene and opaque oxides are probably hornblende relicts. Augite, ferroaugite, and bytownite phenocrysts and glomerophenocrysts are also present. The age of the quartz-bearing olivine andesite flow is probably latest Pleistocene or early Recent in age.

Three small rhyolite domes (unit Or, Fig. 3) have been extruded on the southwest side of the glaciated valley that heads back of Russian Bay (Pl. I). The domes rest on glaciated surfaces of the basement complex and the older hypersthene-bearing andesite of Mount Recheschnoi. The rhyolite contains phenocrysts of andesine, some with labradorite cores, biotite, quartz, hornblende, opaque oxides, and hypersthene in order of decreasing abundance. Rare epidote(?) is at the center of quartz-potash feldspar

spherulites in a glassy groundmass.

The volcanic rocks of Mount Vsevidof comprise the cone of Mount Vsevidof (Pl. I) and consist of nearly 10 cubic miles of volcanic rock. The cone of Mount Vsevidof with its associated andesitic flows rests on the glaciated westward-dipping flank of Mount Recheschnoi and to less extent on the dioritic plutonic rocks. The volcanic rocks of Mount Vsevidof are subdivided into older volcanic rocks (unit Qv, Fig. 3) and younger volcanic rocks (unit Qvf, Fig. 3), depending on whether they are older or younger, respectively, than the pyroclastic beds of the last major summit eruption. Lava flows of Mount Vsevidof range from basaltic andesite to latite in composition. The basaltic andesite and latite flows are hypersthene-bearing. Andesite and latites have been recognized only in the younger flows of Mount Vsevidof (unit Qvf, Fig. 3) but doubtless exist among the older flows.

The pyroclastic beds of the last major summit eruption of Mount Vsevidof (uppermost part of unit Qvf, Fig. 3) consists of an underlying 40-foot bed of rhyodacite pumice that is gradational with an overlying 30-foot bed of dark andesitic scoria containing clots of andesitic glass. Similar xenocrysts both in the andesitic scoria and glass are apparently derived from limonite-stained dioritic inclusions. Pumice ash beds in the soil profile at Nikolski (Pl. I) are similar petrographically to the rhyodacite pumice in the cone of Mount Vsevidof and may be correlative. The relationship of rhyodacite pumice, which is

gradational with and overlain by andesitic scoria, indicates that the rhyodacitic magma was erupted first, followed by andesitic magma.

The beginning of the upbuilding of Mount Vsevidof began in latest Wisconsin or early Recent. The age of the pumice ash beds at Nikolski is about 3,000 years, according to carbon 14 dating (Arnold and Libby, 1951, p. 118). If these ash lenses and the rhyodacite pumice at Mount Vsevidof are correlative, the date of the last summit eruption of Mount Vsevidof is likewise about 3,000 years. The post-pumice flows have been extruded since that time up to possibly as late as 1880, when the last volcanic activity was observed at Mount Vsevidof, according to the local inhabitants.

Glacial Deposits

Surficial deposits of southwestern Umnak include two or possibly three different ages of Wisconsin(?) and Recent tills, in part interbedded with beach deposits. The oldest till, probably Wisconsin in age occurs as scattered patches on the rolling, glaciated plain of southern Umnak. Recessional moraines of this till or a younger till, possibly late Wisconsin in age, occur 2 to 3 miles beyond the fronts of the modern glaciers. Still younger till is confined to moraines within a mile of the present glacier fronts (Pl. 7) and probably records the most recent glacial advance 100-300 years ago (Matthew, 1930; Thorarinsson, 1939; Ahlmann, 1948; Lawrence, 1950; Sharp, 1951; and Mathews, 1951).

Moraines of the older till are covered in part by old beach ridges. Similar beach ridges inland but parallel to the present coast have been observed in many places in the Aleutian Islands and are interpreted as the result of a retreat of sea level from a stand six to ten feet higher than at present. At two widely separated places in the Aleutian Islands bedrock benches are preserved nine to ten feet above the present tide-water bench (Bradley, 1948, p. 226). Various investigators have ascribed this high stand of the sea to the post-Wisconsin thermal maximum, 4,000-6,000 years ago. (See chiefly Flint and Deevey, 1951, pp. 275-278; also Fairbridge, 1948, pp. 62-63; idem, 1950, pp. 181-184; MacNeil, 1950, pp. 1307-1308; Newell et al., 1951, p. 11; Ives, 1951, pp. 220-221; Upson, 1951, pp. 425-427; and others). The oldest, farthest island beach ridge must therefore be about 6,000 years old. As the oldest beach ridge covers older till, it must be older than 6,000 years. This till is possibly correlative with the till of the "Later Glaciation" in the Wolf Creek area of the St. Elias Range (Sharp, 1951, p. 100).

Nine large glaciers and several small ones head on the slopes of Mounts Recheschnoi and Vsevidof (Pl. I). The glaciers of the north slope are long and narrow and extend within 200 feet above sea level. The glaciers of the south slope are broader and shorter than the glaciers of the north slope and extend down to within nearly 1,000 feet of sea-level. The differences in the behavior of the glaciers on the north and south slopes are probably due to a warmer, moister climate on the southern slope in contrast to that of the northern slope.

Rocks of Bogoslof Island, 1947

The rocks exposed on Bogoslof Island in 1947 are all of historic age, with one possible exception. The oldest rock, which may be of prehistoric age, is an andesitic vent agglomerate(?) (Fig. 4) in contact with the hornblende andesite of Castle Rock. Like all other Bogoslof rocks, this vent agglomerate is hornblende-bearing. The andesine-hornblende andesite dome of Castle Rock (Fig. 4) was extruded in 1796. Porphyritic plagioclase consists of anorthite-bytownite cores (An_{79-94}) jacketed by andesine (An_{25-50}). Oxyhornblende with extreme birefringence probably contains iron that is entirely in the ferric state. Ferrosalite, magnetite, apatite, and sphene, in order of decreasing abundance are also present. The groundmass is a fine-grained aggregate of oligoclase-albite, orthoclase, analcite and glass. Albite of the groundmass veins a few of the andesine phenocrysts.

The lava dome of Fire Island (Fig. 4) was extruded in 1883 following a violent eruption. The rock, a hornblende basalt with a slight amount of normative nepheline, was described by G. P. Merrill (1885, p. 33).

Basaltic extrusives erupted during the most recent activity of Bogoslof during 1926 contain phenocrysts of anorthite-bytownite, salite, hornblende, and opaque oxides. The dome erupted in early 1927 (Fig. 4) is a bytownite-salite-hornblende basalt and is similar petrographically to the ash, except that the hornblende has largely decomposed. The outermost zone of many of the

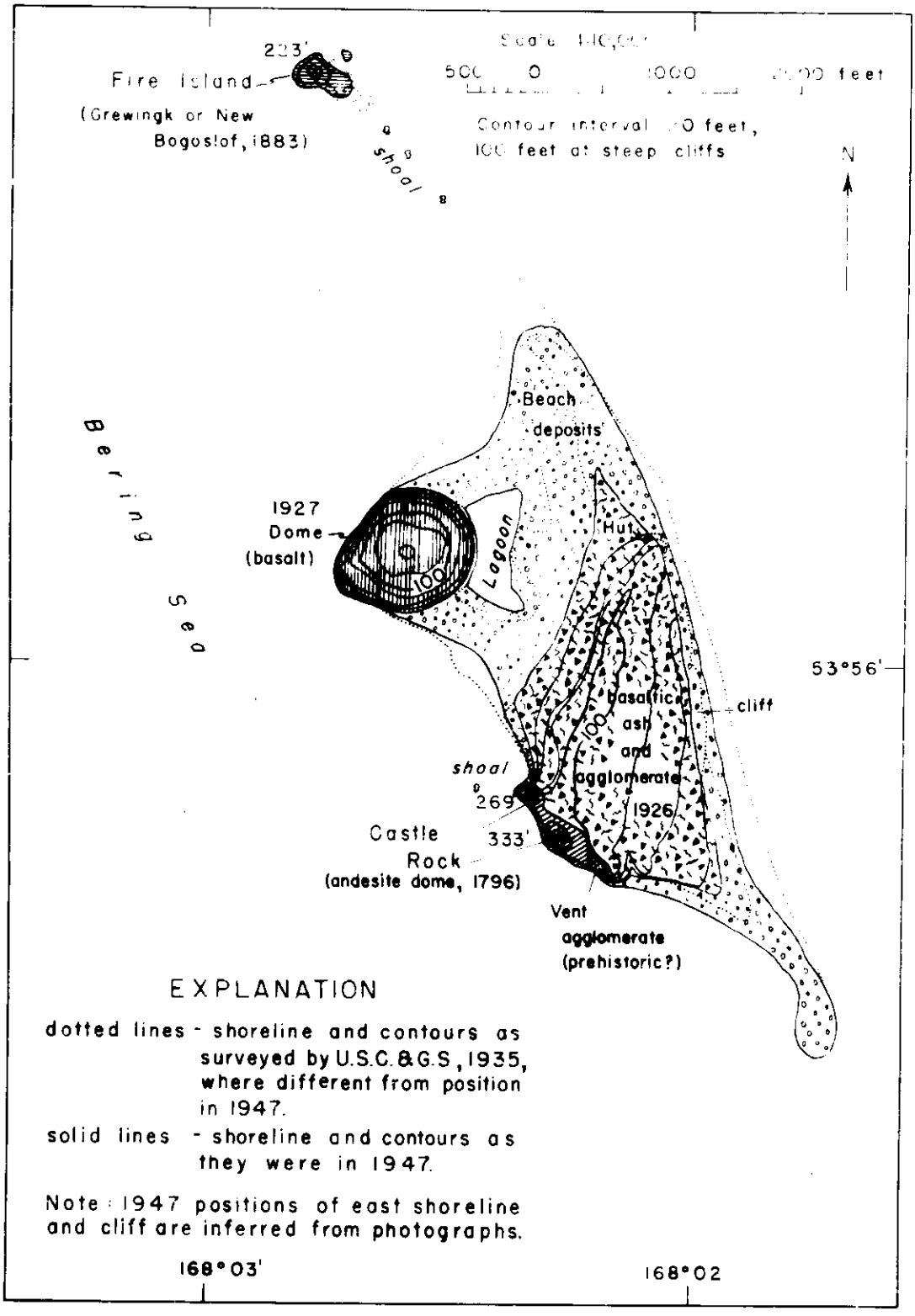

Figure 4.--Geologic map of Bogoslof Island, showing rock units in 1947 and marine erosion between 1935 and 1947.

plagioclase phenocrysts is a potassic feldspar, which is also present in the groundmass. The hornblende basalt dome of 1927, like the 1883 dome, contains a small amount of nepheline in the norm.

Volcanic Activity on Umnak Island, 1946-1948

Manifestations of volcanic activity in 1946 and 1948 comprised fumaroles of cones A and C and thermal springs of cone D on northeastern Umnak and thermal springs, geysers, and fumaroles south of Inanudak Bay on southwestern Umnak. The following data are summarized from Byers and Brannock (1949, pp. 719-734) and are included here because they contribute to certain inferences reached in the theoretical section on petrology. Acid fumaroles associated with the summit crater of cone A when sampled during the summers of 1946 and 1947 contained CO_2 and SO_2 in a ratio of approximately 3:1 in addition to water vapor and atmospheric gases (Byers and Brannock, 1949, pp. 722-723). Many fumaroles associated with the summit crater of cone C had had an odor of hydrogen sulfide during the period 1946-1948. Thermal springs of cone D in 1946 and 1947 had large discharge, low temperatures, and low concentrations of only a few hundred parts per million of total solids. The sulfate radical predominates (Fig. 5). Thermal springs south of Inanudak Bay were characterized by low discharge, high temperature and high concentration up to over 2,000 parts per million. Boron and chloride predominated in these springs (Fig. 5), and the arsenate ion reached seven parts per million

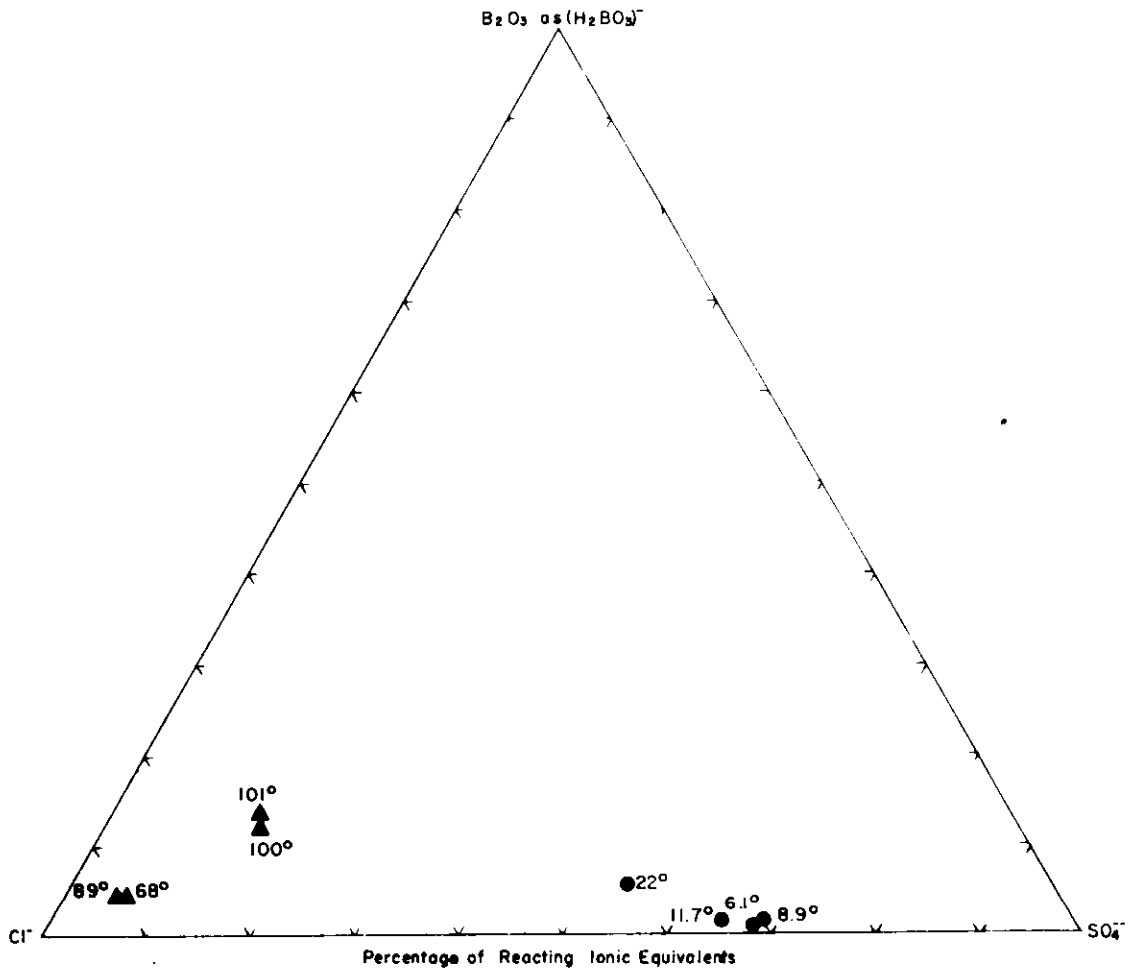

Figure 5.--Temperatures and percentages of principal anions in thermal springs of Umnak Island, 1946. Circles, thermal springs of northeastern Umnak (Cone D); triangles, thermal springs of southwestern Umnak south of Ianudak Bay.

in one of the springs. About 100 tons of B_2O_3 per year were being contributed to the sea by the springs of southwestern Umnak at the 1946-1947 discharge rates. The southwestern Umnak hot springs have been in existence for many years, probably for centuries.

PETROGRAPHY

In the preceding section the geologic relationships and petrography of the rock units have been summarized. In this section the variations of the minerals in the rocks are correlated with variations in chemical composition, in so far as possible. Complete chemical analyses of 35 rock specimens from Umnak and Bogoslof Islands are presented as Table 7 in the APPENDIX. Petrographic analyses of these same 35 rocks follow as Table 8 in the APPENDIX. These two tables constitute most of the basic petrochemical data, on which the theoretical considerations and the accompanying graphs are based. The number at the head of each column (Tables 7 and 8) containing chemical or optical data identifies the rock described in the footnotes beneath Table 7. These numbers, identifying the individual specimens, are used in all the tables and graphs of this paper.

Petrographic Methods

The rock specimens were studied by thin section and by powder in immersion oils. The volume percentages of the minerals as seen in thin section (the mode) was determined with an adapted mechanical stage as suggested by Chayes (1949). A four-axis universal stage was used for 2V determinations and for measuring the optic orientation in the analyzed minerals. A sodium vapor lamp was used for the refractive index determinations, using immersion

oils, calibrated at 25°C, the average room temperature. As an additional check a thermometer was kept on the microscope table and if the temperature departed more than 2°C, a correction in the index determination was made. It is believed that in general the refractive indices are correct to the nearest 0.002 and that the majority of determinations, particularly on the minerals of the analyzed specimens are within 0.001. A few of the refractive index determinations by the writer were checked to within 0.001 by Richard C. Erd in the Geochemistry and Petrology Branch of the U. S. Geological Survey. Except in the case of the two analyzed specimens, no attempt is made to contribute new mineralogical data. Only those optical properties were determined which were diagnostic for inferring chemical composition, using previously determined curves, chiefly those relating 2V and refractive indices to chemical composition (Kennedy, 1947, pp. 562-567; Hess, 1949, Pl. I).

The modes of nearly all lava groundmasses could not be accurately determined by integrating stage because the smaller groundmass microlites were less than 0.03 mm, the thickness of the thin section. It was found that the finer the grain, the greater the proportion of the microlites of high relief such as clinopyroxene and opaque oxides. This is due to the tendency to count those microlites that are easily seen, regardless of whether they are near the base or near the top of the thickness of the rock slice. Hence, the bias in favor of the minerals of high relief at the expense of feldspar and glass necessitated

discarding all the results obtained in micrometric analyses of groundmasses less than 0.03 mm in average grain size. The common thin section methods for estimating composition of plagioclase, chiefly the method based on combined Carlsbad-albite twinning, are believed inadequate for precise work. This difficulty is perhaps due to the fact that the plagioclase of the Umnak basalts are high temperature plagioclase, whereas the Carlsbad-albite twinning curves are based on the low temperature plagioclase of plutonic rocks as suggested by Kohler (1949, p. 596). Barth and Oftedahl (1947, p. 103) have found that not only do plagioclases fall on either the high or low temperature curves, but may have intermediate orientations, depending on the temperature of crystallization and the rate of cooling.

With respect to refractive index determinations, Chayes's (1950, Fig. 1) γ-index curve through the points from An_{50-100} differs from that compiled by Calkins and Hess (in Kennedy, 1947, fig. 1) by only 2 to 3 percent An content. As a check, an unzoned anorthite phenocryst found by Calkins-Hess refractive index curves, to have an average An content of 93, contained on analysis, about 1.1 percent of alkalis-equivalent to an An content of about 91.

The estimation of average composition in zoned plagioclase phenocrysts in the labradorite-bytownite range was more troublesome, but a reasonably accurate estimate was made in the following manner. The phenocrysts were gouged out of the rock specimen, with a needle or other sharp tool. The grains were

crushed to minus 80 plus 120 mesh (U. S. Standard Sieve Series) and placed in successive index immersion oils covering the range 1.550 to 1.590 in 0.005 intervals. The lowest α' and the highest γ' were thus determined and notes were taken on relative frequencies of α' and γ'. In this manner the effect of a thin outer shell of more sodic plagioclase, corresponding to the composition of the groundmass plagioclase was minimized. It was found in the case of all plagioclase phenocrysts whose average composition was used in petrographic calculations that the An contents corresponding to the mean α' and mean γ' differed by only a few percent of An, using either the Calkins-Hess curves or those based on cleavage fragments prepared by Tsuboi (1925, pl. I). Actually, it makes little difference which set of curves is used as the An content determined by either set agree in the mean An content to within 1 percent of An. Another method of arriving at an average An content of plagioclase phenocrysts is by a method suggested by R. R. Coats (personal communication, 1950). The index immersion oil in which half the plagioclase grains have an index higher and the other half lower than the oil is considered approximately equivalent to the mean β index. The corresponding An content is read from the Calkins-Hess curves. The two An contents usually agree within 3 percent An. The average An contents presented in Table 8 (APPENDIX) are believed to be not more than 5 percent An in error and are probably within 3 percent in most cases. An additional source of error in arriving at the average An content of the plagioclase pheno-

crysts may arise from the tendency to gouge out more of the central portion of the crystal than the outer shells. In several specimens in which phenocrysts contained a thick outer jacket of plagioclase differing radically in An content from the core, a sample of the rock was powdered and sieved, and the ratios of the two plagioclases were determined by grain count on two different sieve sizes. As might be expected from the similar cleavage of all feldspar, the ratios of two plagioclases from the same rock were essentially the same on the two different sieve sizes.

In thin section the relative An content of the various plagioclase zones in a phenocryst was determined by means of extinction angles on 010 (Emmons, 1943, Fig. 51; Duparc and Reinhard in Winchell, 1933, Fig. 275). With the knowledge of the ranges in An content from the immersion work and by observation of the relief of the plagioclase with respect to balsam, it was possible to determine where the different compositions of plagioclase were in the actual rock as shown in thin section.

The determination of refractive indices by immersion technique on the groundmass plagioclase was limited to microlites larger than 0.01 mm. Thus in some of the rocks only the larger microlites could be determined. The average index (ca. β) was approached from both directions, i.e., high and low immersion oils, thereby an average value could be determined. The accuracy of the index determinations on the groundmass plagioclase is probably only within ± 0.003, or within 6 percent of An content. Hence, the composition of the groundmass plagioclase is given

only to the nearest 5 percent of An in Table 8 (APPENDIX). The average An contents of the groundmass plagioclases given in Table 8 are probably slightly too high rather than too low, due to the fact that many of the measurements were made on the larger microlites, which would tend to contain slightly more anorthitic plagioclase than the smaller microlites.

Correlation of Specific Gravities and Refractive Indices of Glasses with Silica Composition

A general correlation exists between specific gravity and silica content of rocks and also between refractive index of glasses and their composition. Bulk specific gravities have been measured on non-vesicular, aphyric and glassy Umnak lavas to the second decimal place by a simple triple beam balance, accurate to 0.01 gram. A rock chip, weighing up to 111 grams (about the size of an ordinary thin-section chip) is weighed both in air and in a beaker of distilled water; from these weights the bulk specific gravity is easily computed. Bulk specific gravity can be determined by this method in a few minutes. Specific gravity of aphyric and glassy rocks measured by this method are probably more accurate than those measured by pycnometer. Porphyritic and highly crystalline rocks, even though non-vesicular, do not give consistent results. Refractive indices of glassy rocks are determined in the usual manner, but in order for the measurement to be of significance the rock or at least the groundmass must be almost entirely glassy so that the silica composition of the

glass can be analyzed or computed by subtracting composition of phenocrysts from the bulk analysis.

From determinations of refractive indices and specific gravities on rocks of known silica composition, the two curves shown in Figure 6 have been constructed. Several dark, non-vesicular lavas in addition to the analyzed specimens (Table 7) were analyzed for silica only and hence are unnumbered on Figure 6. Two of the refractive index points, 3g and 8g, are aphyric palagonites. Their water-free silica contents are plotted on the abscissa, and the corresponding refractive indices were determined on unpalagonized cores of shards. The silica composition of the chilled sideromelane groundmass of the porphyritic basalt of cones C and D has been computed from the bulk analysis of the analyzed specimen (see column 7, Table 7, APPENDIX), which has the same proportions of phenocrysts as the chilled lava. The specific gravities show more of a scatter, owing probably to the effect of heavier elements such as iron and titanium on specific gravity. For example, the least silicious vitreous andesite (column 15, Table 7, APPENDIX) contains about $11\frac{1}{2}$ percent iron oxide and $2\frac{1}{2}$ percent titanium oxide, which are somewhat more than the content of these oxides in other andesites or basaltic andesites of similar silica content.

From the curves thus constructed it has been possible to infer the silica content of unanalyzed lavas probably to within a few percent. A reasonable degree of correlation in rocks of one magmatic province is to be expected, as pointed out recently by Mathews (1951a, pp. 92-93).

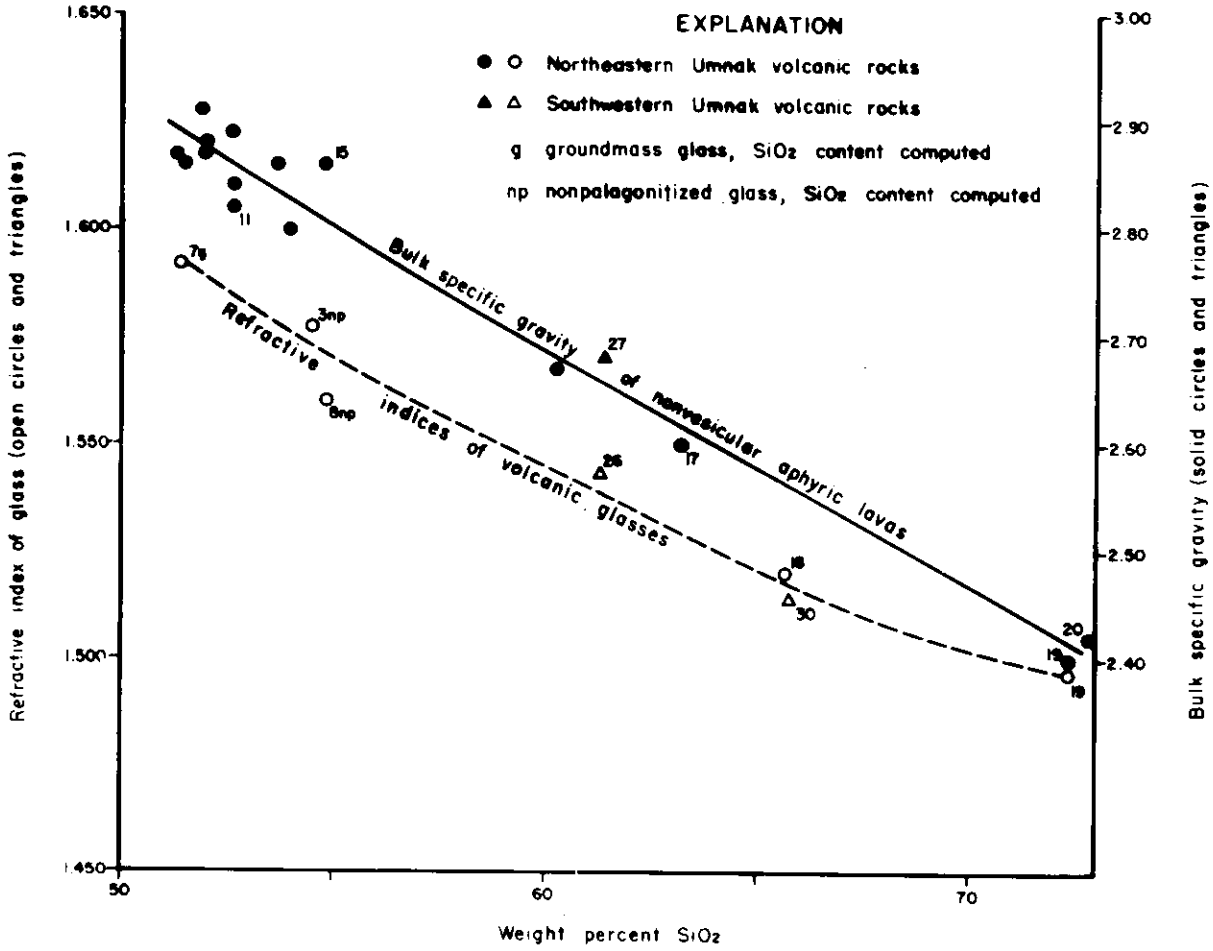

Figure 5.--Variation of silica content with refractive indices of glasses and with bulk specific gravities of non-vesicular, aphyric lavas. Numbers refer to analyzed specimens, table 7, Appendix.

Mineralogy

Primary Rock Minerals

Quartz.--Quartz along with orthoclase is the latest mineral to crystallize in the plutonic rocks of southwestern Umnak (columns 24 and 33, Table 7, APPENDIX). In the granophyre quartz and orthoclase are in graphic intergrowth that forms most of the rock (column 33, Table 8).

In the extrusive rocks quartz occurs as a primary phase only in the silicious southwestern Umnak rhyolite (column 32, Table 8, APPENDIX), in which quartz occurs as sparse anhedral phenocrysts with rounded equidimensional outlines. The quartz phenocrysts in the rhyolite are colorless to bluish gray and clear to slightly translucent within the same crystal. The bluish gray quartz is separated from the colorless variety, apparently by fractures rather than crystal faces. Because of the bluish gray color, equi-dimensional outlines and fracturing, the crystals may once have been β-quartz, suggesting that they may have formed above 573°C (Wright and Larsen, 1909, p. 438).

Quartz occurs in anhedral crystals up to 2 mm in the quartz-bearing olivine andesite (column 22, Table 8, APPENDIX), but because of its rounded outlines and clinopyroxene reaction rims it is certainly a xenocryst in this rock. The decomposed hornblende relics in this rock indicate a temperature probably slightly above 1000°C (Williams, 1929, p. 195).

Potash-rich feldspar.--Anhedral orthoclase is present in

increasing proportions from diorite to granophyre in the plutonic rocks. Potash feldspar, probably adularia, has been introduced in the older hydrothermally altered greenstone lavas of the basement volcanic complex. Anhedral orthoclase occurs as xenocrysts in the andesitic glass of the pyroclastic rocks of Mount Vsevidof.

Potash feldspar, possibly anorthoclase, is most commonly found in the groundmasses of the coarser-grained basalts and andesites of Umnak and Bogoslof Islands and is in the fine-grained groundmass of the Recent glassy latite flow of Mt. Vsevidof. In the coarse-grained basalts and andesites anhedral anorthoclase(?) is commonly found in the mesostasis with brownish glass. The exact composition of this anorthoclase(?) cannot be determined but its refractive indices suggest that it is richer in potash than soda. In the historic(?) latite flow of Mt. Vsevidof (column 28, Table 8, APPENDIX), groundmass orthoclase(?) euhedra poikilitically include clinopyroxene, opaque oxide, and plagioclase microlites. Thus potash-rich feldspar is a late mineral to crystallize if it crystallizes at all, and in many aphanitic or glassy basic rocks of Umnak and Bogoslof it has not crystallized.

Plagioclase.--Plagioclase is by far the most abundant mineral constituent of all except the more silicious rocks. Plagioclase (An_{97-56}) forms 65 percent of the quartz diorite (column 24, Table 8, APPENDIX). The anorthite basalt (column 5, Table 8, APPENDIX) contains about 30 percent of anorthite phenocrysts in addition to the plagioclase of the groundmass. Albite

forms over 70 per cent of the quartz keratophyre (column 29, Table 8, APPENDIX). A diagram summarizing the compositions of the plagioclases with respect to SiO_2 content of the rocks is given in Figure 7. All the compositions shown on Figure 7 are based on the optical determinations (F. C. Calkins, unpublished charts; Kennedy, 1947, Fig. 1) in order that all plagioclase compositions may be comparable.

The most calcic plagioclase phenocrysts in the northeastern Umnak basic lavas are commonly about An_{95} though in a few rocks, which are not analyzed and therefore not plotted on Figure 7, cores of phenocrysts approach pure anorthite. The plagioclase phenocrysts of the basalts, particularly the porphyritic basalts with fine-grained groundmass, are commonly slightly zoned sodic anorthite or calcic bytownite cores, which comprise the bulk of the phenocrysts. The cores are commonly enclosed by thin outer shells of sodic bytownite or calcic labradorite of the same composition as the groundmass plagioclase. This relationship of the plagioclase also holds in the case of basaltic andesites such as the analyzed specimen (no. 6, Fig. 7) of the cone B lava flow. Kuno's statement (1950, p. 965): "Andesites with fine-grained groundmass sometimes carry phenocrysts of anorthite surrounded by narrow rims, which are as calcic as bytownite," is true for many of the Umnak rocks classed as basaltic andesite. In those porphyritic basalts with a microgranular groundmass, indicative of slower cooling, the plagioclase phenocrysts are zoned through a wider range of composition. The inner core of bytownite-

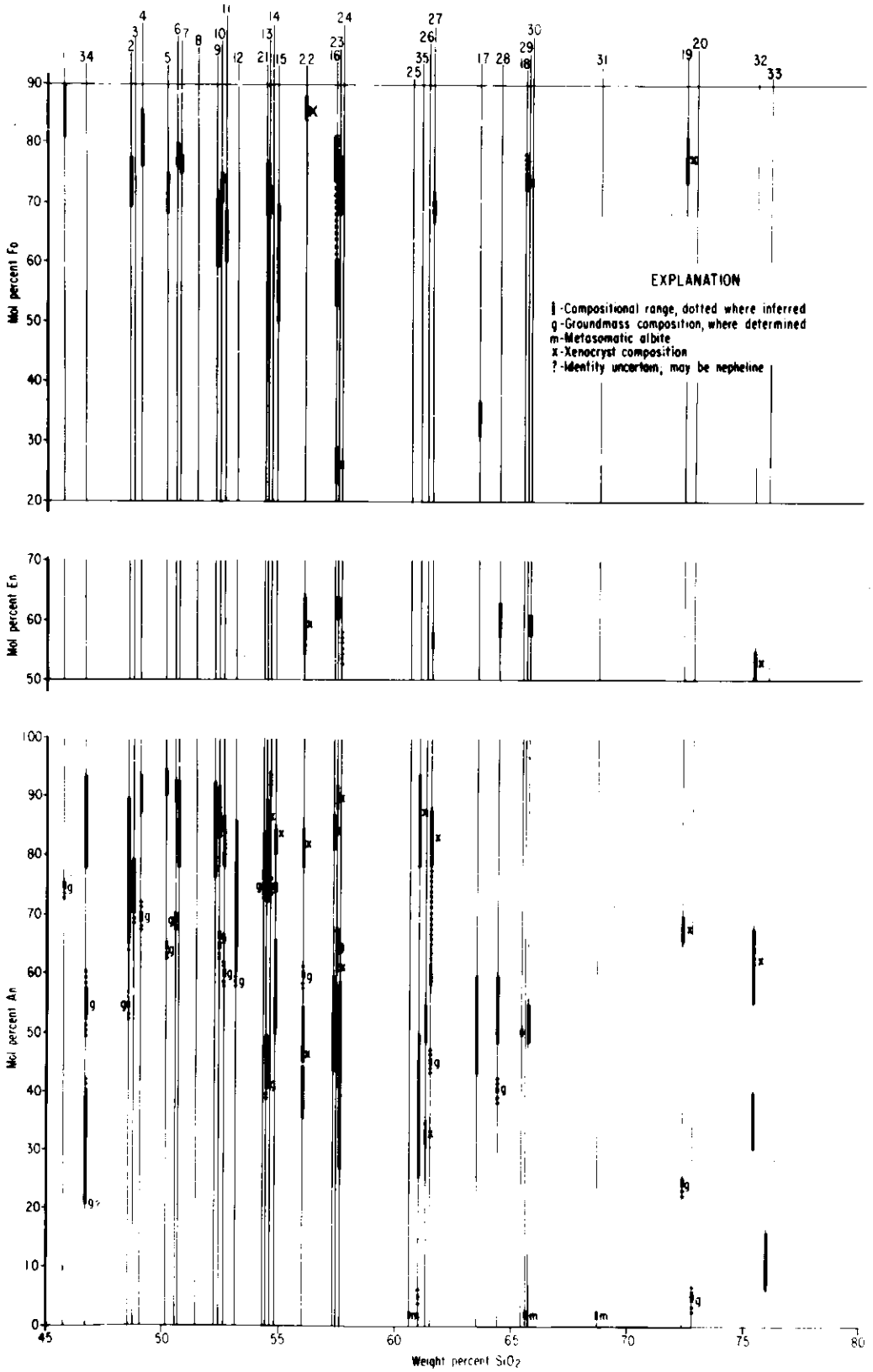

Figure 7.--Range of composition of plagioclase, hypersthene, and olivine with respect to silica content of Umnak-Bogoslof rocks. Numbers at top refer to analyzed specimens, table 7 (Appendix).

anorthite is rimmed by a thick jacket commonly ranging from bytownite into labradorite, less commonly into andesine. The bytownite-salite-hornblende basalt dome (no. 34, Fig. 7) of Bogoslof Island contains some phenocrysts whose outer zones pass through labradorite, andesine, oligoclase (potassic?), and finally into a potash-rich feldspar (anorthoclase?).

The anorthite phenocrysts in the anorthite basalt flow near Inanudak Bay (no. 5, Fig. 7) were amenable to special study. Enough material (0.2g) was assembled for determination of alkalis by flame photometer. These determinations with calculated values for the other major oxides (see Table 4, p. 95) indicate a composition of An_{91}, which agrees well with the determination of An_{93} by optical determination. The orientations of optic elements, as determined by measurements of six anorthite phenocrysts on the universal stage are given in Figure 8. The optic orientation and other data indicate that five of the six phenocrysts measured on the universal stage are distinctly anorthitic. Measurement on phenocryst number 2 indicates calcic bytownite. The anorthite is twinned most commonly according to the Carlsbad law, but albite and pericline twinning are also common. The anorthite phenocrysts occur chiefly as stubby euhedral crystals and less commonly as anhedral crystals. Some of the anhedral crystals are irregularly embayed by the groundmass. Both the euhedral and anhedral anorthite phenocrysts contain a thin rim or shell of plagioclase that approaches the groundmass plagioclase (An_{65}) in composition. Apparently, the anorthite was not in equilibrium with the liquid,

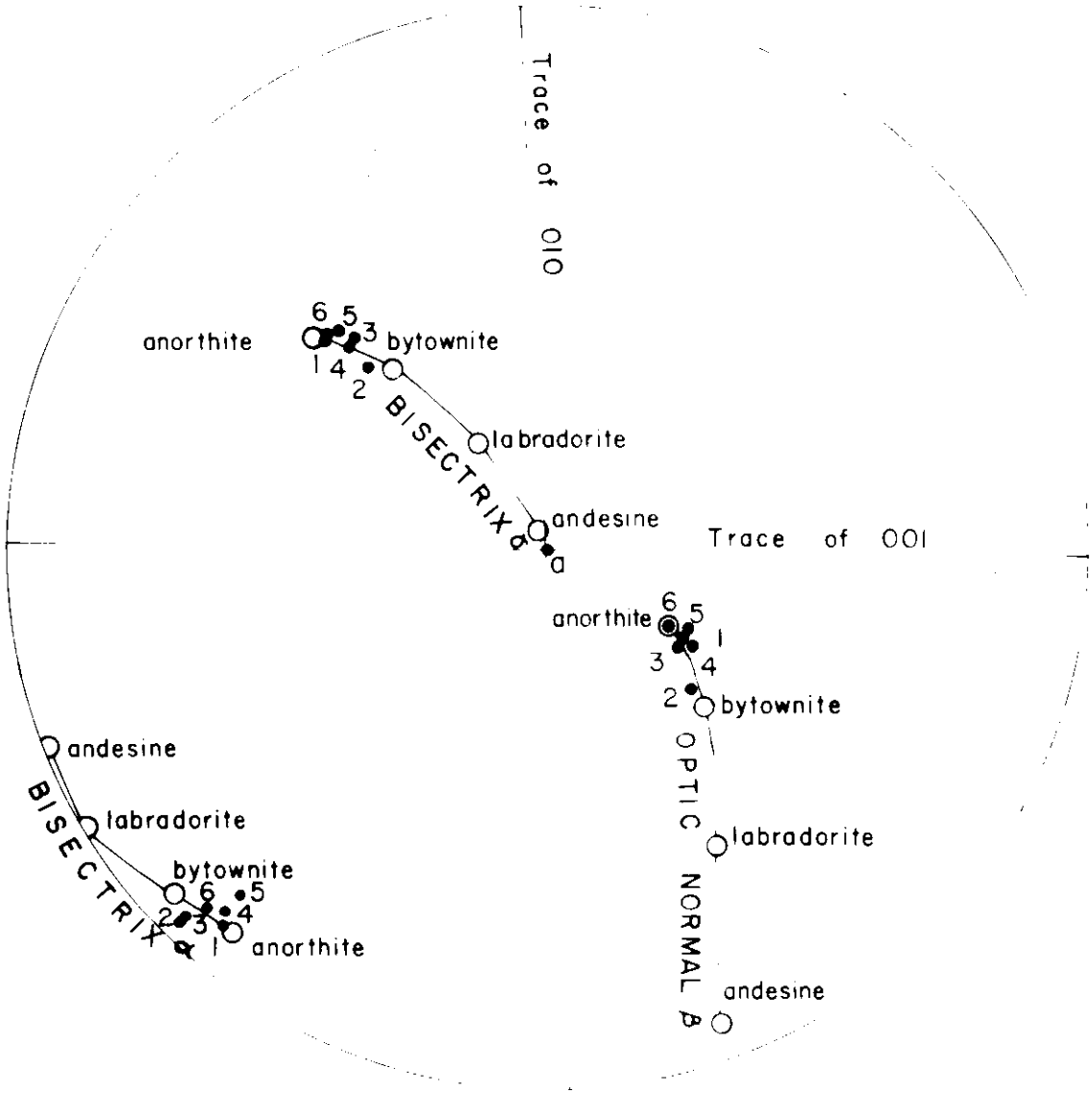

Figure 5.--Orientation of optic elements in anorthite phenocrysts from anorthite basalt flow near Inanudak Bay. Numbers refer to individual phenocrysts. Migration curves of plagioclase optic elements after Reinhard (in Winchell, 1933).

now groundmass, just prior to solidification.

Zoned labradorite phenocrysts, in most rocks extending into andesine are most typical of the andesites, whether they are in the form of flows, plug-domes, or welded agglomerate beds. Almost all the intermediate plagioclase in the phenocrysts of the andesine-hornblende andesite dome of Bogoslof Island (no. 35, Fig. 7) form armored jackets around earlier anhedral bytownite-anorthite cores, which apparently acted as seed crystals in the melt. The plagioclase phenocrysts in the rhyodacitic pumices (nos. 18 and 30, Fig. 7) show strong oscillatory zoning in thin section, but the range in composition is rather narrow and centers close to An_{50}. In another sample of rhyodacitic ash from the Okmok formation the plagioclase phenocrysts are unzoned An_{50}. Plagioclase phenocrysts in the siliceous rhyolite dome (no. 32, Fig. 7) of southwestern Umnak Island range from An_{30-40}, although a few have mottled cores of labradorite. In the strongly zoned plagioclase phenocrysts of extrusive rocks, the more calcic plagioclase forms the cores or early precipitated crystals. In some lavas the break in composition between the more calcic early plagioclase and more sodic late plagioclase is marked, suggesting a radical change in the composition and possibly the environment.

Plagioclase xenocrysts (marked by "x" on Figure 7) associated with phenocrysts in two-plagioclase rocks are found in welded agglomerate beds (nos. 13 and 16, Fig. 7), volcanic pipes, and volcanic domes (nos. 15 and 32, Fig. 7). The calcic plagioclase xenocrysts in the welded agglomerates are probably derived

from plagioclase phenocrysts left over from the melting or assimilation of the groundmass of porphyritic basalt xenoliths which can be recognized microscopically in all stages of disintegration. The two-plagioclase plug-domes suggest lack of equilibrium conditions owing to high viscosity. The basalt flows, basaltic andesite flows, and the (volatile-rich) rhyodacitic pumices contain only one range of composition in the plagioclase phenocrysts, perhaps owing to their lower viscosity and greater approach to ideal crystal-liquid phase equilibrium.

The abundant intermediate plagioclase xenocrysts in the hypersthene-bearing andesites present a special problem. Plagioclase xenocrysts in the hypersthene-bearing andesites of southwestern Umnak (nos. 22, 23, and 27, Fig. 7) commonly show reverse zoning and are associated in the same rock with normally zoned phenocrysts (Fig. 7). In the same rock andesine or sodic labradorite also occurs in separate anhedral crystals. These commonly contain a zone of dust inclusions, like those described by Fenner (1926, p. 693) in Katmai andesites and more recently by Kuno (1950, Fig. 5) in Hakone andesites. Other anhedral sodic plagioclase crystals show mottled extinction. These crystals or xenocrysts are more sodic than the outermost zone of plagioclase, which is equivalent in composition to the groundmass plagioclase. The distinction between xenocrysts and phenocrysts in the plagioclases cannot always be made since such a distinction rests on genesis.

The plagioclase of the plutonic rocks (nos.24 and 33, Fig.

7) of Umnak Island is much less calcic than the plagioclase phenocrysts in the lavas and near surface intrusives. Although the plagioclase is normally zoned through a moderate range in composition, there are no breaks or hiatuses in composition, such as those in the volcanic rocks. The quartz diorite (no. 24, Fig. 7), which is chemically similar to the hypersthene-bearing labradorite andesite flows (e.g., no. 23, Fig. 7) contains plagioclase that averages andesine in composition. A quartz monzonite facies (not analyzed) of the quarts diorite contains normally zoned plagioclase through andesine, oligoclase, and even calcic albite. Granophyre dikes (no. 33, Fig. 7) in the quartz diorite contain sodic plagioclase that ranges from An_6 to An_{16}.

The groundmass plagioclase in almost all lavas where such determination could be made had a composition more sodic, in some rocks considerably more sodic than the plagioclase phenocrysts. In most rocks studied plagioclase of the outermost zone of the phenocrysts was essentially the same composition as the plagioclase microlites of the groundmass. Coarseness of groundmass (i.e., degree of crystallinity) appears to be a factor in determining the composition of the groundmass plagioclase. The groundmass plagioclase is generally slightly lower in the anorthite molecule in the microgranular (i.e., more slowly cooled) groundmasses than microlitic plagioclase in hyalopilitic or pilotaxitic (quickly chilled) groundmasses, because of the greater time available for reaction in the more slowly cooled rocks. The

plagioclase microlites are generally either simple crystals or single albite twins.

Albite, probably close to pure albite in composition has been extensively introduced in the albitized meta-sedimentary and igneous complex of southwestern Umnak Island (unit Tvs, Fig. 3). In the albitized sedimentary and igneous rocks (nos. 25, 29, and 31, Fig. 7) the albite has largely replaced the groundmass feldspar, glass, and the plagioclase phenocrysts with little veining or other evidence of subsequent alteration.

Biotite.--Biotite is almost entirely confined to rocks of southwestern Umnak Island. The proportions in the rock and β indices of a few biotites are given in Table 8 (see APPENDIX). The biotites of the albite diorite and the keratophyre resemble the chlorite group in having a birefringence of only about 0.02 and weak pleochroism yellowish green to green, but the optic orientation and indices are typical of biotite. From their relationship to the general texture of the rocks it appears probable that a typical biotite crystallized from these rocks during the original consolidation and was subsequently altered to a green biotite with lower birefringence during the albitization of the plagioclase. The biotite of the plutonic rocks is a dark brown biotite. The absorption is nearly complete in thin section parallel to the cleavage. The 2V is nearly zero and the β indices range from 1.650 to 1.667 (Table 8, APPENDIX). The biotite phenocrysts of the rhyolite domes contain higher indices, optic angles, and greater absorption than those of the Umnak plutonic biotites.

These anomalous optical properties suggest a maximum temperature of 650°C for the temperature of extrusion, by comparison of the data obtained by Kozu and Yoshiki (1927, pp. 182 and 189) on artificially heated biotites. Actually, the temperature of extrusion may have been slightly lower, for the naturally heated biotite of the rhyolite might have achieved the same properties on having been heated during a much longer time and at a lower temperature than the laboratory-heated biotites. The temperature of extrusion could scarcely have been much lower than 650°C, inasmuch as the rhyolite would be completely crystalline and incapable of extrusion.

Amphibole.--The occurrence of amphibole on Umnak Island closely parallels the occurrence of biotite. In the extrusives of Bogoslof Island, however, amphibole without biotite is a common constituent. The β indices of amphiboles in rocks of Umnak and Bogoslof Islands is given in Table 8 (see APPENDIX).

The amphibole in the albitized intrusive rocks of southwestern Umnak (Pl. I, Fig. 3) is slightly more greenish and has slightly less distinct pleochroism than the hornblende in the unaltered plutonic rocks. However, the β index (1.674) in the amphibole of the albite diorite (no. 25, Table 8) is slightly higher than those of the hornblendes in the quartz diorite, in contrast to the relationship between β indices of the metasomatic biotite and the plutonic biotite. An amphibole with the optical properties of actinolite occurs as sparse aggregates in the granophyre.

Hornblende occurs sparingly in the rhyolite dome of southwestern Umnak Island (no. 32, Table 8, APPENDIX). This hornblende, like the biotite is of significance in that its indices and absorption are slightly greater than that of the diorite hornblende (see no. 24, Table 8), possibly owing to heating at atmosphere pressure. Again applying the experimental data of Kozu and Yoshiki (1927, p. 189), a maximum temperature of about 700°C is indicated as the temperature to which the hornblende in the southwestern Umnak rhyolite was heated. This estimate compares with the maximum of 650°C obtained in the case of the biotite.

The presence of oxyhornblende and decomposed hornblende in the extrusive domes of Bogoslof also gives a clue to possible ranges of temperature of extrusion by comparison with experimental data. According to Barnes (1930, p. 416) common green hornblende changes to oxyhornblende at 800°C and atmospheric pressure. Hence, the andesine-hornblende andesite must have been heated above 800°C, although movement as a viscous plug may have continued below that temperature, since the reaction

hornblende ⟶ oxyhornblende and hydrogen

is irreversible (Barnes, 1930, p. 416). Williams (1929, p. 195) found that green hornblende of the Marysville (California) andesite changed to oxyhornblende in the range 810° to 850°C, and decomposed in the range 920° to 960°C at atmospheric pressure. If Williams' experiments have general application under surface environments, the maximum temperature of the Bogoslof andesine-

hornblende andesite (no. 35, Table 8, APPENDIX) probably did not exceed 950°C. The maximum temperature at the beginning of extrusion at the surface may have been slightly above 900°C, because the oxyhornblende has close to the maximum birefringence (ca. 0.09) and gamma index (1.735) of any known oxyhornblende.

The hornblende in the bytownite-salite-hornblende basalt dome (no. 34, Table 8, APPENDIX), has largely decomposed, and, if Williams' experimental data (1929, pp. 195-197) may be applied to this dome, a minimum extrusion temperature above 920°C can be inferred. The upper limit of temperature, however, cannot be as precisely inferred, because Williams (1929, pp. 195-197) observed cores of undecomposed hornblende crystals surrounded by magnetite as high as 1100°C, although such crystals were rare at that temperature. Even at 1050°C, Williams found that almost all the hornblende has turned jet black (opaque oxides) under oxidizing conditions at one atmosphere. However, if the slow rate of cooling of the basalt dome is taken into consideration it would appear probable that the maximum temperature of the dome was below 1050°C.

Clinopyroxene.--The clinopyroxenes are common constituents of the rocks of Umnak and Bogoslof Islands and show certain slight differences depending on the area, geologic environment, and paragenesis in the rock. The nomenclature of the clinopyroxenes is taken from Poldervaart and Hess (1951, p. 474). The composition of clinopyroxenes with respect to Ca, Mg, and Fe atoms is given in Figure 9. The plot, representing an analyzed

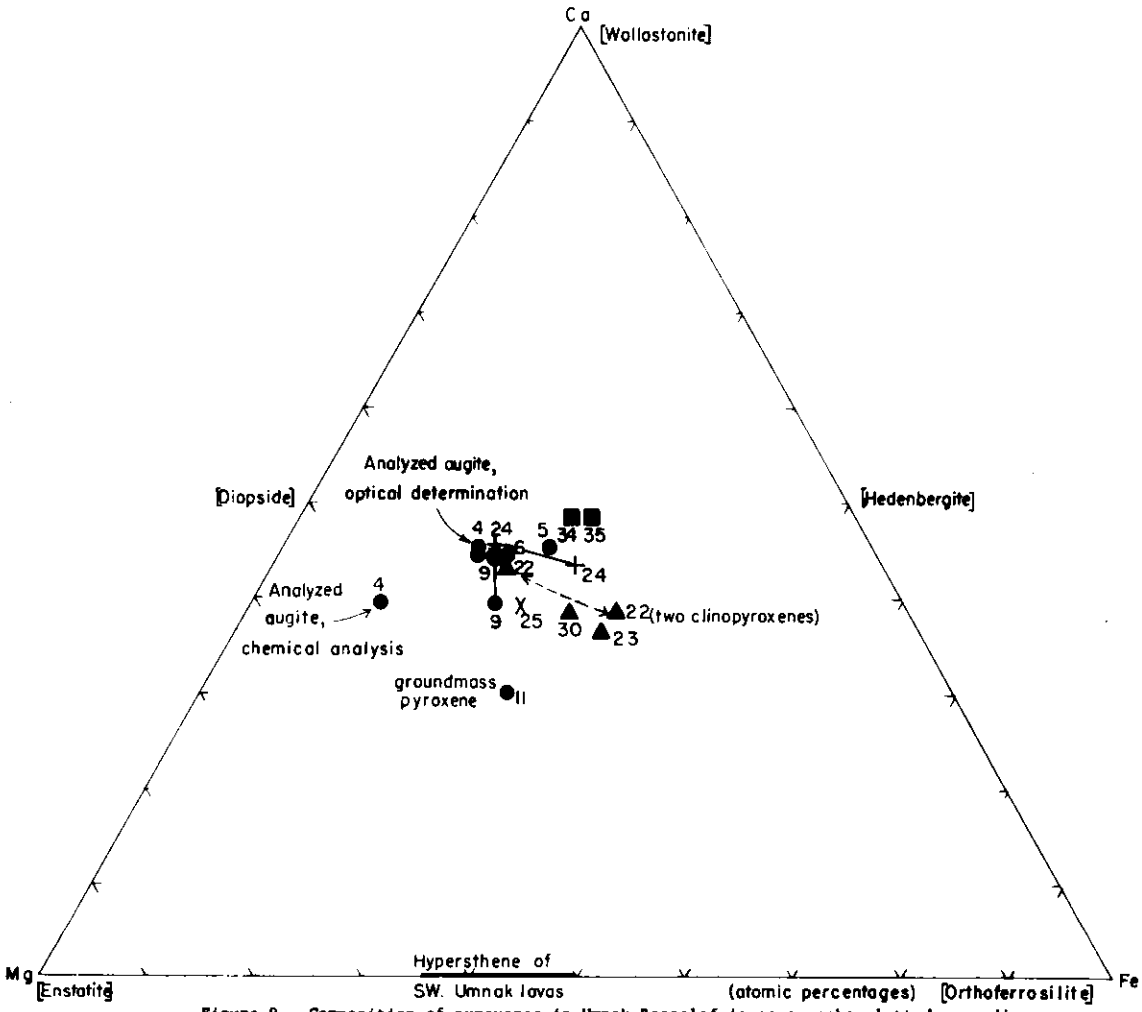

Figure 9.--Composition of pyroxenes in Umnak-Bogoslof igneous rocks plotted according to Hess (1949, pl. 1). Circles, northeastern Umnak augites; squares, Bogoslof salite and ferrosalite; triangles, southwestern Umnak ferriferous augites; diagonal cross, southwestern Umnak augite in albite diorite; cross, augite in quartz diorite. Numbers correspond to analyzed rocks in table 7 (Appendix). Solid line indicates extent of zoning.

TABLE 1

CHEMICAL COMPOSITION[a] AND ATOMIC RATIOS[b] OF AUGITE PHENOCRYSTS IN ANORTHITE-AUGITE-OLIVINE BASALT FLOW

Chemical Analysis (wt. percent)		Atomic Ratios		Fe''' Na	Al Na	2Al Ti	Al Fe'''	Al	Z Y W	Cations to Six O
SiO_2...	49.66	Si	820						Z $899\frac{1}{2}$	1.966
Al_2O_3..	6.00					10	11	$48\frac{1}{2}$		
		Al	119							
								$49\frac{1}{2}$		
Fe_2O_3..	1.93	Fe'''	24	13			11			
FeO....	5.69	Fe	79							
MgO....	17.13	Mg	430						%XY $944\frac{1}{2}$	2.066
CaO....	19.32	Ca	345							
Na_2O...	0.36	Na	11	11						
K_2O....	0.10	K	2	2						
TiO_2...	0.44	Ti	5			5				
Total..	100.68	O	2742							

Al in Z, 6.6 percent Atomic ratios: $Ca_{39}Mg_{49}Fe_{12}$

Density (powder), 3.4

[a] Oxides other than alkalis analyzed by Brynjolf Brunn; alkalis analyzed by W. W. Brennock on flame photometer.

[b] After H. H. Hess, 1949, pp. 624-26.

augite, is based directly on chemical analysis (Table 1), but all other augite compositions are inferred from the β index and 2V determinations (Hess, 1949, plate 7). A fairly large dis-

crepancy exists between the actual composition of the analyzed augite and its inferred composition based on its β index and 2V. The optical properties indicate an Mg content of about 12 percent too low whereas the Ca and Fe contents are each 6 percent too high. Or stated conversely, the analyzed augite should have had a β index of about 1.684 and a 2V of about 47°C in order to fit the Hess diagram (1949, Plate I). Hess (1949, pp. 635-636) points out, however, that the effect of an increase of Cr with increasing Mg would raise the optical properties above those indicated in his diagram. The northeastern Umnak augite has 0.2 percent Cr (see Table 4, p. 95) and also 6.00 percent of Al_2O_3 and 1.93 percent of Fe_2O_3 (Table 1), which are 3.00 percent and 0.43 percent higher, respectively, than the Al_2O_3-Fe_2O_3 percentages, which Hess assumed in constructing the diagram (Hess, 1949, Plate I). Thus, with the exception of the analyzed augite, the pyroxene plots shown on Figure 9 have only relative significance, and the more diopsidic augites are probably as much as 12 percent too low in Mg and about 6 percent too high in Ca and Fe.

The augite phenocryst compositions (circles, Fig. 9) of northeastern Umnak lavas tend to cluster in a small area. These augites are diopsidic, medium dark green, and occur as sparse to abundant phenocrysts along with olivine and anorthite-bytownite. Rarely, augite phenocrysts up to a few percent of the rock occur without olivine and plagioclase phenocrysts but are more commonly associated with these minerals as phenocrysts. One micro-

granular augite basalt (no. 9, Fig. 9), possibly a near-surface sill, contains zoned augite phenocrysts that become poorer in lime (more pigeonitic) in the outer zones as indicated optically by decreasing 2V. This trend is believed continued into the clinopyroxene of the groundmass, inasmuch as the clinopyroxene of an analyzed aphyric basalt (column no. 11, Fig. 7) has a 2V of 35°, indicating a pigeonitic augite. Thus, the groundmass pyroxene of at least one and possibly all the northeastern Umnak lavas tends toward a pigeonitic composition, as has been generally observed by Barth (1931, pp. 195-208) in other Pacific lavas. Diopsidic augite phenocrysts also occur in the relatively few mafic basalts of southwestern Umnak and occur as rare to sparse xenocrysts(?) in the hypersthene andesites (see no. 22, Fig. 9).

The dominant clinopyroxene of the southwestern Umnak lavas is a small, greenish black augite or ferroaugite with slightly lower 2V and slightly higher β indices, corresponding to an increase in iron content (triangles, Fig. 9). No pigeonite has been found in the southwestern Umnak rocks, even after a special search, although the rocks are chemically and mineralogically similar to hypersthene-bearing andesites, in which pigeonite has been found (Kuno, 1950, p. 1003).

The augites of the albitized igneous rocks (no. 26, Fig. 9) are slightly more diopsidic than the ferroaugites of the hypersthene andesites. Whether or not the original composition of these augites was changed during albitization is open to conjecture, but they appear very fresh in thin section. The augite

of the quartz diorite (no. 24, Fig. 9) has an inner core that falls among the diopsidic augites of the porphyritic basalts. The outer zones of the plutonic augite become richer in iron (increasing β index) as indicated on Figure 9. Thus the change in composition of the quartz dioritic plutonic rock tends during consolidation toward ferriferous augite, like the augite phenocrysts of the porphyritic andesites, whereas the augite of the basalts of northeastern Umnak becomes more pigeonitic.

The Bogoslof clinopyroxenes (nos. 34 and 35, Fig. 9) are nearly the same in composition as indicated by the β index and 2V, although the clinopyroxene of the andesine-hornblende andesite (no. 35) is slightly richer in Fe with respect to Mg than the clinopyroxene of the bytownite-salite-hornblende basalt (no. 34). The Bogoslof clinopyroxenes are close to the salite-ferrosalite line of division (50 diopside-50 hedenbergite) as deduced from their optical properties (Hess, 1949, pls. I and VI). Moreover, the Bogoslof clinopyroxenes are weakly pleochroic in green and yellow, a property typical of the salites and ferrosalites studied by Hess (1949, pp. 656-657).

It is noteworthy that no true pigeonite has been positively identified in Umnak or Bogoslof rocks, despite the fact that Kuno (1950, p. 1003) has identified pigeonite phenocrysts in rocks that have closely petrographic resemblance to certain southwestern Umnak rocks and despite the assertion of Poldervaart and Hess (1951, p. 473) that pigeonite has probably been overlooked in many basic rocks. A special search was made for

pigeonite in all rocks examined and this much can be said: If pigeonite does indeed exist in Umnak rocks, it occurs as groundmass clinopyroxene that is too small for measurement of optic angles. Only one questionable 2V measurement of a groundmass clinopyroxene gave a 2V approaching zero degrees; more reliable measurements indicate a 2V ranging from 35 to 40 degrees.

Hypersthene.--Hypersthene occurs almost entirely in the rocks of southwestern Umnak, chiefly in the hypersthene-bearing andesites, and rarely in the pyroclastic effusives of the Okmok formation of northeastern Umnak. All the hypersthene shows the typical faint rose to faint green pleochroism. A few hypersthene phenocrysts show inclined extinction up to 10 degrees, as was observed by Verhoogen (1937a, pp. 66-69) in Cascade lavas. As far as the present writer could determine the other optical properties of the Umnak "clinohypersthene" were similar to those of the "orthohypersthene." From the present observations, the "clinohypersthene" observed in southwestern Umnak rocks could be explained by an oblique section in which only one plane of the prismatic cleavage was developed (Johannsen, 1937, Vol. 3, pp. 212-213). The enstatite (En) content of the hypersthene (Table 8, APPENDIX) is based on curves correlating optical properties with chemical composition (Hess and Phillips, 1940, Pl. I; Kennedy, 1947, Fig. 3). The variation in En content of the hypersthene with silica content of the rocks is shown diagrammatically in Figure 7. The enstatite (En) content of the hypersthene of the igneous rocks of southwestern Umnak shows a slight though

distinct decrease from andesite (nos. 22, 23, and 27, Fig. 7) to rhyolite (no. 32, Fig. 7), in which hypersthene is rare. The hypersthene of the rhyolite dome, like the labradorite cores of the plagioclase was probably not in equilibrium with the rhyolitic magmatic liquid at the time of extrusion. Rare hypersthene was observed in thin section in the welded agglomerates and rhyodacitic ash beds of northeastern Umnak but could not be isolated for optical study in crush grain mounts. This hypersthene is probably xenocrystic in origin.

Hypersthene is rare in the quartz diorite (no. 24, Fig. 7) and occurs only as irregular cores armored with augite. No hypersthene crystals could be segregated from the quartz diorite for optical determination, but the 2V, determined in thin section, is 48 degrees. By slight extrapolation of the 2V curve of two hypersthenes whose average indices are known, the most likely composition of the plutonic hypersthene is about En_{55}. This composition is about 6 per cent richer in iron than the corresponding curves presented by Hess and Phillips (1940, pl. I) and Kennedy (1947, Fig. 3) but is not a unique solution since the 2V curve passes through a maximum in the vicinity of 45 degrees. The hypersthene phenocrysts in the southwestern Umnak andesites are enclosed by reaction rims of ferriferous augite.

Olivine.--Olivine is common as phenocrysts in the mafic basalts of Umnak Island and is rare to sparse in the aphyric basalts, andesites, and hypersthene andesites, in which rock

types it commonly shows a reaction relationship to augite. It also occurs as xenocrysts in the rhyolite and in the welded andesitic agglomerate beds of northeastern Umnak. Olivine is absent in the rocks of Bogoslof Island, where hornblende and salite are the mafic phenocrysts.

The Umnak olivines, analogous to plagioclase, have a wide range in the ratio of the pure end members (see Fig. 7) as one might expect from the olivine diagram (Bowen and Schairer, 1935, p. 197). The most magnesian olivine found in Fo_{90} in the cores of abundant phenocrysts in the olivine basalt at Cape Idak (no. 1, Fig. 7). The most ferriferous olivine, Fo_{23}, is in rare, broken olivine crystals in a northeastern Umnak welded agglomerate (no. 16, Fig. 7), in which it is probably xenocrystic. Wager and Deer (1939, p. 75) are followed in the classification of the olivine series:

Forsterite	Fo_{90-100}
Chrysolite	Fo_{70-90}
Hyalosiderite	Fo_{50-70}
Hortonolite	Fo_{30-50}
Ferrohortonlite	Fo_{10-30}
Fayalite	Fo_{0-10}

This classification contains the same numerical divisions as those of the plagioclase classification and, indeed, analogous members of the plagioclase and olivine series are associated in many of the rocks of northeastern Umnak.

Magnesian chrysolite is common as phenocrysts in olivine

and olivine-augite basalts of northeastern Umnak Island and in the mafic basalt of southwestern Umnak (Obo, Fig. 3). Chrysolite commonly forms at least 6 percent of the mafic basalts, and in the olivine basalt of Vane Mak, it forms 22 percent of the rock (no. 1, Table 6, APPENDIX). Ferroan chrysolite is found generally as sparse to common phenocrysts in the plagioclase-rich porphyritic basalts, in which the olivine generally ranges downward into magnesian hyalosiderite. The hypersthene-bearing andesites of southwestern Umnak also contain rare ferroan chrysolite phenocrysts that range in composition slightly into hyalosiderite.

The xenocrystic olivine of the quartz-bearing olivine andesite (no. 22, Fig. 7) ranges from Fo_{84-88}, which is typical of the olivine phenocrysts of the most olivine-rich basalts. The obsidian phase of the rhyolite dome of northeastern Umnak (no. 19, Fig. 7) also contains xenocrysts of ferroan chrysolite, which were left from mixing with a basaltic andesite liquid or resorption of solid groundmass of basaltic andesite xenoliths. The ferroan chrysolite of the welded andesitic agglomerates of northeastern Umnak (nos. 13 and 15) is probably of xenolithic origin.

The entire range of hyalosiderite is represented in the least siliceous vitreous andesite (no. 15, Fig. 7) of northeastern Umnak. The more siliceous vitreous andesites and latite (no. 17, Fig. 7) contain hortonolite that ranges in composition into ferrohortonolite. These ferroan olivines occur as rare

phenocrysts but the ferroan olivine in the upper welded andesitic agglomerate bed of the Okmok formation is probably derived from the partial assimilation or melting of vitreous andesite or latite xenoliths. Ferroan olivines in lavas as silicious as dacites (Hawkes, 1924) have been recorded in Iceland. It is interesting to note that Bogue and Hodge (1940, p. 633) record a break in the composition of zoned Cascade olivines at Fo_{23}. Like the olivine phenocrysts in Cascade rocks, the more ferroan Umnak olivine phenocrysts are small--less than 0.5 mm. The presence of ferroan olivine in these silicious lavas instead of orthopyroxene is doubtless due to the instability of ferroan orthopyroxene (Bowen and Schairer, 1935, p. 159) in silicate melts, the stable crystal phases being either clinopyroxene, or olivine and tridymite, which commonly refuses to crystallize out of glassy lavas because of high viscosity at time of extrusion.

Olivine is present in rare amounts in the groundmasses of mafic basalts containing more than about 5 percent of olivine phenocrysts. Much of the groundmass olivine in the Umnak mafic basalts appears to be unresorbed remnants rather than euhedral crystals that crystallized with the other minerals of the groundmass.

Accessory Minerals

Opaque iron-titanium oxides.--The most common accessory minerals are magnetite, probably titaniferous, and ilmenite. Because of their close association in the rock and the inherent

difficulties in distinguishing between these opaque greyish black minerals, by ordinary petrographic methods, they are grouped together as opaque oxides in the rock descriptions and tabulated modes (Table 8, APPENDIX). Magnetite is probably more abundant than ilmanite.

The opaque oxides occur as euhedral microphenocrysts in the two analyzed rocks of Bogoslof Island (nos. 34 and 35, Table 8, APPENDIX). These microphenocrysts have rhombic cross-sections, indicating octahedra, and are strongly magnetic, indicating that magnetite is probably the sole mineral. Euhedral magnetite(?) also occurs sparsely in the rhyodacite pumice of Mt. Vsevidof (no. 30, Table 8, APPENDIX). Rare to sparse segregations of anhedral opaque oxides, which commonly replace mafic phenocrysts, occur in the vitreous andesite, latite and rhyolite plug-domes (no. 15, 17, and 19, Table 8) and in the welded andesitic agglomerate beds of northeastern Umnak (nos. 13 and 16, Table 8). Closely related to these occurrences are the opaque oxide pseudomorphs after amphibole in the quartz-bearing olivine andesite of southwestern Umnak (no. 22, Table 8) and in the bytownite-augite-hornblende basalt dome of Bogoslof Island (no. 34, Table 8). The anhedral and certainly the pseudomorphic segregation of opaque oxides are the latest minerals to crystallize; in some rocks they appear to have crystallized after the rock had become essentially solid, possibly owing to action of a gaseous phase. In parts of the lithic phase of the rhyolite dome of northeastern Umnak Island (no. 20, Table 8) vuggy magne-

tite crystals in thin veinlets cut the rock.

The groundmass of the basalts contains in general opaque oxide euhedra, largely magnetite ranging from about 0.005 to 0.05 mm in average diameter. In the augite basalt flow (no. 9, Table 8) the opaque oxide euhedra approach 0.1 mm in diameter. Many aphyric basalt and andesite flows including the welded andesitic agglomerates of northeastern Umnak contain very fine-grained opaque oxides, which impart a dark, nearly opaque cloudy appearance to the groundmass, the so-called "opaque oxide-charged groundmass" of many petrographers.

The opaque oxides in the plutonic rocks of southwestern Umnak (nos. 24 and 33, Table 8, APPENDIX) are anhedral and commonly replace the mafic minerals, particularly biotite and amphibole. Thus the opaque oxides, like quartz and orthoclase, are among the latest minerals to crystallize in the plutonic rocks but replace mafic minerals and possibly in part crystallize with the later mafic crystals, such as amphibole and biotite.

Apatite and sphene.--The plutonic rocks (nos. 24 and 33, Table 8, APPENDIX) and albitized intrusives (no. 25, Table 8) contain sparse euhedral apatite, generally in the form of microscopic needles, but in a few plutonic rocks (not analyzed), stubby crystals approaching 0.1 mm across and 0.3 mm in length are not uncommon. Similar stubby apatite crystals occur sparsely as microphenocrysts in the andesine-hornblende andesite of Bogoslof Island (column 35, Table 8). The albitized rocks of southwestern Umnak contain needle-like, apatite crystals up to

0.3 mm in length. They appear to be an original constituent of the rock as they are found as inclusions in andesine core remnants of the albite diorite.

Sphene has been recognized only as sparse microphenocrysts up to 0.3 mm long in the andesine-hornblende andesite of Bogoslof Island. Tiny euhedral crystals of sphene also are found around the borders of the (titaniferous?) magnetite microphenocrysts of this rock.

Secondary Minerals

Zeolites.--Minerals of the zeolite group are almost entirely secondary. Actually, the zeolites, largely chabazite, in the younger volcanic rocks were probably introduced during the late stages of cooling. Chabazite(?) was probably deposited during the cooling stage of the volcanic rocks, inasmuch as many of the lavas and agglomerates containing chabazite(?) are very young rocks forming the present constructional surface. A near-primary zeolite, analcite, was confirmed by Richard C. Erd of the U. S. Geological Survey, and occurs as a groundmass mineral and as cavity-filling in the 1796 andesine-hornblende andesite (no. 35, Table 8) of Bogoslof Island. Rare ptilolite(?) was observed in palagonitized andesitic scoria (column 8, Table 8) from a sequence of palagonitized pyroclastic rocks that form part of Okmok Volcano (unit 2, Fig. 2).

Zeolite minerals vein and replace the plagioclase phenocrysts and groundmasses of hydrothermally altered porphyritic

andesites and basalts (no. 12, Table 8) of the basement volcanic complex. The zeolites are in places found in veinlets associated with quartz, calcite, and epidote. One of the zeolites occurs as an amygdaloidal filling of vesicles with quartz. From their crosscutting relationship to the primary constituents of the rock and their association with other secondary minerals not found in the primary basalts and andesites, it follows that these zeolites were produced during the hydrothermal alteration of the rock. The zeolites tentatively identified include heulandite, natrolite, and less commonly chabazite. In general, the calcic plagioclase phenocrysts have broken down into a soda-rich zeolite, calcite, and epidote.

Chlorite-serpentine minerals.--Minerals of the chlorite-serpentine group are common in the older rocks of Umnak Island. These minerals are not found in very young lavas that form the present constructional surface, although they occur to a limited extent in the rather recent palagonitized pyroclastic rocks of northeastern Umnak.

The chlorite-serpentine minerals are most common in the hydrothermally altered rocks of the basement volcanic complex. Former olivine and to less extent, augite phenocrysts in the basalts and basaltic andesites are altered to at least two minerals; penninite and antigorite(?). The birefringence of the antigorite(?) is 0.15-0.20, and the indices range from about 1.53 to 1.58 in different specimens. Essentially the same mineral association is found in the older basaltic flows and necks of Okmok

Volcano, but much of the olivine still remains.

A pleochroic chlorite with rather high indices veins and replaces augite and albite in certain albite diorite sills of southwestern Umnak. The indices and pleochroism are

α. . . . . 1.612 (colorless)
γ. . . . . 1.618 (light green)

These optical properties suggest a chlorite with a high iron content, such as prochlorite or ripidolite (Winchell, 1933, part II, p. 284). Similar chlorites are produced in the partial alteration of the biotite in the plutonic rocks of southwestern Umnak, although some of this chlorite shows the typical "Berlin blue" anomalous interference colors characteristic of penninite.

Still different chlorites are found in the palagonitized pyroclastic rocks of Okmok Volcano on northeastern Umnak Island (unit 2, Fig. 2). The chlorites consist of three varieties: (1) minute concentric fibers that line zeolite-filled vesicles, (2) radial fibers that have apparently replaced the palagonite around zeolite-filled cavities. This second type suggests the "fibro-palagonite" or "chlorophaeite" described by Peacock (1926) and Noe-Nygaard (1940). (3) A third unusual chloritic(?) mineral that is yellowish to reddish brown and completely fills the vesicles. This mineral has the form of crudely spherulitic aggregates with curved concentric fibers radiating from more than one center within the vesicle. The fibers have a birefringence of about 0.010, and a positive elongation, and indices ranging from 1.56 to 1.57.

Epidote.--Epidote (α ca 1.735) is probably late primary in its occurrences in plutonic rocks that are otherwise unaltered. The granophyre of southwestern Umnak (no. 33, Table 8) contains sparse epidote that appears to have been a primary constituent of the rock. Rare epidote(?) enclosed in white cloudy spherulites was also noted in the rhyolite of southwestern Umnak Island (no. 32, Table 8). In general, however, epidote is formed as one of the alteration products of calcic plagioclase and augite in the moderately hydrothermally altered basaltic rocks of the basement volcanic complex.

Tourmaline.--Rare to sparse tourmaline is found in the older hydrothermally altered volcanic rocks of the basement volcanic complex. Two varieties were noted: (1) in the moderately altered lavas and tuffs, a greenish blue tourmaline that preferred plagioclase as its host mineral has the following optical properties:

ϵ. . . . . 1.638 (colorless)
ω. . . . . 1.655 (light greenish blue)

The optical properties of the tourmaline are such that it fits either the dravite-schorlite or the elbaite-schorlite series. (2) Sparse, small rosettes of black tourmaline (schorlite) that preferred former ferromagnesian phenocrysts as host mineral are scattered through the most intensely altered potash-feldspathized silicified rocks of the basement volcanic complex.

Calcite.--Calcite is a rare to common constituent in both the albitized rocks of southwestern Umnak Island and the hydro-

thermally altered rocks of the basement volcanic complex. It occurs mainly as veinlets and aggregates replacing plagioclase and augite. Part or all of the lime probably was furnished by the breakdown of these minerals. Calcite also occurs as porphyroblasts in some of the keratophyres and gives the rock a pseudo-porphyritic appearance.

Pyrite.--Minute, rare to sparse cubes of pyrite are scattered through the moderately to intensely hydrothermally altered rocks of the basement volcanic complex. Pyrite also occurs in some of the albitized igneous rocks where they have been affected by later hydrothermal alteration.

Sericite and prehnite(?).--Sericite is present rarely as an alteration of plagioclase in the albitized rocks, the plutonic rocks, and more commonly in the hydrothermally altered rocks of the basement volcanic complex. Rare prehnite(?), which has the form of radiating sheaflike aggregates, occurs in the feldspar and biotite of some plutonic rocks that have been partly altered along a contact aureole adjacent to granophyre.

Adularia(?).--A feldspar with low indices typical of the potash feldspars occurs commonly as veinlets in the plagioclase and in the groundmass of the hydrothermally altered rocks of the basement volcanic complex. This mineral is most abundant in the potash feldspathized, silicified rocks of the basement volcanic complex. Because of its optical character and association with other minerals typical of low temperature hydrothermal alteration, this potash feldspar is presumed to be adularia.

Carpholite(?).--An unusual pleochroic mineral is sparingly represented among the alteration products of hornblende in the bytownite-augite-hornblende basalt dome of Bogoslof Island. The mineral, seen only in thin section, had the following pleochroism:

α . . . . . light yellowish orange
γ. . . . . colorless

The mineral is in rod-like crystals with parallel extinction, positive elongation, moderate birefringence, and relief. This combination of optical properties (Winchell, 1939, vol. 3, determinative tables) fits only carpholite ($H_4MnAl_2Si_2O_{10}$). If correctly identified, this may be a new geologic occurrence for carpholite.

Volcanic Mineral Incrustations

Minerals that are formed at the surface at or near the site of present or recent volcanic activity are grouped as volcanic incrustations. These have been described in part in a previous publication (Byers and Brannock, 1949, pp. 719-734) but are included here for completeness.

Copper-bearing incrustations.--A large patch of bright green stain can be seen on an exposed joint surface of the topmost flow of the basalt flows on the southeast side of Crater Creek Gorge. This mineral is chrysocolla, a hydrous copper silicate and was identified by Miss Jewell J. Glass of the U. S. Geological Survey. Aggregates of minute yellow scales on some of the chrysocolla are tentatively identified as meta-

voltine, a hydrous iron-potassium sulphate, according to Miss Glass. These minerals were probably deposited along the joint surfaces during the late stages of cooling of the lava flow.

Paratacamite, $CuCl_2.3Cu(OH)_2$, and caledonite, $2(Pb,Cu)O.SO_3.H_2O$, occur as greenish microbotryoidal incrustations coating fragments in thin ash beds erupted in 1926 on Bogoslof Island. These minerals were identified by Richard C. Erd of the U. S. Geological Survey. Gypsum and botryogen accompany the copper minerals in the incrustations of the Bogoslof ash. These occurrences have not been previously described in the literature.

Incrustations of active cones.--Cones A and C of northeastern Umnak (Pl. I) contain sulfate incrustations on the ash, where volcanic gases are presently escaping. Cone A, which is actively discharging SO_2-bearing gases, is covered with bright-colored yellow and green incrustations. These were found by Miss Jewell J. Glass of the U. S. Geological Survey to be essentially vari-colored specimens of the same mineral, halotrichite ($FeO.Al_2O_3.4SO_3.22H_2O$); which apparently changes color, depending on the relative humidity of the atmosphere. Minor gypsum and soda alum were also identified by Miss Glass.

Cone C is actively discharging H_2O, H_2S and CO_2 gases through a clay-like aggregate. An inner zone of apparently more intense alteration had produced a cream-color, which is surrounded by a dark bluish gray clayey mass. Orthorhombic sulfur, a ferric sulfate mineral and aragonite are in the cream-colored

mass, and a clayey, apparently amorphous material contained about 15 percent of crystabolite and anatase (X-ray examination by Joseph M. Axelrod of the U. S. Geological Survey). The dark-bluish gray mass outside the cream-colored area contains aragonite, opaline silica, and minute cubes of pyrite, 0.01 to 0.2 mm on edge. Apparently, in the dark bluish gray area hydrogen sulfide had produced the pyrite by reaction with the original magnetite of the basaltic ash. In the cream-colored area, pyrite has oxidized to a ferrous sulfate mineral and sulfur was being deposited.

PETROCHEMISTRY

Methods and Reliability of Analyses

The major oxides ordinarily determined in a rock were analyzed largely by the new rapid methods developed in the Geochemistry and Petrology Branch of the U. S. Geological Survey (see Shapiro and Brannock, 1952). Two analyses were made by W. K. Carron of the Survey, using the conventional "wet" methods. Owing to the difficulty of obtaining reliable analyses of silicate rocks immediately following World War II, certain northeastern Umnak rocks were analyzed outside the Geological Survey laboratories. In order for the reader to judge for himself the accuracy of those analyses obtained outside the Geological Survey laboratories, the following case history is given for those particular rocks.

In 1946 and 1947, following World War II, the Geological Survey chemical laboratory had about a three-year backlog of rock specimens for chemical analysis. Because of this tremendous backlog nine rock specimens from northeastern Umnak were sent by the Survey laboratory to a large commercial chemical laboratory. The results of the analyses, which were received in August, 1947, were considerably below the standards of accuracy generally acceptable for a good rock analysis. Five analyses totaled outside the 99.75-100.5 percent range, commonly considered as a good

summation, and two analyses were outside the range, 99-101 per cent. One other analysis that had a good summation nonetheless had a suspiciously high Al_2O_3 content. In the spring of 1948 the writer, while on leave from the Geological Survey, reran the main portion (SiO_2, Al_2O_3, Fe_2O_3, FeO, MgO, CaO, and TiO_2) on six of the nine original rocks submitted outside the Survey for analysis and also analyzed two additional rocks. Laboratory space was kindly provided by the Geology Department of the University of Chicago. The writer's new analyses were somewhat different from the corresponding analyses of the commercial laboratory but totaled within the range, 99.75-100.5 percent. Furthermore, four duplicate runs of the writer's analyses checked closely. As a final check, the SiO_2 content of four specimens were checked by the U. S. Geological Survey chemical laboratory. The determination of SiO_2 in the first rock analyzed by the writer was 0.45 percent too low according to the determination by the Geological Survey chemist, but in the other three specimens excellent agreement, within 0.07 to 0.11 percent, was found between the writer's SiO_2 determinations and those of the Survey chemist. Hence, the writer believes that the percentages of those oxides determined by him are not outside the limits of error necessary for petrologic interpretation.

The chemical analysis made by the newly developed rapid methods of the U. S. Geological Survey are given in Table 7 (APPENDIX) only to the nearest 0.1 percent for the more abundant constituents. For petrologic interpretation involving variation

within a rock suite, the results of the rapid analyses are believed sufficiently accurate. Some discrepancies exist between quantitative spectrographic determinations by different spectrographers in different laboratories, as pointed out by Ahrens and Gorfinkle (1950, p. 565). This bias is being reduced to some extent by common reference standards of granite and diabase available to laboratories. However, spectrographic analyses for petrologic interpretation should be made ideally in the same laboratory by the same spectrographer using the same set of reference standards. Unfortunately, the Umnak and Bogoslof rocks were analyzed at different times by three different spectrographers (K. J. Murata, A. T. Myers, and A. Chodes) in two different laboratories of the Geological Survey. Hence, some of the apparent variations of the minor elements with respect to certain major elements may be due to variation because of different laboratory conditions.

The minor elements reported in Table 7 (APPENDIX) include only those present above the minimum concentration present for spectrographic determination (cf. Tilley et al., 1937, pp. 98-104). These minimum concentrations have been listed by Claffy (1947, pp. 35-48) and more recently by Ahrens (1950, pp. 142-145). All the minor elements reported in Umnak rocks are detectible in concentrations as low or nearly as low as 0.001 percent, but a few minor elements not found or not reported (e.g. lithium) may be present in concentrations above .001, but are below the sensitivity possible in 1951 in the U. S. Geological Survey laboratories.

Major Oxides

Certain descriptive features of the variations of the major oxides are discussed in this section. The petrogenetic significance of these features is postponed to the section on petrology.

Of the major oxides in the rock, silica ranges from 45.7 in the mafic basalts to 77 percent in granophyre. The mafic basalts because of their content of olivine or hornblende are undersaturated with respect to silica (see columns 1, 2, 4, 6, and 34; Table 7, APPENDIX). In addition, the bytownite-salite-hornblende basalt of Pogoslof (no. 34) contains a slight amount of normative nepheline over that caused by the hornblende in the rock. The silica percentage at which northeastern Umnak rocks are just saturated with respect to silica is slightly above 50 percent. The rhyolites contain about 72 to 7[illegible] percent of silica.

Because of the greater abundance of silica over all other oxides, a convenient method of plotting rock analyses is to plot silica percentage on the abscissa and the other oxides on the ordinate as shown in Figures 10 and 11. This diagram, commonly called a silica variation diagram, was first used by Iddings (1893, pp. 173-174) and has been used by Harker (190[illegible], p. 123), Bowen (192[illegible], pp. 92-101) and many other petrologists. Some petrologists have plotted oxide ratios other than or in addition to silica on the abscissa (cf. Larsen, 1938, pp. 50[illegible]-

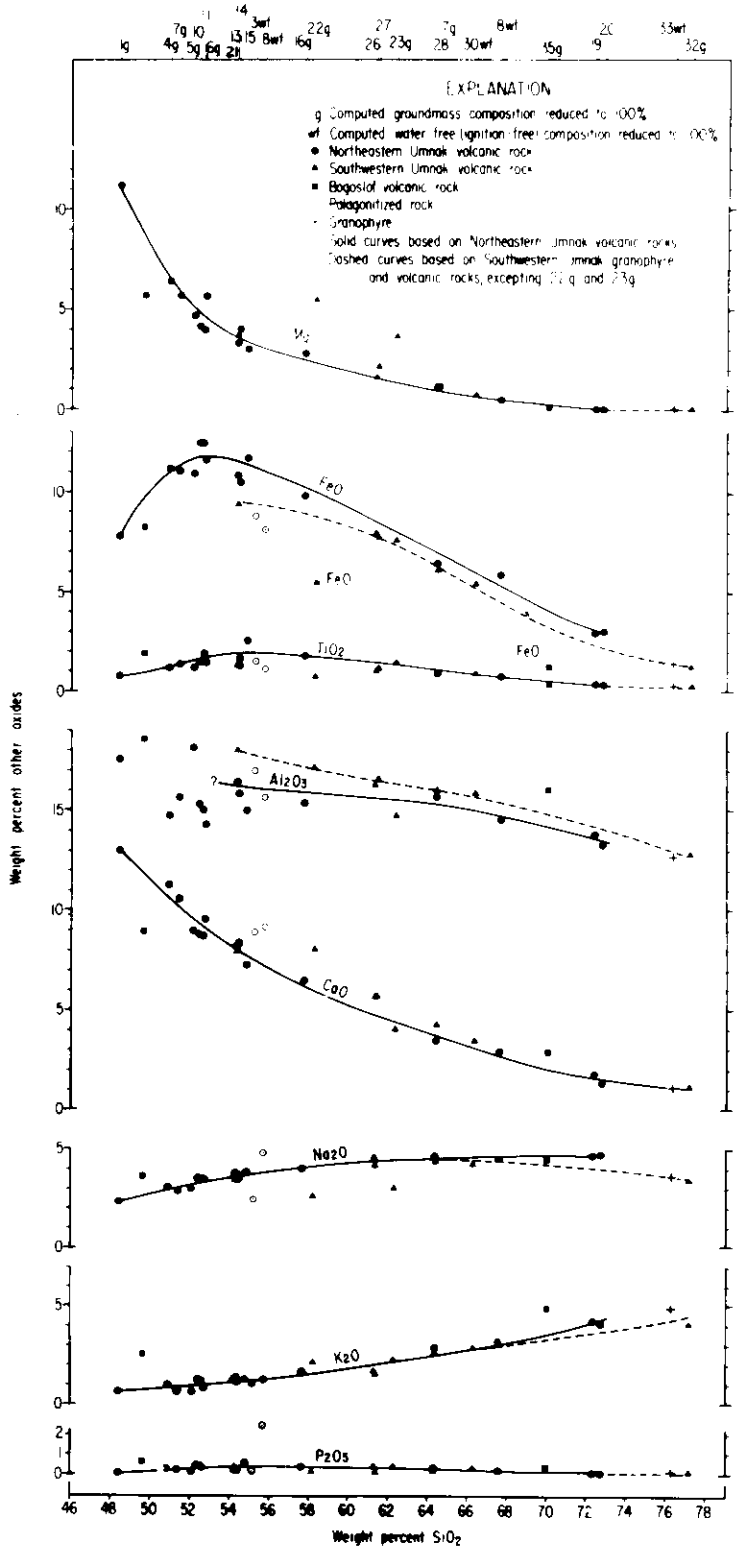

Figure 10.--Silica variation diagram of major oxides in lava groundmasses, aphyric lavas, and granophyre. Numbers at top refer to analyzed specimens (see table 7, Appendix).

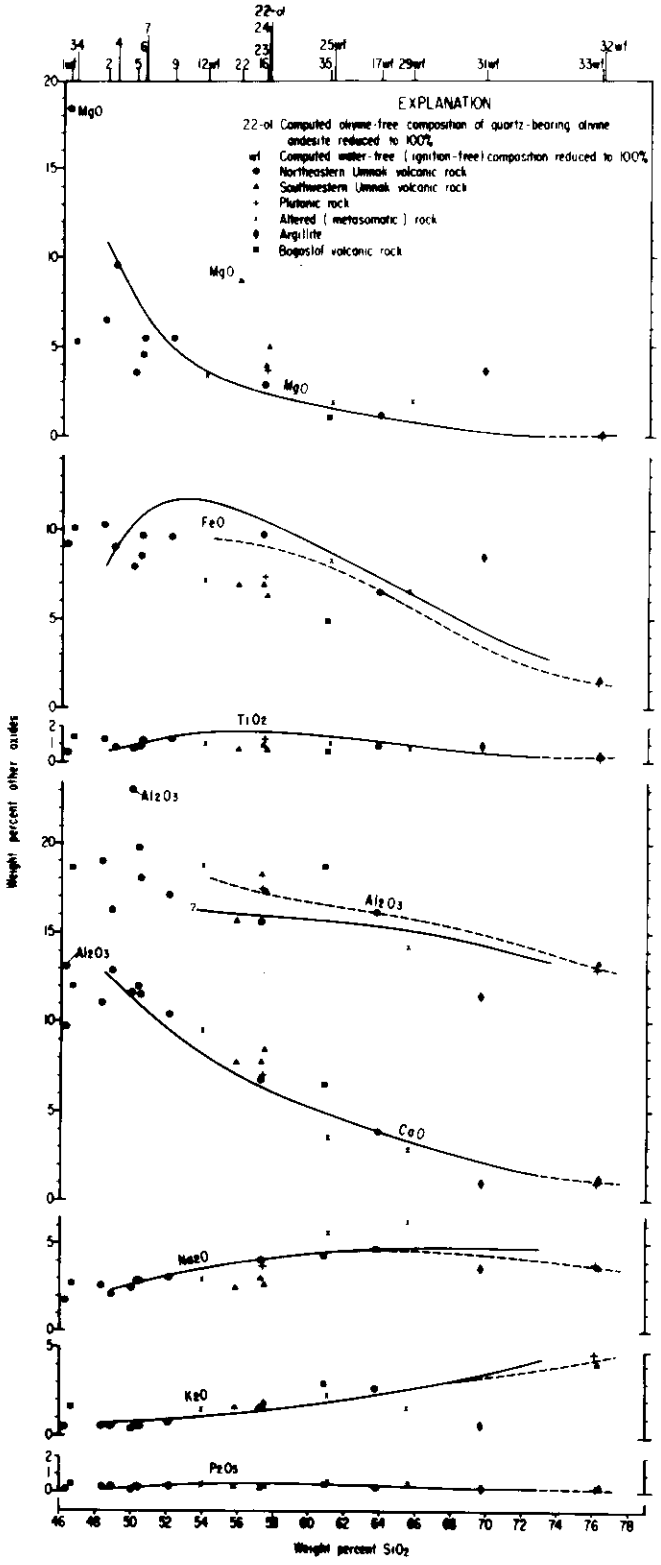

Figure 11.--Silica variation diagram of major oxides in porphyritic lavas, plutonic rocks, altered (metasomatic) rocks, and argillite. Numbers at top refer to analyzed specimens, table 7 (Appendix). Curves are same as those in figure 10.

520; Walker and Poldervaart, 1949, p. 653) though attempts to modify the straightforward silica variation diagram have drawn criticism in some quarters (cf. Nockolds and Mitchell, 1948, p. 533). The chief advantages of the silica variation diagram are its simplicity and straightforwardness, as pointed out by Bowen (1928, p. 92). The silica variation diagram serves both as a graphic presentation of the basic analytical data and as basis for theoretical discussion. The many other diagrams for representing bulk analyses of rocks that have been proposed (see review by Bacon, 1947, pp. 259-260) are in the writer's opinion more complicated and abstruse and necessitate grouping some of the constituents.

A variation diagram of aphyric lavas and computed groundmass compositions based on the bulk analyses and the petrography of porphyritic lavas is presented in Figure 10, and the diagram of porphyritic lavas and other rocks not shown in Figure 10 is shown in Figure 11. These rocks whose water-free summation deviates from 100 percent by more than 0.5 were recomputed to 100 percent before plotting on the variation diagrams.

The trend of the various oxides with respect to silica approach smooth curves far more closely in Figure 10, in which aphyric lavas and lava groundmasses are plotted, than in Figure 11, in which porphyritic lavas, altered rocks, etc., are plotted. The reasons for such behavior have been discussed by Bowen (1928, pp. 93-96); namely, the aphyric lavas and groundmasses represent quenched magmatic liquids, and hence are generally

completely gradational in composition in any one magmatic province. The trends of the various oxides are apparent from the graphs and are typical of calcalkaline rocks. Alkali-lime indices (Peacock, 1931, pp. 54-67) of Umnak-Bogoslof magmatic rocks are shown in Table 2.

TABLE 2

ALKALI-LIME INDICES OF UMNAK-BOGOSLOF MAGMATIC SUITES

	Aphyric Lavas and Groundmass of Porphyritic Lavas	Porphyritic Lavas	Plutonic Rocks
Northeastern Umnak, etc., rocks[a/]	58½	59	...
Southwestern Umnak rocks.....	61[b/]	64	61[c/]
Bogoslof rocks.....	56	59	...

[a/] Includes aphyric lavas of SW Umnak.

[b/] Includes groundmasses only of SW Umnak porphyritic lavas.

[c/] Although alkali-lime index is the same as that of the porphyritic lava groundmasses, the absolute values of alkalis and lime are somewhat higher.

The alkali-lime index of the northeastern Umnak and Mt. Vsevidof aphyric lavas and groundmasses is 58½, similar to that of a normal calcalkaline rock suite. However, the alkali-lime index of the porphyritic lavas (see Fig. 11) containing largely plagioclase phenocrysts is slightly higher. The index of the southwestern Umnak porphyritic andesite-rhyolite association is about

54, which is generally considered typical of calcic rocks of the circum-Pacific suite. It thus becomes apparent that most of the excess lime in these porphyric lavas, typical of the Pacific suite, occurs in the phenocrysts of calcic plagioclase. The alkali-lime index of the Fogoslof porphyritic lavas is about the same as that of northeastern Umnak porphyritic lavas although this apparent similarity is misleading, owing to the greater abundance of plagioclase phenocrysts in the Fogoslof lavas. The index of the Fogoslof groundmasses is lower by $2\frac{1}{2}$ than the index of the northeastern Umnak lava groundmasses.

In general, the rocks of southwestern Umnak, shown by triangles on Figures 10 and 11, are lower in iron and higher in alumina than rocks of corresponding silica content on northeastern Umnak. The strong upswing of the lime and magnesia points at the low silica end of the diagram indicates that most of the groundmasses of porphyritic (mafic) basalts of northeastern Umnak Island, are considerably more magnesic and calcic than any known aphyric lavas of Umnak. This feature of the lime and magnesia curves is also coupled with a slight downswing of the alkalis. Iron oxide and titania rise to broad maxima at 53-54 percent of silica (basaltic andesites). Phosphoric passes through a very broad maximum in the andesite range (53-60 percent of silica). The iron oxide and magnesia curves of northeastern Umnak lavas cross at 49 percent of silica, or, stated in another way, lavas and groundmasses containing less than about 49 percent of silica contain more magnesia than iron oxides. Alumina

is more erratic in distribution and tends not to fall close to smooth curves (Fig. 10), particularly in the porphyritic lavas (Fig. 11).

Certain of the rock and groundmass compositions do not fall on the smooth curves determined by most of the oxides of aphyric lavas and porphyritic lava groundmasses. The oxides of the porphyritic andesite groundmasses of southwestern Umnak (nos. 22g and 23g, Fig. 10) largely fall some distance off the curves in contrast to the approach to smooth curves of the northeastern Umnak porphyritic basalt groundmasses (nos. 1g, 4g, 5g, 6g, and 7g, Fig. 10). The oxides of the Bogoslof porphyritic basalt groundmass (no. 34g) also fall off the smooth curves like those of the porphyritic andesite groundmasses. The water-free oxide plots of the northeastern Umnak palagonites (3wf and 8wf, Fig. 10) also fall off the smooth curves. Partial analyses of three progressively altered rocks (Table 3) were made to demonstrate the trend of potassium metasomatism in "hydrothermally altered" zones of the basement volcanic complex (see Fig. 2). The numbers of these three specimens are consistent with those of Tables 7, 8, and 9 of the APPENDIX.

TABLE 3

PARTIAL ANALYSES[a] OF POTASH FELDSPATHIZED ROCKS OF THE BASEMENT VOLCANIC COMPLEX

No.	12	12A	12B
Total Fe as FeO.....	7.3	5.5	3.2
MgO.....	3.4	3.0	0.31
CaO.....	9.3	5.0	0.45
Na_2O.....	2.8	2.3	1.9
K_2O.....	1.4	2.9	5.8
Bulk specific gravity.	2.67	2.43	2.26

[a] For complete analysis of No. 12, see column 12, Table 7, APPENDIX. Alkalis of 12A and 12B, analyzed by E. J. Benton, Petrographic Laboratory, U. S. Bureau of Reclamation: total iron, lime, and magnesia of 12A and 12B, analyzed by Herbert M. Ochs, Denver, Colorado.

12--Slightly altered porphyritic basalt (47ABy44) or basaltic andesite flow collected near Inanudak Bay (Lat. 53°17.1'N, Long. 168°19.2'E).

12A--Moderately altered (uralitized, partly zeolitized) porphyritic basic lava (47ABy43A) from south side of Bottleneck Pass (Lat. 53°16.7'N, Long. 168°19.3'E) about 0.7 mile SW. of No. 12. Outcrop areas occur as "islands" in 12B

12B--Completely altered (silicified, feldspathized, zeolitized, tourmalinized) rock (47ABy43B) collected about 50 feet from 12A. Predominant rock of area.

Minor Elements

A comprehensive treatise on geochemistry by Rankama and Sahama was published in 1950 by the University of Chicago Press. Most of the comparisons made in the following discussion of minor elements are taken from Rankama and Sahama's book, which summarizes all recent literature available to the Western scientific world up to early 1948. Several more recent references have also been consulted.

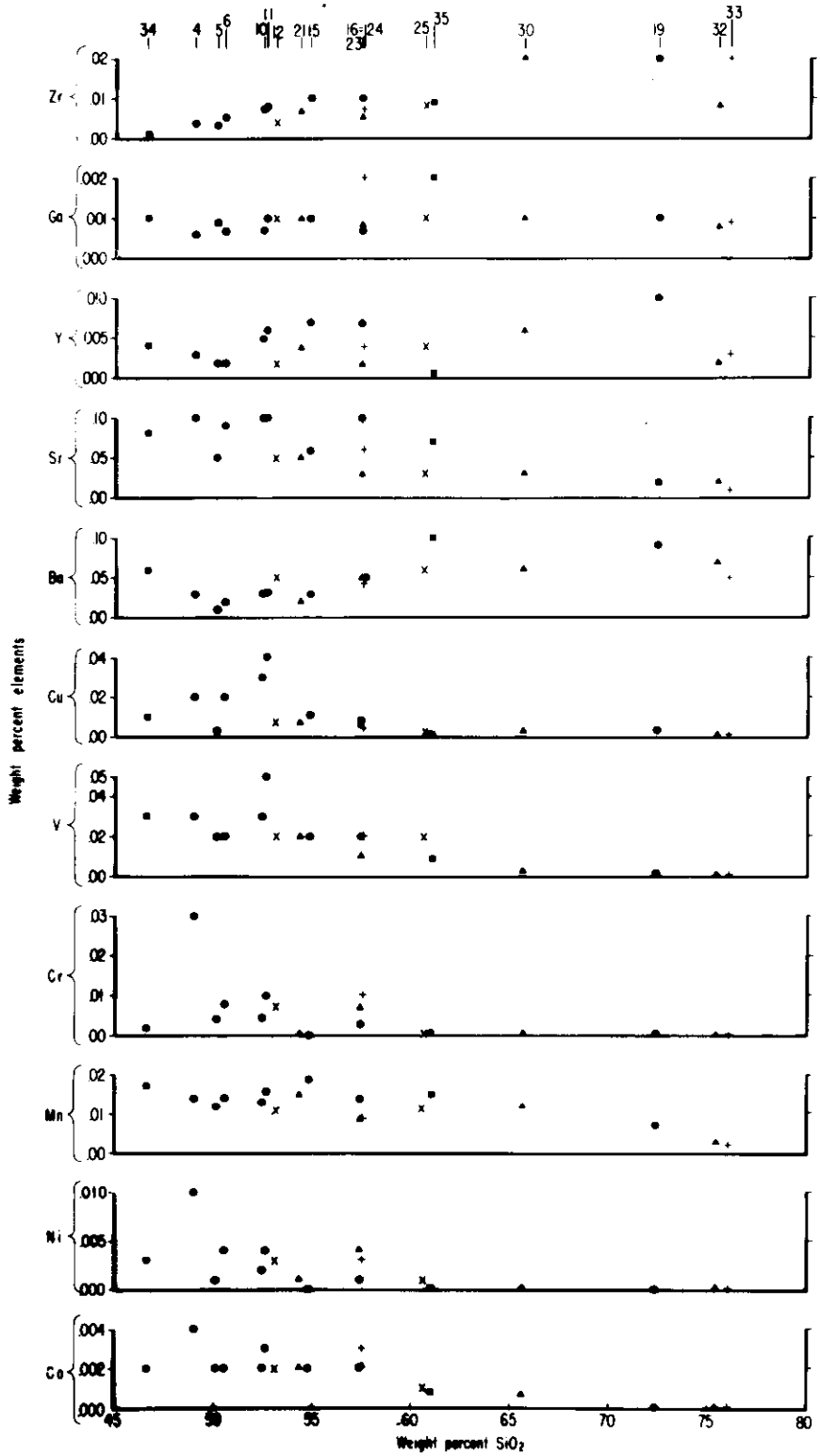

Figure 12.--Silica variation diagram of common minor elements in Umnak-Bogoslof rocks. Numbers at top and symbols are same as those in figures 10 and 11.

A silica variation diagram of most of the minor elements has been prepared (Fig. 12) similar to the variation diagram of the major oxides. This diagram shows rough approximation to geochemical variation of the elements with respect to silica content of the different rock types. Although it would have been more consistent to plot the percentages of minor elements against elemental silicon, following Nockolds and Mitchell (1948, Fig. 1), it is probably less confusing if percentage of silica is retained as a framework of reference for expressing composition of rocks. Manganese is considered as a minor element because of its low concentration in Umnak rocks and because of its tendency to diadochically replace ferrous iron, a major element. Concentrations of the different elements are shown by different symbols, corresponding to locality and genetic type as in Figures 10 and 11.

Fluorine, Chlorine, and Sulfur

The volatile elements, fluorine, chlorine, and sulfur were determined on only a few of the more siliceous extrusive rocks and the quartz diorite (nos. 24, 30, 32, and 35, Table 7). No pyrite or other sulfides were observed in any of the rocks analyzed for sulfur; the form of the sulfur in the rocks is not known. About the same quantities of these elements are present in the southwestern Umnak siliceous extrusives (nos. 30 and 32, Table 7). The quantities of each of the halogens in the quartz diorite specimen (no. 24) and in the andesine-hornblende andesite speci-

men (no. 34), are slightly greater than the sulfur. The predominance of the halogens in these two specimens is doubtless due to the presence of hornblende, and other minerals which retain the halogens, particularly fluorine, in their crystal structures.

Part of the slightly higher chlorine in the andesine-hornblende andesite specimen (35) of Bogoslof may be due in part to sodium chloride contamination from sea water. Fenner (1926, p. 706) reports 0.31 and 0.20 (0.08) percent of chlorine and sulfur trioxide (sulfur), respectively, in a specimen from the andesine-hornblende andesite dome (Harriman Alaska expedition, specimen 146, 1899), or about three times the quantities of these constituents reported in the more recent analysis by A. C. Vlisidis of the U. S. Geological Survey. The higher chlorine and sulfur found by Fenner might well be due largely to contamination by sea water if, as seems likely, a slightly vesicular specimen was collected near sea level. The Geological Survey specimen was collected from an altitude of approximately 100 feet and hence might be expected to contain less chlorine and sulfur than the specimen Fenner analyzed, if sea water contamination is largely the source of the chlorine in the specimen that Fenner analyzed.

The content of fluorine, chlorine, and sulfur, in the four Umnak-Bogoslof rock specimens are not far from the averages reported for similar rocks (Rankama and Sahama, 1950, pp. 746 and 760; data on F after Troger, 1934; data on Cl after Seliva-

nov, 1940), but much more data are needed with respect to sulfur and halogen content of extrusive rocks.

Zirconium

The maximum zirconium content of about 0.2 percent is found in the more silicious rocks of Umnak, although the southwestern Umnak rhyolite specimen (no. 32, Table 7) contains only 0.002 percent. The average Zr content of gabbros, diorites, and granites is 0.014, 0.028, and 0.046 percent, respectively (Hevesy and Wurstlin in Rankama and Sahama, 1950, p. 566). Ahrens and Gorfinkle (1950, p. 565) report about 0.01 percent in the standard diabase. No zirconium minerals were observed in any of the Umnak-Bogoslof rocks in which zirconium is reported.

Gallium

As in most magmatic provinces, gallium is rather evenly distributed throughout the rocks of Umnak and Bogoslof Islands (Fig. 12), doubtless owing to its diadochic substitution for aluminum in rock minerals (Rankama and Sahama, 1950, p. 720; Ahrens and Gorfinkle, 1950, p. 565). There is, however, a slight increase in the Ga/Al ratio in the more silicious rocks as found in general for all igneous rocks by Sandell (1949, pp. 40-49). Except for two specimens, the gallium content of Umnak rocks is within the narrow range of 0.0007-0.001 percent. In the two exceptions, quartz diorite of southwestern Umnak (no. 24, Fig. 12) and hornblende andesite of Bogoslof (no. 35), 0.002 percent of gallium is reported. The average gallium content of igneous

rocks reported by Goldschmidt (in Rankama and Sahama, 1950, p. 119) is 0.0015 percent. Ahrens and Gorfinkle (1950, p. 565) report a slightly higher value in the standard diabase, namely, about 0.002 percent.

Scandium, Yttrium, and Rare Earths

Because of the similar geochemical behavior of scandium and yttrium to the rare earths (lanthanides), these elements are all classed together, following Rankama and Sahama (1950, chap. 18). Of the rare earths, only lanthanum and ytterbium have been identified in spectrographic analyses of the Umnak rocks.

Scandium was identified in four Umnak-Bogoslof specimens (nos. 4, 24, 33, and 35, Table 7, APPENDIX) and in both augite and olivine phenocrysts of the anorthite-olivine-augite basalt specimen (no. 4) of northeastern Umnak. Scandium is taken into the lattice of augite in preference to olivine (see Table 4). The scandium ion has the same radius (0.83Å) as the ferrous ion but is trivalent. Because of the triple positive charge, the trivalent scandium ion is captured, replacing the ferrous ion in augite and other complex silicates that can balance the extra electron charge by substituting trivalent aluminum for quadrivalent silicon. In olivine, however, there are no trivalent ions to balance the excess charge of scandium and hence this replacement occurs sparingly (Nockolds and Mitchell, 1948, p. 541). The augite contains 0.01 percent of scandium, which is comparable to 0.015 percent of scandium found in pyroxenes of basic igneous

rocks by Ivar Oftedahl (in Rankama and Sahama, 1950, p. 512). The higher concentration of scandium in the Umnak quartz diorite likewise reflects the presence of plutonic ferromagnesian minerals containing aluminum, such as pyroxene, amphibole, and biotite, and is the same as reported by Goldschmidt in gabbros and by Sahama in the gabbros and dolerites of southern Lapland (Rankama and Sahama, 1950, p. 516). The lower scandium content reported in the granophyre specimen (no. 33) and in the andesine-hornblende andesite specimen (no. 35, Table 7) is of the same order of magnitude reported by Goldschmidt (in Rankama and Sahama 1950, p. 516) in granites and andesites, respectively.

Yttrium appears to be concentrated in the rhyolite obsidian (no. 19, Fig. 12) of northeastern Umnak with respect to the less siliceous rocks (Fig. 12). There appears to be no similar concentration in the rhyolite of southwestern Umnak and in general the southwestern Umnak rocks, whether volcanic, plutonic, or metasomatic, contain only about one-half as much yttrium. Yttrium is about four times as abundant in the bytownite-augite-hornblende basalt (no. 34) as in the andesine-hornblende andesite (no. 35) of Bogoslof Island. The concentration of yttrium in the Umnak-Bogoslof rocks, particularly the northeastern Umnak rocks, is five to ten times that reported in common igneous rocks by Sahama (in Rankama and Sahama, 1950, p. 527) from southern Lapland. Goldschmidt and Peters (in Rankama and Sahama, 1950, p. 527) likewise found less than 0.0008 percent of yttrium in liparites, rhyolites, and dunites. On the other hand, the average

concentration of yttrium in igneous rocks of the Dutch East Indies reported by van Tongeren (in Rankama and Sahama, 1950, p. 510) is about 0.0017 percent. There is the possibility that Aleutian rocks and possibly other high lime rocks of the circum-Pacific belt may contain slightly more yttrium than other petrographic provinces.

Lanthanum was found in only one rock, namely, the northeastern Umnak rhyolite obsidian (no. 19, Table 7, APPENDIX). This element occurs in a concentration comparable to that found by Goldschmidt in granite (Rankama and Sahama, 1950, p. 528).

Ytterbium was found in three of the Umnak rocks. The same quantity, 0.0003 percent, was found in both the quartz diorite (no. 24, Table 7) and the granophyre (no. 33, Table 7) of southwestern Umnak Island. The andesine-hornblende andesite (no. 35) contains 0.00009 percent, equivalent to the quantity found by van Tongeren (1938, p. 171) in igneous rocks of the Dutch East Indies.

Boron

Of all the minor elements detected in Umnak-Bogoslof rocks, boron may be the most significant, chiefly because of the fact that it is fairly common--as high as 4 percent of total dissolved solids--in the thermal springs and geysers of southwestern Umnak. The samples of quartz diorite (no. 24, Table 7, APPENDIX) and of the andesitic and dacitic extrusives of southwestern Umnak all contain 0.002 percent of boron, whereas the analyzed sample of the rhyolite dome (no. 32, Table 7, APPENDIX)

of southwestern Umnak contains 0.00? percent of boron. The northeastern Umnak rhyolite sample (no. 19, Table 7, APPENDIX) contains almost as much boron (0.006 percent) as the southwestern Umnak rhyolite dome, but no detectible quantities of boron (less than 0.001 percent) were found in the less silicious rocks of northeastern Umnak. Hence, boron appears to be enriched in the late differentiates of both northeastern and southwestern Umnak. However, no detectible quantity of boron was found in the granophyre associated with the quartz diorite. Nockolds and Mitchell (1948, pp. 541-542) likewise found little or no detectible boron in the Caledonian aplites but found as much as 0.006 percent in a pyroxene-mica diorite (1948, p. 539). An estimated average of about 0.5 percent of tourmaline--equivalent to slightly more than 0.01 percent of boron--is present in large volumes of hydrothermally altered rock associated with the quartz diorite, suggesting that boron was enriched in the hydrothermal solutions that escaped on crystallization of the quartz diorite. This may account for the lack of boron in the granophyre, which may have lost most of its volatiles on crystallization. The detectible presence of boron in water-rich magmatic rocks of southwestern Umnak and its non-detectible presence (less than 0.001 percent) except in the rhyolite dome in the water-poor northeastern Umnak magmatic rocks is worthy of note. It seems likely that the amount of boron in the rock may be closely related to the quantity of volatiles, chiefly water (hydroxyl) retained in the rock (cf. Nockolds and Mitchell, 1948, p. 542).

Goldschmidt and Peters (in Rankama and Sahama, 1950, p. 496) report an average of only 0.0003 percent of boron in German granites and gabbros whereas Lundegardh (in Rankama and Sahama, 1950, p. 485) report 0.003 percent of boron in igneous rocks of Sweden. As Rankama and Sahama (1950, p. 495) point out, considerable variation in the boron content of the sialic crust is probably the rule. This variation is probably due to the extent to which boron, like water, is retained in the magmatic fluids and would be expected, considering the small ionic radius (0.23Å) of boron.

Beryllium

Beryllium was found in only one rock--the rhyolite obsidian (no. 19, Table 7, APPENDIX) northeastern Umnak, which contains 0.0005 percent. This quantity is approximately the same as reported by various investigators (in Rankama and Sahama, 1950, p. 444) in silicious igneous rocks.

Strontium and Barium

Strontium and barium were found in detectible quantities in practically all rocks and minerals analyzed for these elements. As can be seen in Figure 12, strontium, like calcium, tends to decrease with increasing silica content of the rocks, although there is some variation among the less silicious rocks. Barium, on the other hand, tends to increase with increasing silica content. A slightly higher concentration of barium is present in the two Bogoslof rocks (nos. 34 and 35, Fig. 12) than in Umnak

rocks of similar composition and is paralleled by the higher potassium content of the Bogoslof rocks (see Table 7, APPENDIX). The granophyre of southwestern Umnak (no. 33, Fig. 12) has slightly less strontium and barium than either of the rhyolites, although its potassium content is higher.

Plots of strontium against calcium and barium against potassium in the rocks are shown in Figures 13 and 14, respectively. An approximate positive correlation between these groups is indicated, although there is increasing spread as the amount of the major element increases. The Sr/Ca ratio of the northeastern Umnak basic rocks appears to be about twice that of the southwestern Umnak basic rocks. The Ba/K ratios of Bogoslof rocks are slightly higher than those of Umnak rocks. The plutonic rocks have about one-half the Ba/K ratio of the lavas. Rankama and Sahama (1950, p. 475) note a similar relationship with respect to total strontium. Hence, strontium and barium are probably poor criteria for correlating a plutonic rock with an effusive that is chemically similar with respect to major oxides.

Olivine phenocrysts in the analyzed anorthite-olivine-augite basalt specimen (no. 4, Table 7) of northeastern Umnak contain 0.002 percent of barium but no detectible strontium (Table 4). This concentration of barium, if actually present in the crystal structure, cannot be readily explained; these olivine phenocrysts also contain 0.1 to 0.3 percent of calcium. The diopsidic augite phenocrysts (Table 4) contain slightly less strontium and barium than the rock itself (no. 4, Fig. 12).

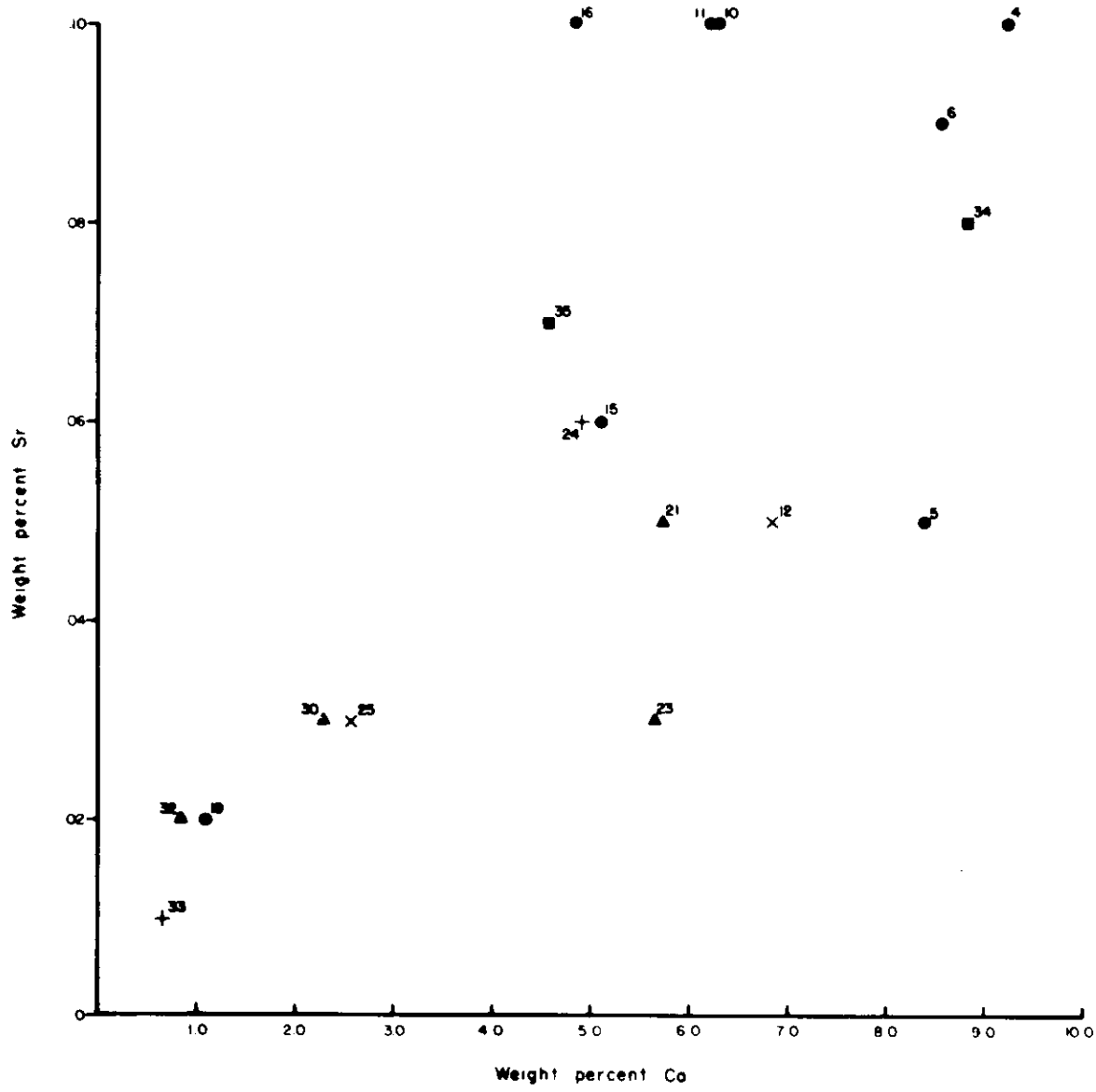

Figure 13.--Plots of strontium against calcium. Numbers and symbols are same as those in figure 12.

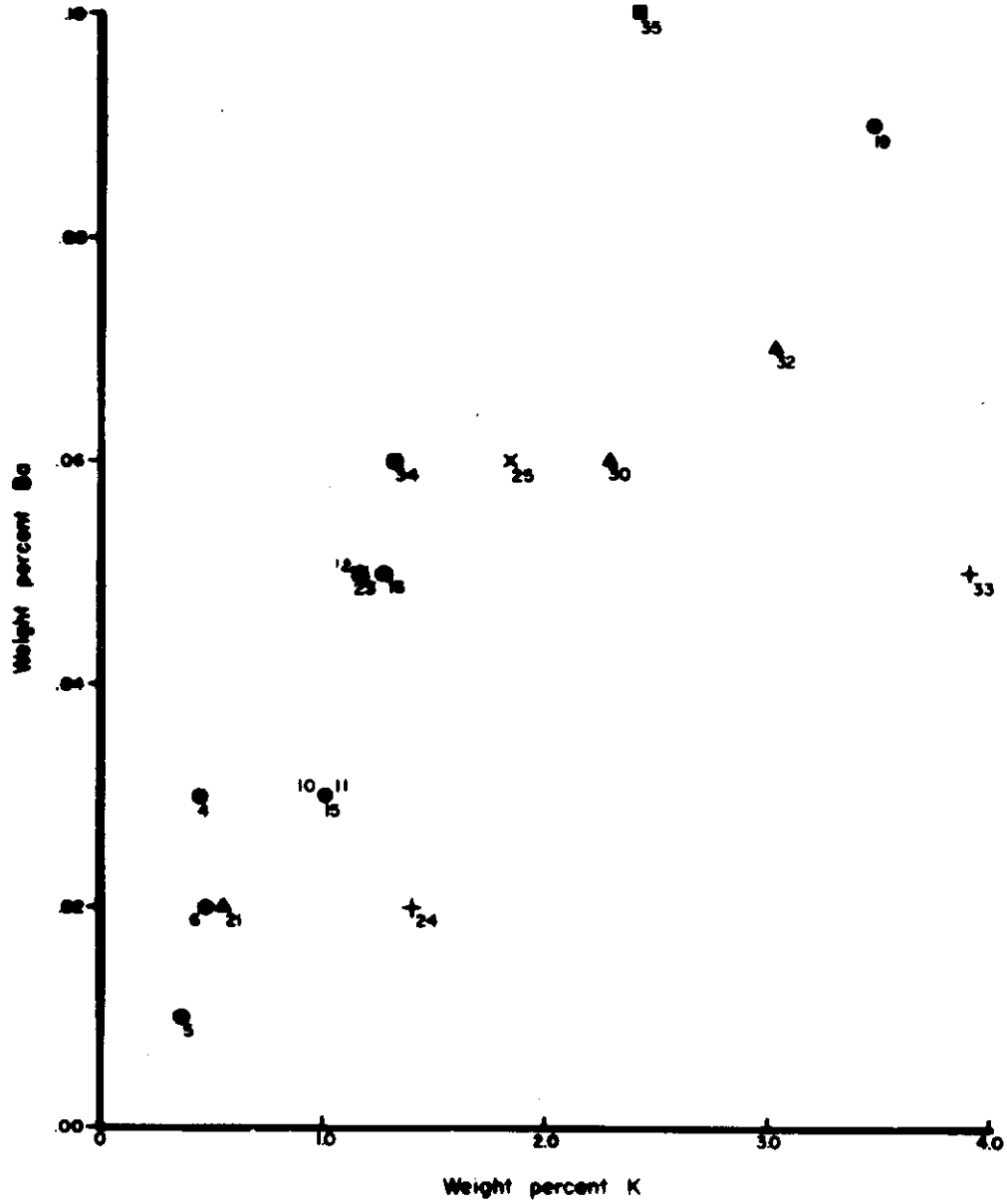

Figure 14.--Plots of barium against potassium. Numbers and symbols are same as those in figure 12.

Hence, strontium and barium were probably not enriched in the early precipated mafic phenocrysts of northeastern Umnak basaltic magmas. Anorthite phenocrysts from one of the anorthite basalt flows of northeastern Umnak (Table 4) contain, surprisingly enough, no more strontium and considerably less barium than the northeastern Umnak aphyric basalts (nos. 10 and 11, Fig. 12).

TABLE 4

QUANTITATIVE SPECTROGRAPHIC ANALYSIS FOR MINOR ELEMENTS IN PHENOCRYSTS FROM TWO PORPHYRITIC BASALTS OF NORTHEASTERN UMNAK

(Janet D. Fletcher, spectrographer)

	1 Anorthite	2 Augite	3 Olivine[a]
Cu.....	.004	.002	.002
Mn.....	.006	.06	.2
Co.....	.....	.003	.02
Ni.....	.0003	.01	.1
Cr.....	.0004	.2	.06
V.....	.....	.03	.....
Ti.....	.01	.2	.01
Zr.....	.....	....	.001
Sr.....	.1	.02	.....
Ba.....	.006	.006	.002
Sc.....	.....	.01	.0004
Ga.....	.0006	....	.....

Looked for but not found: Be, Ag, Mo, W, Ge, Sn, Pb, As, Sb, Bi, Zn, Cd, Tl, Y, La, Th, Nb, Ta, U, B.

[a] 0.1 to 0.3 percent of Ca is also present.

1. Anorthite phenocrysts in anorthite basalt flow (no. 5, Table 7, APPENDIX).

2, 3. Augite and olivine phenocrysts in anorthite-augite-olivine basalt flow (no. 4, Table 7, APPENDIX).

Strontium and barium are present in Umnak-Bogoslof rocks in concentrations generally exceeding average concentrations found in many calcalkaline rocks tabulated by Rankama and Sahama (1950, p. 476). Their averages, however, are based on analyses of rocks from shield areas and stable continental platforms. Concentrations of these elements, similar to those in Umnak-Bogoslof rocks, are also found in the rocks of Adak and Kanaga Islands (Coats, 1952, pp. 508-509). Strontium and barium, like calcium, may be present in slightly greater concentrations in rocks of the Aleutian Island arc than in older mountain chains, and this relationship may hold for circum-Pacific rocks in general.

Lead

Lead was detected in only the aphyric andesite (no. 15, Table 7, APPENDIX) and the rhyolite obsidian (no. 19, Table 7) of northeastern Umnak. In viewing the scanty data with geologic occurrence, it seems possible that lead is progressively enriched in magmatic liquids, indicated by the lava sequence aphyric basalt-aphyric andesite-vitreous latite-rhyolite obsidian. Strangely enough, no lead was detected in the silicious rocks of southwestern Umnak, though 0.0001 percent of lead was detected in dried salts from a boriferous spring of southwestern Umnak--equivalent to two parts per billion in the spring water (Byers and Brannock, 1949, p. 732). The content of lead in the northeastern Umnak rhyolite obsidian is somewhat higher than that

found by Sandell and Goldich (1943, pp. 110, 170) in most granitic rocks of central United States. Nockolds and Mitchell (1948, p. 571) report as much as 0.01 percent of lead in potash feldspar. The enrichment of lead in the siliceous rocks follows that of potassium in potash feldspar, owing to the similarity in size of their ionic radii (1.33Å) (Sandell and Goldich, 1943, p. 169).

Molybdenum

Molybdenum was found in only two rocks: the quartz diorite sample (no. 24, Table 7, APPENDIX) from southwestern Umnak and the Bogoslof andesine-hornblende andesite sample (no. 35, Table 7), in which the presence of molybdenum may be due to the presence of sphene (Nockolds and Mitchell, 1948, p. 549). Tetravalent molybdenum (0.68Å) apparently substitutes for tetravalent titanium (0.64Å). In two samples of dried salts from two thermal springs of southwestern Umnak, 0.002 and 0.004 percent of molybdenum were detected, respectively, corresponding to 5 parts per billion in each spring (Byers and Brannock, 1949, p. 732). The concentrations of molybdenum found in the two Umnak rocks are within the range of molybdenum contents found by Sandell and Goldich (1943, p. 168) in siliceous rocks of central United States. According to the data of Sandell and Goldich (1943, Fig. 11), molybdenum becomes enriched in siliceous rocks. But Nockolds and Mitchell (1948, pp. 538, 753) detected this metal only in the most subsiliceous rocks.

Copper

Copper is most abundant in the two aphyric basalts (nos. 10 and 11, Fig. 12) and a porphyritic basalt of Okmok Volcano, reaching a maximum of 0.04 percent in the upper analyzed aphyric basalt flows of Okmok Volcano. A similar flow of Okmok Volcano has a conspicuous, bright green surface stain of chrysocolla. Other basic rocks of Umnak and Bogoslof Islands (see Fig. 12) contain 0.01 percent or slightly less of copper, and the copper content decreases markedly with increasing silica content. The rhyolite obsidian of northeastern Umnak (no. 14, Fig. 12) with 0.008 percent copper contains ten times the amount found in the southwestern Umnak rhyolite and granophyre. Thus, there seems to be considerably more copper in the volcanic rocks of Okmok Volcano than in igneous rocks of southwestern Umnak, though the contrast is less marked in the andesite range. The sulfur-rich volcanic emanations of Okmok Volcano are consistent with the high copper content of the basalts, because it is reported that the copper in igneous rocks, mainly basalts, largely exists as sulphides (Newhouse, Ramdohr in Rankama and Sahama, 1950, p. 697; Sandell and Goldich, 1943, p. 175; Wager and Mitchell, 1951, pp. 190-191).

That copper also enters the mafic minerals of the basalts to a limited extent is demonstrated by copper contents (0.002 percent) of the augite and olivine phenocrysts of the anorthite-augite-olivine basalt (see Table 4). The copper reported in the anorthite phenocrysts (Table 4) may be from minute inclusions

of opaque oxides as was suggested by Nockolds and Mitchell (1948, pp. 569-570).

The copper content of the two samples of aphyric basalts from Okmok Volcano (nos. 10 and 11) is considerably above the average content of copper (0.0149 percent) in subsilicic rocks (Sandell and Goldich, 1943, p. 175) and is slightly above the copper content of Keweenawan diabases analyzed by Grout (in Sandell and Goldich, 1943, p. 174).

Vanadium

As can be seen from Figure 12, vanadium shows a consistent decrease with increasing silica content of the rocks. A maximum of 0.05 percent vanadium was found in one of the analyzed aphyric basalt flows (no. 11, Fig. 12) of Okmok Volcano. There is no apparent geographic distribution of the vanadium in Umnak-Bogoslof rocks. In the augite phenocrysts of the anorthite-olivine-augite basalt flow (no. 4), 0.03 percent of vanadium was found (Table 4), essentially equivalent to the vanadium content of the basalts. Wager and Mitchell (1951, p. 186) likewise found 0.03 percent of vanadium in the early formed pyroxenes of the Skaergaard intrusion, East Greenland.

In Figure 15, a plot of vanadium against total iron (as FeO) shows that in general vanadium tends to increase in the rocks with increasing iron. This is probably due to the fact that vanadium occurs principally with the opaque oxides (Hankama and Sahama, 1950, p. 598). The vanadium content of the Umnak-Bogoslof basalts is about the same as that reported by Lunde-

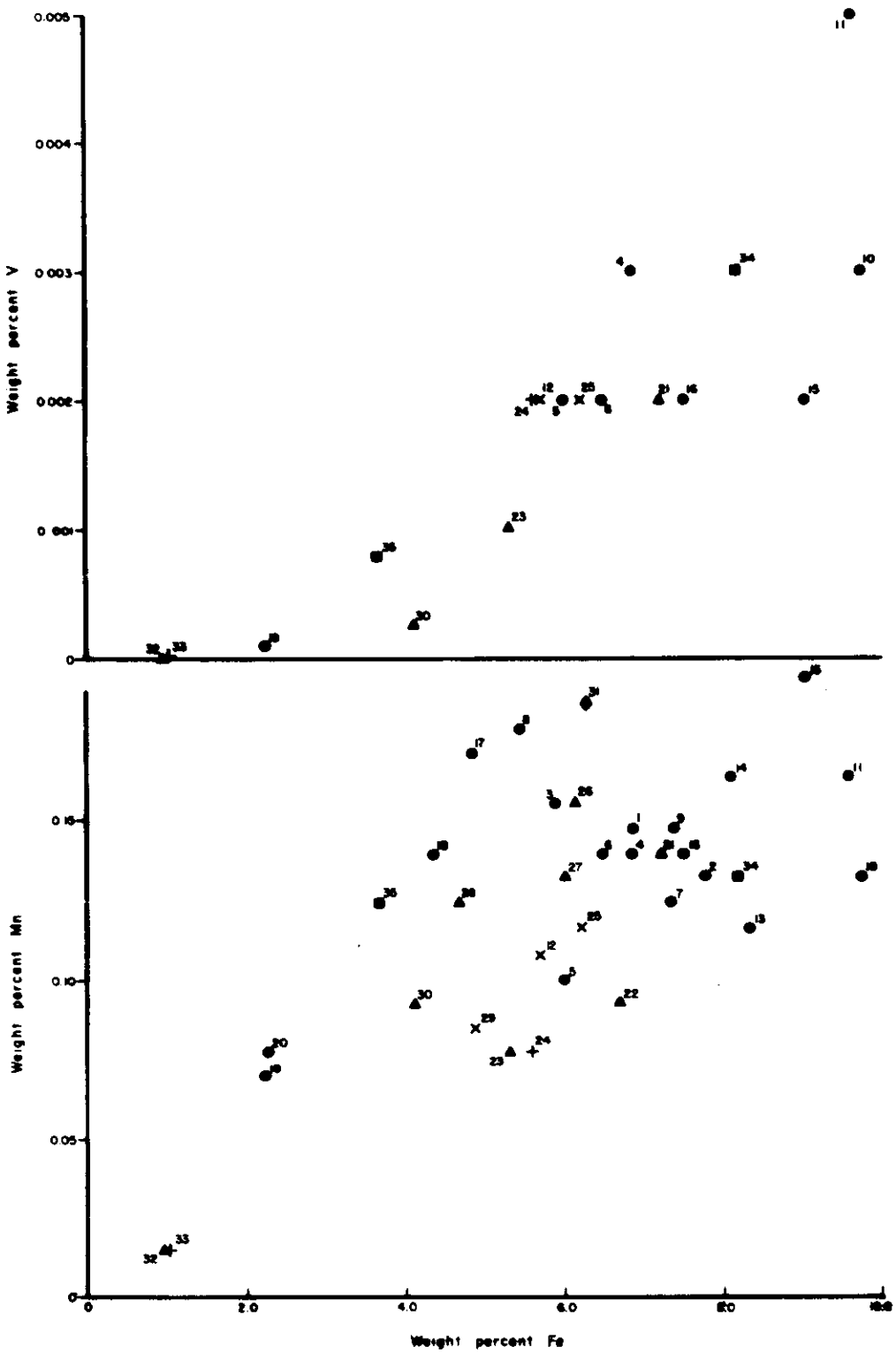

Figure 15.--Plots of vanadium and manganese against total iron. Symbols and numbers are same as those used in figure 12.

gardh in the basic igneous rocks of central Roslagen, Sweden (Rankama and Sahama, 1950, p. 596).

Chromium

In the silicious rocks of Umnak and Bogoslof chromium is in very low concentrations (Fig. 12). In the basalts and andesites of Umnak the distribution and concentration of chromium appears somewhat erratic. The maximum percentage of 0.01 is contained in one of the analyzed aphyric basalts (no. 11, Fig. 12) of Okmok Volcano and in the quartz diorite (no. 24) of southwestern Umnak. The basaltic andesite of Mt. Vsevidof (no. 21), however, contains barely detectible quantities of chromium, and the analyzed, northeastern Umnak vitreous andesite (no. 15) contains no detectible quantity of chromium (less than 0.0001 percent). This vitreous andesite contains relatively high iron and titania like the Skaergaard intermediate rocks, which likewise do not contain detectible quantities of chromium (Wager and Mitchell, 1951, pp. 183-84).

The distribution of chromium in the Umnak-Bogoslof subsilicious rocks probably reflects several different geochemical laws. According to Rankama and Sahama (1950, pp. 621-22) chromium enters the structure of many ferromagnesian minerals of petrologic importance, the amount depending on the temperature, pressure, and degree of consolidation of the magma. The early magnesian olivines are generally rich in chromium, but the later-formed, iron-rich olivines contain barely detectible amounts.

According to Rankama and Sahama (1950, pp. 621-622) diadochic replacement of aluminum by chromium (and ferric iron) seems to be possible only if Al forms (AlO_6) groups in the ferromagnesian structure and does not occur in (AlO_4) groups, in which aluminum replaces silicon. This principle is believed demonstrated by the high chromium content (0.2%) of the analyzed augite phenocrysts of the anorthite-augite-olivine basalt (see Table 4). The 6 percent of alumina in this augite (see Table 2) must therefore contain the 0.2 percent of chromium, which is equivalent to approximately $3\frac{1}{2}$ "atoms" in the $48\frac{1}{2}$ "atoms" regarded as alumina in the WXY group (see Table 2). Nockolds and Mitchell (1948, p. 572) and Wager and Mitchell (1951, p. 183) report similar high concentrations of chromium in the early-formed pyroxenes. The olivine phenocrysts from the same augite-olivine-basalt contains significantly less chromium, namely 0.06 percent (see Table 4), owing to the fact that trivalent ions are not readily admitted or captured by the olivine lattice. The distribution of chromium between the augite and the olivine in this anorthite-augite-olivine basalt is in accordance with the observation of Rankama and Sahama (1950, p. 622) that chromium tends to be enriched in the clinopyroxene when magnesium-rich olivine and clinopyroxene occur together.

The chromium content of the Umnak-Bogoslof subsilicious rocks is one-eighth to one-half the averages reported in igneous rocks by several investigators cited by Rankama and Sahama (1950, p. 619).

Manganese

Manganese, although ordinarily determined in the analysis of major oxides, is here treated as a minor element, because of its small concentration in Umnak rocks and its tendency to diadochically replace iron in ferromagnesian silicates. In Figure 12 manganese, like iron, tends to decrease with increasing silica content of the rocks. In Figure 15 total manganese is plotted against total iron. Manganese appears to increase roughly with increasing iron. The presence of manganese in the plagioclase feldspar (see Table 1), like copper, is believed due in part to opaque oxide inclusions and perhaps also due to a slight tendency for bivalent manganese (0.91Å) to substitute for sodium (0.98Å) and calcium (1.06Å) as suggested by Nockolds and Mitchell (1948, pp. 569-570).

However, the curve is not quite a straight line, for the Mn/Fe ratio increases slightly from about 0.019 in the subsilicious Umnak-Bogoslof rocks to about 0.03 in the silicious rocks. Similar behavior and concentrations of manganese in igneous rocks are reported by Rankama and Sahama (1950, p. 643).

Nickel and Cobalt

As elsewhere, nickel and cobalt occur in greater concentration in the subsilicious rocks of Umnak and Bogoslof Islands. These elements reach maximum concentrations of 0.004 and 0.002, respectively, in the basaltic rocks (Fig. 12). The Co:Ni ratio ranges from one-half in those basalts and andesites rich in

nickel to greater than 80 in the analyzed vitreous andesite (no. 15, Fig. 12), which contains nearly as much cobalt as any subsilicious rock but, strangely enough, no detectible nickel (see no. 15, Table 7, APPENDIX). In the intermediate to silicious rocks (andesine-hornblende andesite, no. 35, and rhyodacite, no. 30) cobalt is present in one order of magnitude over nickel (Co/Ni ratio = 10). Equal amounts of nickel and cobalt just at the limits of detection were found in the granophyre (no. 33, Table 7), but neither element was found in the Umnak rhyolites (nos. 19 and 32, Table 7). Thus, while both tend to decrease in general with increasing silica, cobalt appears to decrease less rapidly in the silicious andesite to rhyodacite range, like the behavior of iron with respect to magnesium. This trend in the Co:Ni ratio is also similar to that found by Wager and Mitchell (1951, p. 139) in successive layered rocks of the Skaergaard intrusion.

In efforts that have been made to simplify the geochemistry of nickel and cobalt, many conflicting statements have appeared in the literature (Rankama and Sahama, 1950, pp. 682-683). In order to explore more fully the occurrences of nickel and cobalt with respect to iron and magnesium four plots are shown in Figure 16: nickel-magnesium, nickel-total iron, cobalt-magnesium, and cobalt-total iron.

A good linear correlation exists between cobalt and magnesium, and fair linear correlations are indicated for cobalt-iron and nickel-magnesium. The linear correlation indicated

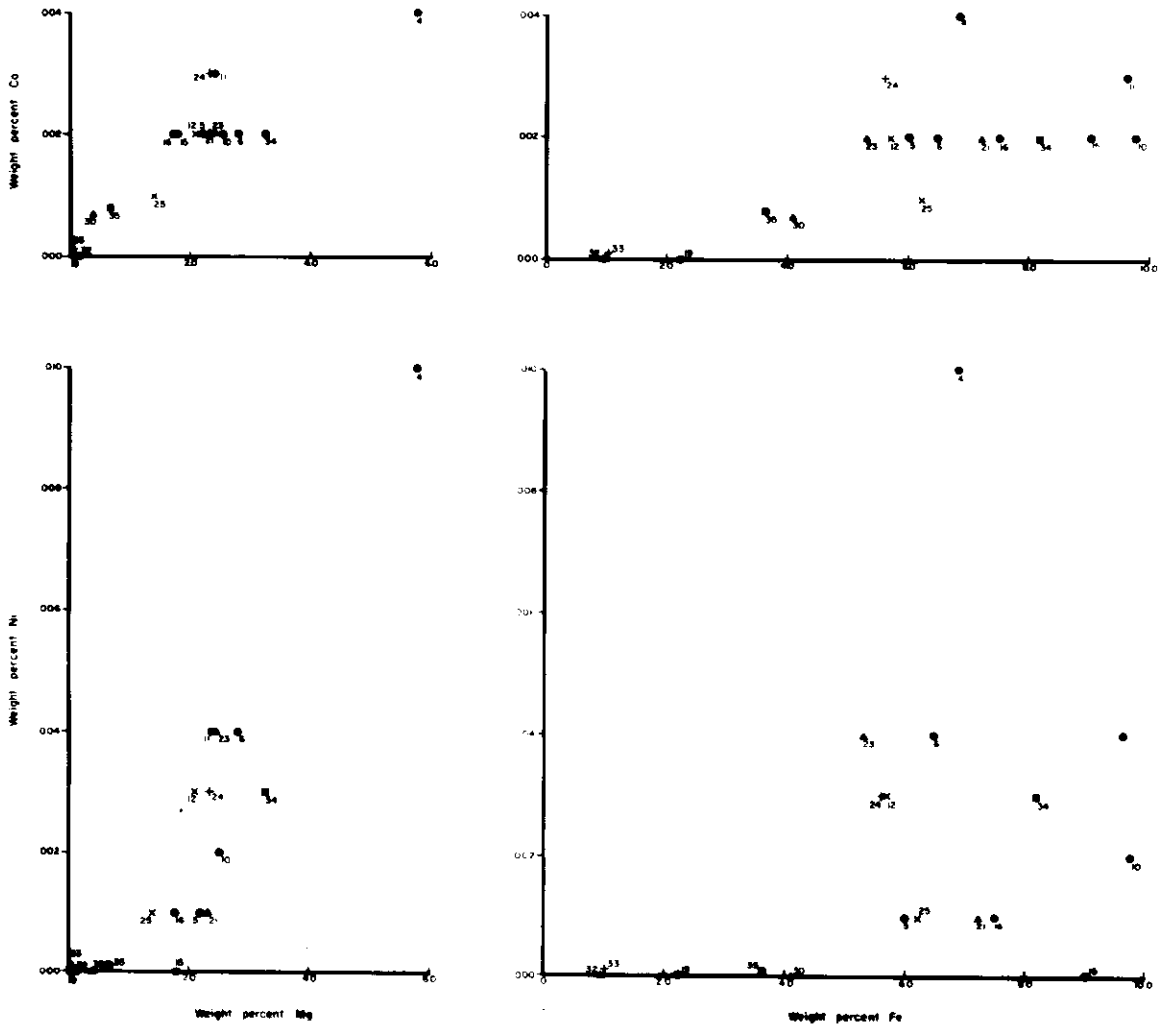

Figure 16.--Plots of nickel:magnesium, cobalt:magnesium, nickel:iron, and cobalt:iron. Symbols and numbers are same as those used in figures 10, 11, and 12.

between cobalt and magnesium agrees fairly well with that found by Sandell and Goldich (1943, p. 176) for igneous rocks (United States) investigated by them.

As can be seen in Figure 16, nickel is much more erratic in its distribution with respect to iron than is cobalt. The wide scattering of points in the nickel-iron plot indicates scarcely any simple relationship between nickel and iron other than the iron-poor rocks contain the lowest amounts of nickel, probably because these rocks contain little magnesium. The complete absence of detectible amounts of nickel (0.0001%) in the analyzed vitreous andesite (no. 15, Table 7) which contains 11.59 percent of total iron as FeO and 2.48 percent of TiO_2 is, as with chromium, analogous to the barely detectible amount of nickel found in intermediate rocks of the Skaergaard intrusion (Wager and Mitchell, 1951, p. 188).

Addition information on the distribution of nickel and cobalt in the Umnak rocks is gained by the presence of both these elements in the augite and olivine phenocrysts of the anorthite-augite-olivine basalt (see Table 4). Nickel and cobalt are enriched in the olivine phenocrysts in concentrations on order of magnitude greater than those in Umnak-Bogoslof subsilicious rocks. Nickel is also in somewhat greater concentration in the augite than in any Umnak-Bogoslof rock, but cobalt is in about the same concentration as in the subsilicious Umnak rocks. That nickel is enriched with respect to cobalt in the early ferromagnesian crystallates of the Umnak rocks is indicated by the low Co:Ni

ratios of 0.2 and 0.3 in the olivine and augite, respectively.

To summarize, nickel and, to much less extent, cobalt tend to be concentrated in the Umnak-Bogoslof basalts, and probably in the low-iron andesites of southwestern Umnak Island. Nickel, however, rapidly falls off to 0.0001 per cent or less in the iron-titanium-rich andesites and more silicious rocks, whereas cobalt falls off less rapidly, resulting in Co:Ni ratios of greater than 20 in the iron-rich andesites. Cobalt shows a fairly regular increase with increasing magnesium and iron, but nickel is more sporadic, particularly with respect to iron in the andesite range. The closer geochemical association of cobalt and iron than of nickel and iron is believed due to the following geochemical laws:

1. Perhaps the most important are (a) the ease with which the cobaltous ion is oxidized to cobaltic ion, like iron but unlike nickel and magnesium, and (b) the similarity in size of the resulting cobaltic ion (0.65Å) with the ferric ion (0.67Å) so that the cobaltic ion would continue to diadochically replace iron as ferric ion in crystal structures.

2. The radius of both the cobaltous and ferrous ion is 0.83Å, whereas that of nickel is 0.78Å, but this difference probably does not cause much geochemical differentiation of nickel and cobalt.

Niobium (Columbium)

In the sample of quartz diorite (no. 24, Table 7, AP-

PENDIX), 0.002 percent of niobium (columbium) was detected. This is the same concentration reported by Goldschmidt (in Rankama and Sahama, 1950, p. 606) in the average diorite, and slightly more than twice the average given by van Tongeren (1949, p. 178) for the East Indian rocks. As pointed out by Rankama and Sahama, niobium (columbium) occurs in some biotites, and it seems plausible that the niobium (columbium) in the quartz diorite is probably in the 8 percent of biotite (no. 24, Table 7, APPENDIX) contained therein.

CLASSIFICATION AND NAMING OF THE ROCKS

The problem of naming extrusive rocks, particularly those from the circum-Pacific belt, is all the more complex, when their petrochemistry is compared with their petrography. Whereas many of the classifications proposed are consistently logical in themselves (e.g., Johannsen, 1939, pp. 141-161) and may afford a convenient means for naming rocks in the field, yet most fail to distinguish between distinct genetic types in any one area and commonly lead to an absurd arrangement when the chemical character of the rocks becomes known. Petrographic classifications alone are not applicable to a volcanic suite, such as the Umnak-Bogoslof rocks, many of which are glassy and incompletely crystalline. Chemical classifications that have been proposed fall short in that they take no account whatsoever of the petrography of the rock and commonly do not lead to a familiar rock name.

The ideal classification is perhaps a combined mineralogical and chemical classification that can be applied with nearly consistent results to both the crystalline intrusive rocks and the incompletely crystalline volcanic rocks. An attempt at such a classification, presented in Table 5, is based on earlier classifications by Chand (1927, pp. 152 and 185, and 1947, pp. 206-245). This classification is a further refinement of the Chand classification in that it more strictly defines Chand's

TABLE 5

CLASSIFICATION (MODIFIED AFTER SHAND, 1924, AND 1947) OF UMNAK-BOGOSLOF CALC-ALKALINE IGNEOUS[a] ROCKS

1	2		3
Approximate Silica Saturation[b]	Feldspar[c]		Rock Name Suggested by Shand[d]
Quartz (Q) or Olivine (Ol), Nepheline (Ne)	Or, Ab, and An		volcanic / plutonic
Oversaturated Rocks +20% Q	Or>Ab		potash rhyolite / potash granite
	Or>An	Ab>Or, Or>3An	soda rhyolite / soda granite
		Ab>Or, 3An>Or	rhyodacite / granodiorite
	An>Or	Ab>An	soda dacite / soda tonalite
		An>Ab	lime dacite / lime tonalite
Transitional or Intermediate Rocks +5% Q to +20% Q	Or>Ab		[d] (quartz) potash trachyte / (quartz) potash syenite
	Or>An	Ab>Or, Or>3An	(quartz) soda trachyte / (quartz) soda syenite
		Ab>Or, 3An>Or	(quartz) trachyandesite / (quartz) monzonite
	An>Or	Ab>An	(quartz) soda andesite / (quartz) soda diorite
		An>Ab	(quartz) lime andesite / (quartz) lime diorite
Saturated Rocks ±0% Q[b] to ±5% Q	Or>An		trachyte, latite, rare types / syenite, monzonite, rare types
	An>Or	Ab>An	soda basalt / soda gabbro
		An>Ab	lime basalt / lime gabbro
Undersaturated Rocks - Q = Ol + Ne	An>Or	Ab>An	soda subbasalt / soda subgabbro
		An>Ab	lime subbasalt / lime subgabbro

TABLE 5--Continued

4	5		6		7	8
Rock Names Applied to Umnak-Bogoslof Rocks[e/]	Average Quartz Content (Fe + Cl = -4)		Average Color Index[1/]		Number of Chemical Analyses	Average silica content
volcanic / plutonic	Molecular norm	Volume pct. (modal) (Fe + Cl = -4)	Molecular norm	Volume pct. (mode)		
---						
granophyre	33	26	3	3	1	76.0
rhyolite	28	n.d.	4	n.d.	3	73.5
---						
rhyodacite	20	n.d.	10	n.d.	2	65.2

---						
latite	15	n.d.	13 1/2	n.d.	2	64.0
quartz monzonite	--	16	--	12	0	--
andesite g/, basaltic andesite	9	n.d.	24	n.d.	8	57.3
quartz diorite, diorite	8	10	22	19	1	57.3
h/ andesite	8	n.d.	29 1/2	n.d.	2	56.7

---						
aphyric basalt	4	n.d.	34	n.d.	2	52.5
diorite or andesine gabbro(?) i/	--	--	--	--	0	--
plagioclase, augite basalts	1	n.d.	31	n.d.	4	50.9

---						
hornblende, olivine basalts j/	-13	-10[k/]	43	n.d.	4	47.4

Footnotes to Table 5:

[a] Palagonitized, albitized, and hydrothermally altered rocks are excluded from this classification.

[b] According to molecular percentage of quartz or olivine plus nepheline in molecular norm (Niggli, 1936, pp. 295-317; Barth, 1945, pp. 11-13). In absence of chemical analysis, modal quartz, if present, or modal olivine can be used. Some flexibility is taken in the use of olivine as a means of separating saturated from undersaturated rocks, owing to tendency of olivine in some rocks to separate in excess of its stoichiometric ratio (Bowen-Andersen effect).

[c] Computed from molecular norm in case of fine-grained volcanic rocks and from mode in case of coarse-grained intrusive rocks.

[d] "Quartz" would be added as modifier of transitional rocks, where in excess of 5 percent in the mode.

[e] Mineral modifiers are used for rocks in which phenocrysts or significant minerals (e.g. quartz or olivine) exceed 5 percent by volume (cf. Johannsen, 1939, pp. 141-161). Significant or unusual minerals in quantities less than 5 percent are hyphenated with "bearing."

[f] Molecular percent of heavy minerals (incl. C and Ap) in molecular norm, or volume percent of heavy minerals (greater than a specific gravity of 2.8; Chand, 1947, p. 233) in mode of coarse-grained intrusive rocks.

[g] Also includes the andesine-hornblende andesite dome of Vogoslof.

[h] Includes the analyzed hypersthene-bearing labradorite andesite of Mount Recheschnoi and the quartz bearing olivine andesite.

[i] A few of the Umnak rocks--probably not exposed--may belong here. For discussion of this group, see text.

[j] Includes olivine basalt, plagioclase - olivine basalt, anorthite - augite - olivine basalt, and bytownite - salite - hornblende basalt.

[k] Does not include slight amount (<1%) of modal olivine in groundmasses of Umnak olivine basalts.

transitional or intermediate rock group with lower and upper limits of 5 and 20 percent of excess quartz (modal or normative), respectively. Such a classification based on excess quartz or silica content is best suited to an igneous rock suite of an orogenic belt, such as the Aleutian volcanic arc. The rock names suggested by Shand, indicated in the third column of Table 5, are included as a general frame of reference; most petrographers favor the use of mineral modifiers to chemical modifiers in describing rocks (cf. Wenk, 1946, p. 286). The arbitrary divisions between the different categories are based on the molecular norm of Niggli (1936, pp. 295-317) in the case of the incompletely crystalline rocks or on the mode in the case of the crystalline rocks. As emphasized by Barth (1945, pp. 11-13) the molecular norm of Niggli generally agrees closely with the (volumetric) mode as determined in thin section. Essentially all petrographers are agreed that volumetric proportions of minerals, rather than weight percent, should be used in classifying a rock (cf. Shand, 1947, p. 235; Johannsen, 1931, p. 151).

Distinction between Andesite and Basalt

Many workers have found difficulty in classifying circum-Pacific or other rocks of high lime content, particularly if a classification based on plagioclase feldspar is used (cf. Wenk, 1946, p. 284). As early as 1900 Josiah Spurr, a pioneer Alaskan geologist, felt the necessity of making a new classification to fit Alaskan rocks. Spurr (1900, p. 210) wrote:

> The necessity for writing clearly and intelligently about the Alaskan rocks made him draft a classification for those collected in 1898. The idea in this was simply to elucidate the nature and relations of these Alaskan rocks, and no idea was entertained of proposing a classification which should find general favor.

He was apparently troubled, like many later workers, by the elusive andesite-basalt boundary, for he proposed the name "aleutite," after a Katmai porphyritic lava that was transitional between andesite and basalt. Spurr's "aleutite" is approximately equivalent to the hypersthene-bearing labradorite andesite of southwestern Umnak (no. 23, Table 7, APPENDIX). If these moderately siliceous porphyritic lavas, containing up to 13 percent normative quartz, are classified according to the older (Zirkel-Rosenbusch) classifications based on plagioclase feldspar they are of course basalts. The controversial andesite-basalt boundary has troubled many workers in dealing with rocks of the Pacific (high line) suite. For example, in the Cascade province of western United States, Buddington and Callaghan (1938, p. 424), Coombs (1936, pp. 174-75), and Thayer (1937, pp. 1624-25) have considered this problem. Buddington and Callaghan suggested the term "labradorite andesite" or "basalt andesite" for siliceous lavas similar to andesite but containing an average plagioclase feldspar richer in anorthite content than An_{50}. Williams (1950, pp. 234-235), faced with similar problems in describing the rocks of the Neo-volcanic zone of Mexico, defined "basaltic andesite" on the basis of its saturation with respect to silica (qz value from 0 to 20), although the rocks so defined also have calcic

feldspar and hence are similar to the basaltic andesite of Buddington and Callaghan.

The present writer, more or less following Williams' example in Mexico, considers that a more fundamental separation of Umnak-Bogoslof andesites and basalts is achieved by drawing the line at about 5 percent quartz (Table 5) as determined by the moledular norm. Only one exception may be noted and it is essentially a borderline case. A welded andesitic agglomerate bed of the Okmok formation contains only 4.6 normative quartz but is distinctly andesitic in character on the basis of genesis (e.g. "welded tuff"), average plagioclase (An_{45}), color index (29) and overall silica content (54.35%). Except in the example just mentioned, the drawing of the boundary at 5 percent (molecular) normative quartz corresponds to a division on the basis of silica content at about 53 percent.

Color index (Farbzahl) proved unsatisfactory as a means of separating andesite from basalt, unless many exceptions are made. The chief difficulty is that as the porphyritic basalts become more enriched in bytownite or anorthite phenocrysts, the color index (and also the silica content) decreases. If a color index of 40 (Ellis, 1948, p. 460) or even 30 (Shand, 1947, p. 235) were used, a rock such as an anorthite basalt (e.g., no. 5, Table 7, APPENDIX) with a silica content of 50 percent and a color index of 22, would be classed as andesite, whereas actually, such a rock is the extrusive equivalent of an anorthositic gabbro and should therefore be called basalt. The effect of increas-

ing percentage of calcic plagioclase phenocrysts on the color index of the basalts is also reflected in the higher average color index (34) of the aphyric basalts than that (31) of the porphyritic basalts (see Table 5).

The term "basaltic andesite" is not rigidly defined according to the classification given in Table 5, but is applied to certain aphyric andesites of basaltic character. These rocks contain only slightly more than 5 percent normative quartz and a calcic plagioclase.

Exception to the present classification would probably have to be made for a deep seated intrusive equivalent in chemical composition to the aphyric basalt (nos. 10 and 11, Table 7, APPENDIX). Because of the excess of normative albite over anorthite in such a magma, a chemically equivalent plutonic rock that had cooled very slowly under conditions approaching equilibrium would contain andesine as the average modal feldspar (cf. Wenk, 1948, p. 383) and some interstitial quartz. Such a rock would be classed as a diorite by most petrographers following the Zirkel-Rosenbusch classification, but under the classification given in Table 5 the rock would have to be classed as an andesine gabbro. However, classifications while providing a convenient frame of reference should not be inflexible. As Turner and Verhoogen (1951, p. 62) in their recent text have pointed out, "gabbro (plutonic) and basalt (volcanic) are not exactly equivalent either in mineral composition or in range of chemical composition." From their statement, it would follow that distinction

between andesite and basalt cannot be defined in exactly the same manner, chemically or mineralogically, as the distinction between diorite and gabbro. The qualitative Zirkel-Rosenbusch mineral classification may be applicable to most suites of plutonic rocks but different quantitative limits are commonly necessary in classifying rock of a volcanic suite.

Separation of Saturated from Undersaturated Rocks

The theoretical division between saturated (with respect to silica) and undersaturated rocks at 0 percent normative quartz or olivine corresponds generally to about 2 percent modal olivine because of the tendency of olivine to separate in excess of its stoichiometric ratio (Bowen-Andersen effect). The quartz-bearing olivine andesite, a hybrid rock, is of course an exception to this general rule. However, the most olivine-rich basalt (no. 1, Table 7, APPENDIX) contains less olivine as phenocrysts than normative olivine; possibly more olivine is present in the groundmass of this lava than is apparent in thin section.

Distinction between Oversaturated and Transitional Rocks

The oversaturated rocks, i.e. those with a considerable excess of silica, include those rocks with more than about 20 (molecular) percent of normative quartz. Unlike the boundary between andesite and basalt, the division between the intermediate rocks and the oversaturated rocks is more of a distinct chemical break. Chayes (1952, pp. 217-219) in his statistical study of

New England "granites" (including granodiorites) likewise found that the 146 granitoid rocks that he studied contained at least 20 percent of excess silica. The transitional rocks represented by andesites, latites and quartzose plutonic rocks of Umnak do not contain more than about 16 percent of normative quartz (see Table 5), whereas the oversaturated rock with the next higher content of normative quartz contains about 20 percent (water-free); namely, the rhyodacite pumices.

The rock name, "rhyodacite," for the extrusive equivalent of granodiorite, has not been widely accepted by petrographers, though the need for such a name is shown in the following statement by Charles A. Anderson (1941, p. 396) in his study of the lavas of the Medicine Lake Highland, California:

> In chemical composition . . . the Medicine Lake Highland dacites depart from the average dacite in having a higher potash content, and correspond more closely to the average granodiorite. Since there is no term in current use for the volcanic equivalent of a granodiorite, petrologists must choose between dacite or quartz latite.

Quartz latite would be ruled out for many extrusives unless they actually contain quartz. The writer, following Shand, would prefer to restrict "dacite" to those extrusives that are chemically equivalent to tonalite, although it is realized that many Cascade lavas described as dacites would fall in Shand's rhyodacite group.

Objections against using "silica percentage" as a basis for igneous rock classification have been made recently by A. K. Wells (1949, pp. 689-92). Basing his argument on a plot of

modal quartz against silica percentage of nearly 200 intrusive rocks he found that the silica percentage boundary that would include all rocks with more than 10 percent modal quartz had to be placed at 52 percent of silica. Conversely, he found that in order to exclude all those rocks with less than 10 percent of modal quartz would necessitate placing the boundary at 69 percent of silica. He thus concluded that silica percentage was unsatisfactory as a means of separating granite and oversaturated rocks from the intermediate rocks.

Wells, however, did not consider using a percentage of excess silica higher than 10 percent as a lower limit for the quartz-rich rocks: granite, granodiorite and tonalite. In taking 10 percent modal quartz as a boundary between intermediate and silicous rocks, Wells probably was near the frequency distribution peak of the intermediate rocks (e.g. quartz diorites, quartz monzonites, etc.) with respect to modal quartz so that the great range in silica percentage would not only be expected but was actually found. Had Wells (1949, Fig. 1) considered using 20 percent modal quartz (cf. Chayes, 1952, p. 219), only one of the rocks with more than 20 percent modal quartz would fall below 62 percent of silica and, conversely, only one of the rocks with less than 20 percent modal quartz contains over 70 percent silica. Thus, had Wells used 20 percent modal quartz as the lower limit of the granite-granodiorite-tonalite rocks, the silica percentages of these rocks, with only 2 exceptions, would range from 62-70 percent according to Wells's diagram. Similarly, had Wells

used 15 percent modal quartz as his lower limit, again with only two exceptions, rocks above the range 60-68 percent of silica would be included in the granite-granodiorite-tonalite clan. Hence, the writer would conclude from Wells's plot that 15 or 20 percent modal quartz is a more natural break between the oversaturated rocks and the intermediate rocks in most areas of calcalkaline rocks.

PETROLOGY

Diagrammatic Representation

The petrologic relationships of the Umnak-Bogoslof rocks and magmas can be visualized principally on the chemical differences between the rocks, crystals (phenocrysts and xenocrysts), and groundmasses, aided by conventional triangular diagrams. The variation diagrams (see Figs. 10 and 11) are of some aid in visualizing the variations of the major oxides with respect to silica, but minor variations among major oxides with respect to each other may not be readily apparent in the variation diagrams. Weight percents and norms of Umnak-Bogoslof rocks have been converted to molecular percents reduced to one metallic atom per oxide following the method of Niggli (1936, pp. 295-317; see also Barth, 1945, pp. 11-13; Vuagnat, 1946, pp. 185-189). An explanation of Niggli's method of molecular norms is given in Barth's Theoretical Petrology (1952, pp. 76-82). The molecular ratios of oxides reduced to one metallic atom per oxide are proportional to the ratios of the metal atoms in any crystal. These molecular ratios are used to compute molecular norms of the rocks. The molecular percents of oxides and normative minerals of Umnak-Bogoslof rocks including computed compositions of crystals and groundmasses are given in Table 9 of the APPENDIX and are the data used in plotting points in the triangular diagrams. In the following discussions normative minerals based on molecu-

lar percent are capitalized to distinguish them from the commonly used weight percent norm, following the convention established by Niggli (1936).

Although the triangular diagrams used in the present discussion show only the percentages of the chemical components, the actual minerals present are not entirely neglected in plotting the rock analyses on these diagrams. The computed compositions of the phenocrysts (crystals) and groundmasses are based on petrographic work (Table 8, APPENDIX) and are shown separately on the diagrams. Plots of bulk compositions of rapidly chilled (quenched) northeastern Umnak porphyritic lavas, which are probably good examples of crystal fractionation, have been omitted from the triangular diagrams in order to avoid confusion of points. The bulk compositions of the porphyritic lavas of southwestern Umnak and Bogoslof, however, are shown on the diagrams in addition to their crystal and groundmass compositions because other factors in addition to simple crystal fractionation appear to have played a part in producing these rocks.

The triangular diagrams with ferrous oxide as one of the components generally require some adjustment of the ferrous to ferric ratio, because oxidation of ferrous iron in surficial volcanic rocks takes place at or near the surface under nearly atmospheric conditions. Kennedy (1948) has shown that the Fe^{++}/Fe^{+++} ratio in magmas is controlled by the partial pressure of oxygen, which is determined largely by the dissociation of water. In this paper a ratio of the ferrous to total iron oxide (atoms) is

used in considering the origin of rocks largely crystallized from magmas. The following ratio

$$\frac{FeO}{FeO + \frac{1}{2}Fe_2O_3} \text{ (numerically equivalent to } Fe'' \frac{Fe''}{Fe'' + Fe'''}$$

was arbitrarily selected that most likely approached the average conditions in Aleutian magmas at depth. The iron oxide ratio of the Umnak-Bogoslof magmatic rocks that is least oxidized is about five-sixths; hence, in order to make the more highly oxidized, non-magmatic rocks comparable with the normal magmatic rocks, the iron oxide ratios of the non-magmatic rocks are adjusted to 5/6. Also, the same iron ratio is adjusted in crystals subtracted from the porphyritic rocks. Had an iron oxide ratio of three-fourths or seven-eighths been selected the relationships between rocks, crystals and groundmasses would be displaced slightly, but not fundamentally changed. All iron could have been recomputed as ferrous, but such an extreme situation certainly is not true of natural magmas, as indicated by the rapidly quenched volcanic glasses of Umnak.

The strongly electropositive mono- and bivalent metals, potassium, sodium, calcium, magnesium, and ferrous iron (or their oxides reduced to one metallic atom per oxide) are believed to be the most fundamental components that can be used to depict chemical changes in magmas as well as chemical differences between rocks. Manganese is included with iron because manganese replaces iron in a fairly constant ratio. All these metals combine with other less active metals and oxygen, which play a more

passive role in the crystal structures. Thus, the ($\frac{1}{2}K_2O$ - $\frac{1}{2}Na_2O$ - CaO) ternary diagram approximately represents the potential feldspars in the magma, although, depending on the amount of alumina present, some calcium enters the clinopyroxene molecule. Likewise, the ternary diagram with CaO, MgO, and MnO plus five-sixths total iron oxides as FeO illustrates the proportions of pyroxene components. Alkalis and MnO plus five-sixths total iron oxides may occupy two corners with either lime or magnesia occupying the third and show mainly the trends of differentiating magmatic liquids with respect to iron. Similar diagrams have been used by Wager and Deer (1939, pp. 313-316), Walker and Poldervaart (1949, pp. 657-661), and others to show the trend of magmatic differentiation with respect to enrichment of iron.

Diagrams based on normative minerals are apt to be misleading, because the arbitrary rules used in the calculation may result in normative minerals bearing little resemblance to the modal minerals, either in composition or in name. Despite this limitation, the norm is a useful standard for comparing chemical compositions of rocks, particularly saturation with respect to silica and alumina. A triangular diagram of normative Quartz-Albite-Orthoclase is useful in illustrating the trend toward a residual magma at the granite cotectic. A diamond-shaped diagram formed by combining two equilateral triangles along a common side is useful in demonstrating saturation with respect to alumina. In this diagram normative Anorthite-Albite are on the common side and Diopside or Wollastonite is opposite Corundum at the far

corners. Diopside and Corundum are mutually exclusive pairs in the norm calculations so that this diagram shows the saturation with respect to alumina.

The significance of the type of diagrams used in this study is best summarized by Evrard (1949, p. 218), who used a molecular FeO-Fe_2O_3-TiO_2 triangular diagram to show the trend of enrichment of titanium in magmatic titaniferous ores. His statement follows (Evrard, 1949, p. 217).

> The diagram does not represent "A priori" the differentiation of a magma and one can neither speak of it in the sense of the chemical evolution related to the crystallization sequence nor of the relative age of all these rocks, as field investigations have not afforded evidence to verify these questions. However, it is interesting to note that the relations between the three oxides TiO_2, Fe_2O_3, and FeO are not of random kind at stages of the solidification. On the contrary, there is a "solution de continuité."

It should again be emphasized that no single triangular diagram is adequate to express all the changes that take place in the magma. These diagrams are best regarded as ternary projections of components from polycomponent magmas or rocks. As already pointed out, the triangular diagrams illustrated in this section not only serve to show changes of ideal magmatic liquids, but also are used to compare compositions of rocks with these ideal magmatic liquids. The cluster of points about a curve representing changes in ideal magmatic liquids serves as a reference standard for comparing compositions of rocks that depart notably in composition. These diagrams may assist in gaining an insight as to why certain rocks and magmatic liquids do indeed depart from the curve representing ideal magmatic liquids derived by simple crystal fractionation.

Magmatic Rocks

Volcanic rocks yield excellent samples of naturally quenched magmas, provided that chilling has been sufficiently rapid. These naturally quenched magmas, now crystals in a glassy or aphanitic groundmass, yield information on the probable composition of magmatic liquids if these crystals, now phenocrysts are subtracted from the bulk composition of the rock. This approach was used by N. L. Bowen (1928, pp. 114-132) in his discussions of the liquid line of descent in magmatic rocks. The present writer has attempted to continue Bowen's fundamental approach in the petrologic analysis of the Umnak-Bogoslof suite.

Effects of Fractional Crystallization

Northeastern Umnak and southwestern Umnak liquid lines of descent.--As pointed out earlier, the aphyric lavas and groundmasses of porphyritic lavas, especially those of northeastern Umnak, fall closest to smooth curves indicated by solid lines on the variation diagrams (see Figs. 10 and 11). The tendency of the points representing these aphyric lavas and groundmasses to fall along smooth curves is further shown in the accompanying triangular diagrams (Figs. 17 to 21). The aphyric volcanic rocks of southwestern Umnak, fall along the northeastern Umnak curves, except for iron and alumina (see Figs. 10, 17, 20, and 21). Two liquid lines of descent are suggested: one, represented by the rocks of northeastern Umnak is slightly richer in iron, and the other, represented by the aphyric lavas of southwestern Umnak, is slightly richer in alumina.

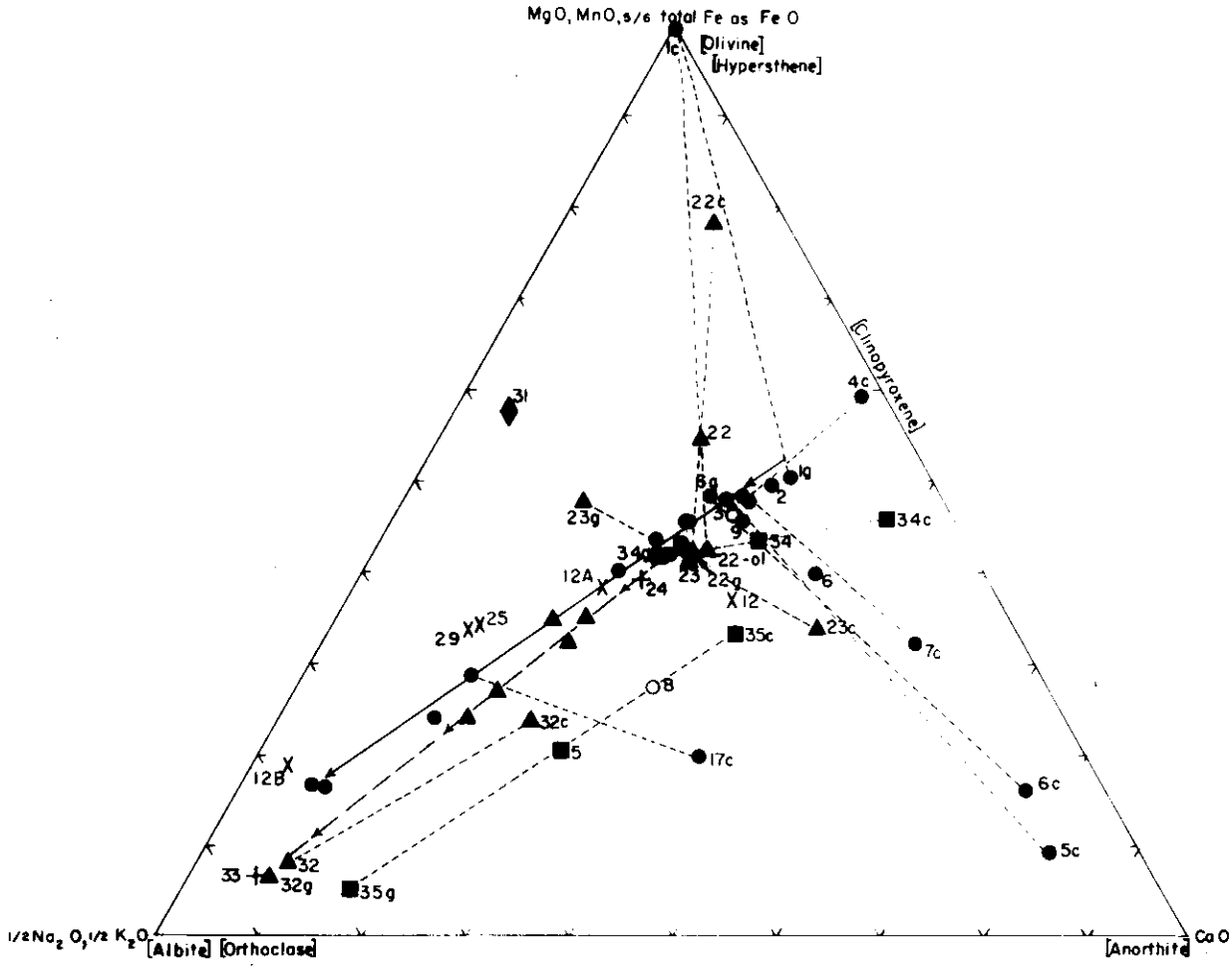

Figure 17.--Ternary plots of rock, crystal (phenocryst), and groundmass compositions with respect to lime-femic-alkali molecular percentages reduced to one metallic atom per oxide. Numbers and letters correspond to those in table 9 (Appendix); symbols as in figures 10 and 11. Solid curve and dashed curve with arrows show trends of northeastern Umnak and southwestern Umnak magmatic liquids, respectively. Points used in plotting curves are same as points used in plotting northeastern and southwestern Umnak curves in the variation diagram (figure 10). Short dashed lines connect plots of crystals (phenocrysts and xenocrysts) with corresponding groundmass compositions.

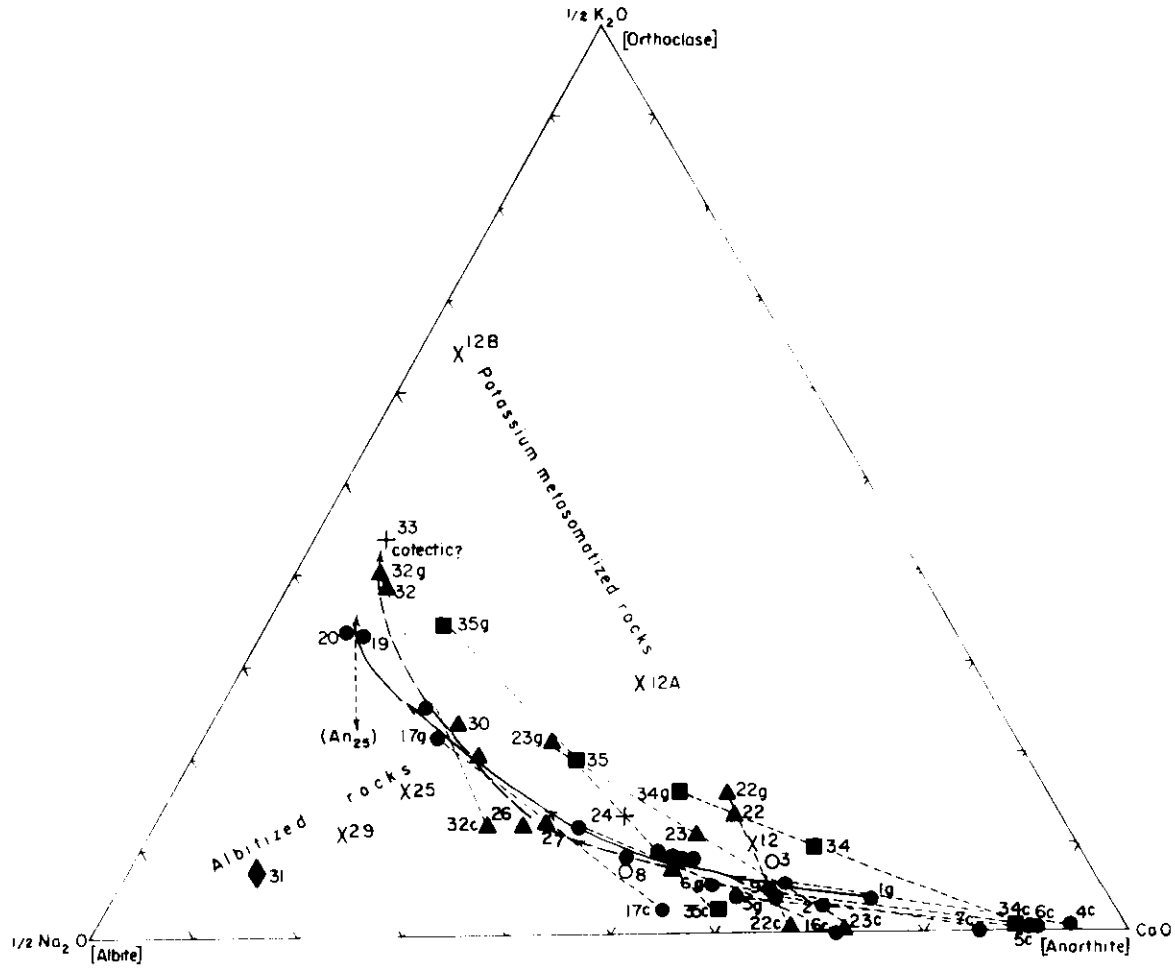

Figure 18.--Ternary plots of rock, crystal (phenocryst), and groundmass compositions with respect to soda-potash-lime molecular percentages reduced to one metallic atom per oxide. For further explanation see figure 17

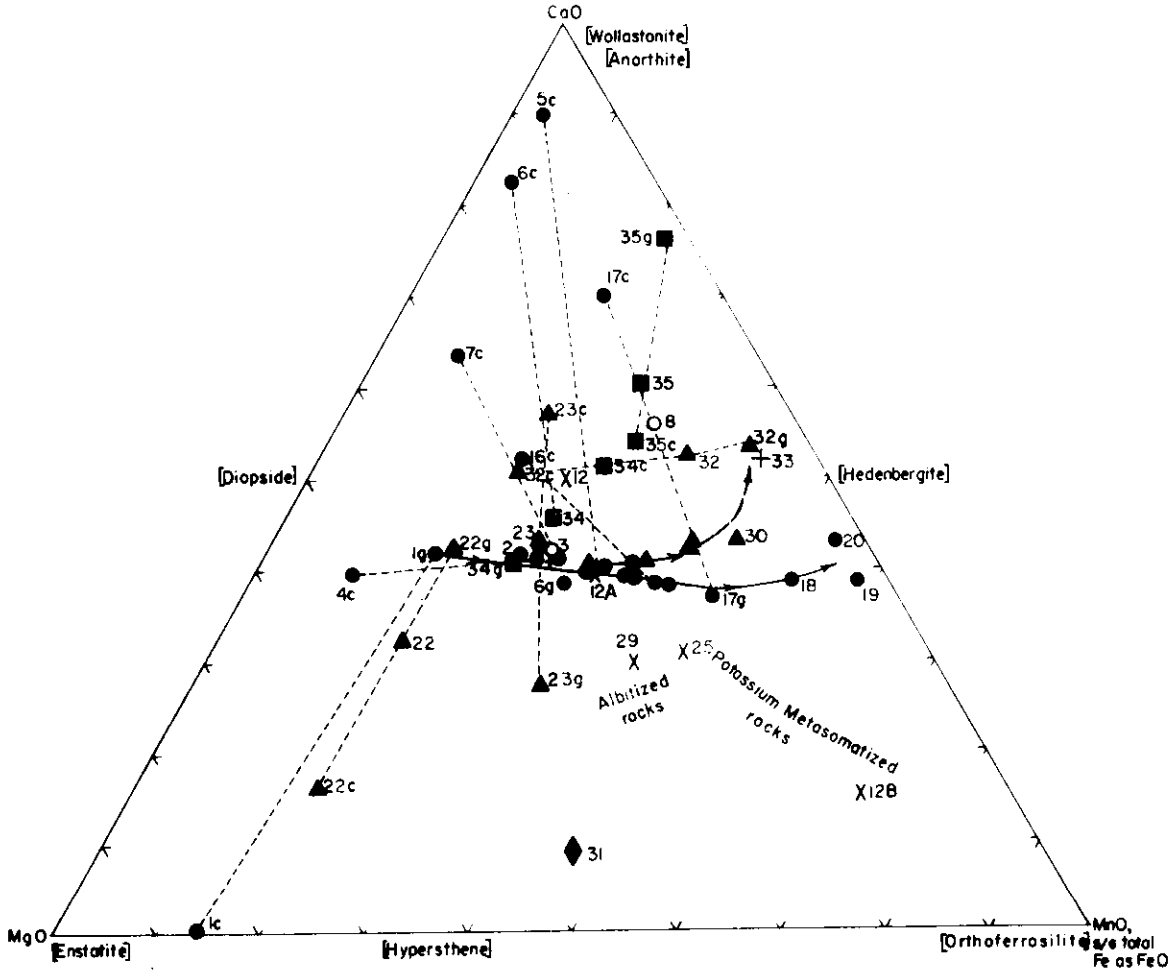

Figure 19.--Ternary plots of rock, crystal (phenocryst), and groundmass compositions with respect to magnesia-lime-ferrous plus manganese oxide molecular percentages reduced to one metallic atom per oxide. Five-sixths of the total iron is represented as ferrous (see text), and manganese is included with the ferrous iron. For further explanation see figure 17.

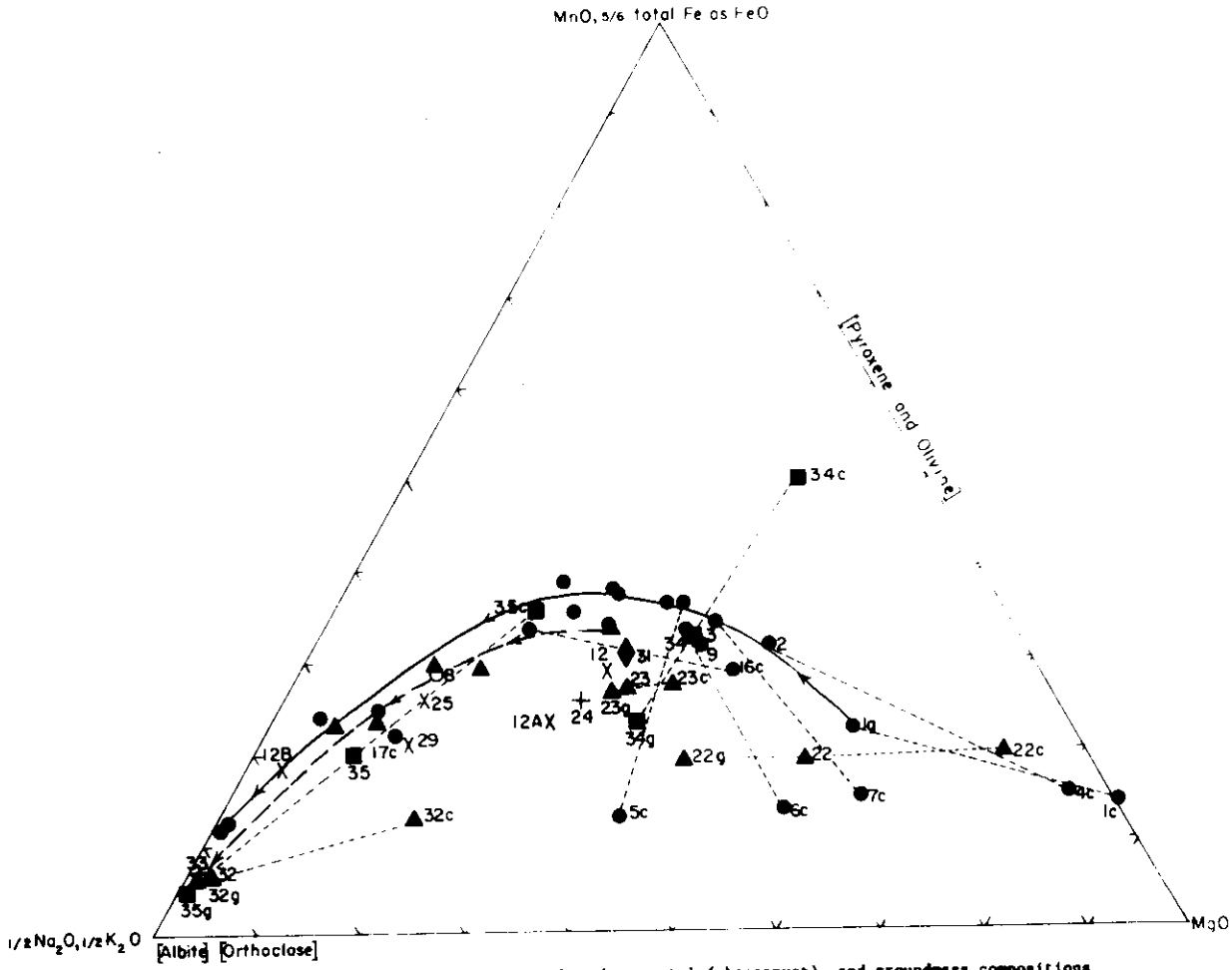

Figure 20 --Ternary plots of rock, crystal (phenocryst), and groundmass compositions with respect to alkalis-ferrous oxide-magnesia molecular percentages reduced to one metallic atom per oxide. Five-sixths of the total iron is represented as ferrous (see text), and manganese is included with the ferrous iron. For further explanation see figure 17.

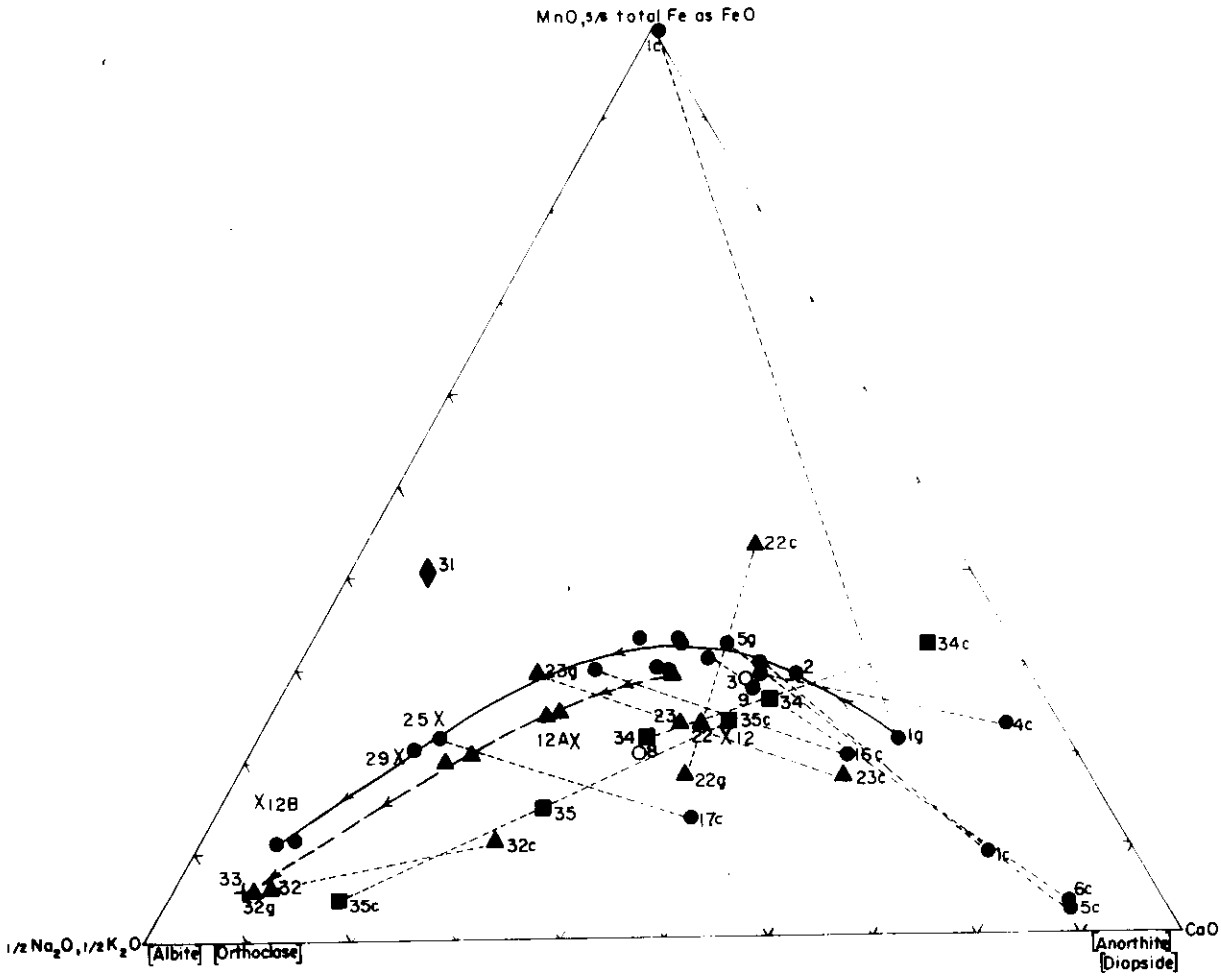

Figure 21.--Ternary plots of rock, crystal (phenocryst), and groundmass compositions with respect to alkalis-ferrous oxide-magnesia molecular percentages reduced to one metallic atom per oxide. Five-sixths of the total iron is represented as ferrous (see text), and manganese is included with the ferrous iron. For further explanation see figure 17.

One reaction series of ferromagnesian minerals is associated with the iron-rich liquid line of descent and another with the alumina-rich liquid line of descent so that rocks derived from the two liquid lines of descent are readily detected petrographically. The reaction series, olivine-diopsidic augite-subcalcic augite of northeast Umnak lavas, contrasts with the (olivine-) hypersthene plus calcic augite-ferriferous augite-ferroaugite series of southwest Umnak lavas (Fig. 22). In the plutonic rocks the place of ferroaugite is in part taken by hornblende and biotite. Olivine and hypersthene were not observed to have a reaction relationship in any rock, but sparse olivine with augite reaction rims commonly occurs without hypersthene in alumina-rich, aphyric basaltic andesites (cf. no. 21), and hypersthene phenocrysts with ferriferous augite reaction rims are found in the alumina-rich aphyric andesites and latites (cf. nos. 27 and 28). The addition of alumina in the magma uses up most of the lime in plagioclase with the result that olivine or hypersthene in the more silicious rocks forms as a separate phase, and the augite that apparently precipitates with the hypersthene is a lime-rich augite that approaches salite in composition (see Fig. 22). Hypersthene and probably calcic augite are unstable during the later part of crystallization, when ferriferous augite or ferroaugite becomes the stable phase (Fig. 22). These pyroxene reactions in southwestern Umnak magmas differ from those outlined by Poldervaart and

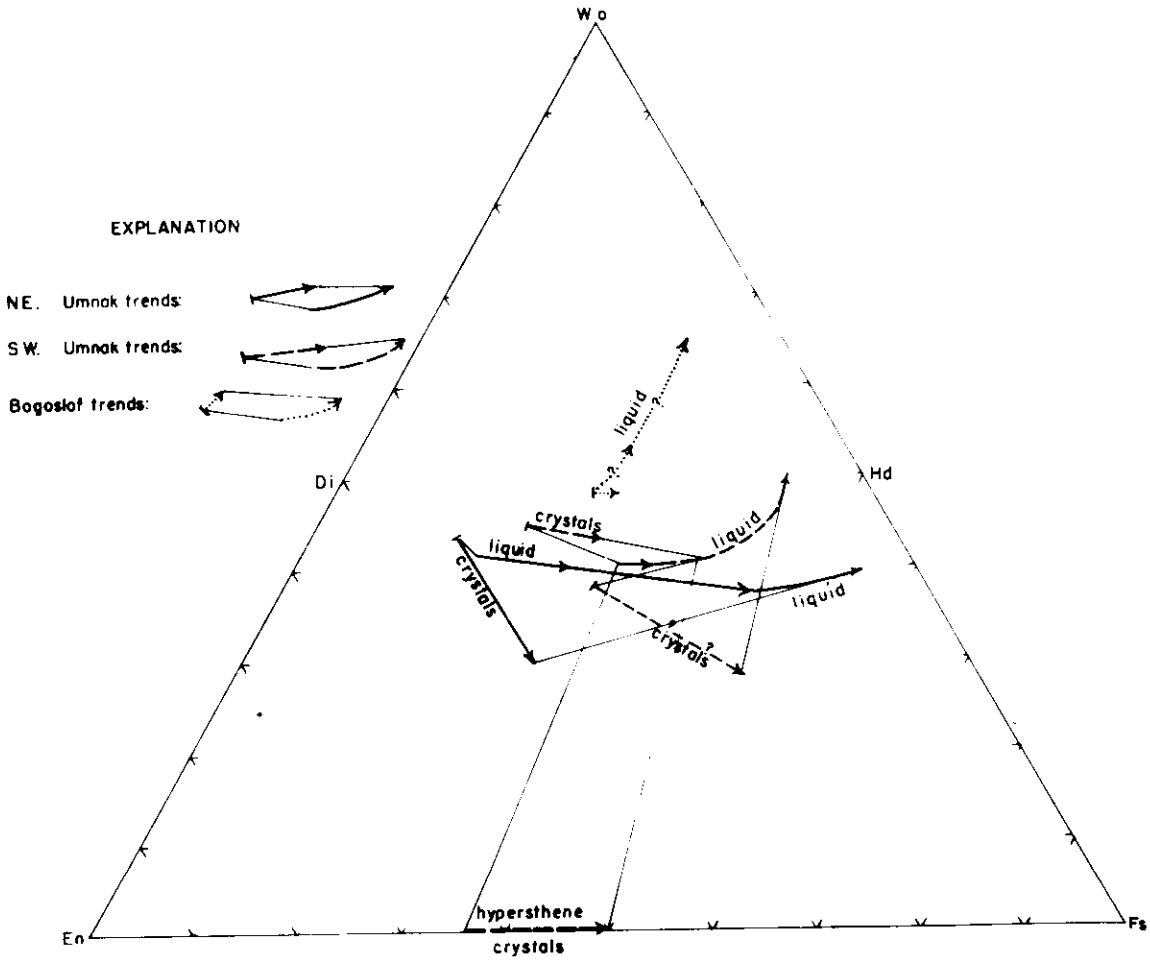

Figure 22.--Idealized triangular diagram showing crystallization of pyroxenes from Umnak-Bogoslof rocks. Arrows show inferred trend of differentiation. Light lines indicate approximate equilibrium between phases.

Hess (1951, p. 479) for a saturated basaltic magma in that pigeonite is not formed in southwestern Umnak magmas, possibly owing to their high lime content.

The precipitation of hypersthene caused by addition of alumina from argillaceous rocks has been noted by Bowen (1922, pp. 550-558), Tilley (1923, p. 419), Read (1924, pp. 438-441), and others. Differences between the northeastern and southwestern Umnak liquid lines of descent with respect to the major components of pyroxene are shown in Figures 17, 19, 20, and 21; the upswing of the southwestern Umnak (dashed) curve toward the lime corner in Figure 19 is believed due to impoverishment of iron and magnesia relative to lime in the magmatic liquids, owing to precipitation of ferroaugite. In Katmai lavas, which are similar in composition to southwestern Umnak lavas, hypersthene appears as a primary phase in rather silicious rocks, but then becomes unstable and is rimmed with augite (Fenner, 1926, p. 692). That precipitation of hypersthene might be affected by varying amounts of alumina in magmas is not considered by Poldervaart and Hess (1951).

The two liquid lines of descent are shown in greatest contrast on the alumina saturation diagram (Fig. 23). The southwestern Umnak curve (dashed) lies closer to the corundum (alumina) corner, and nearly all of the southwestern rocks (triangles) contain hypersthene phenocrysts (H or h). The plot of the argillite (diamond) is closest to the corundum corner of any southwestern Umnak rock. Possibly assimilation of similar

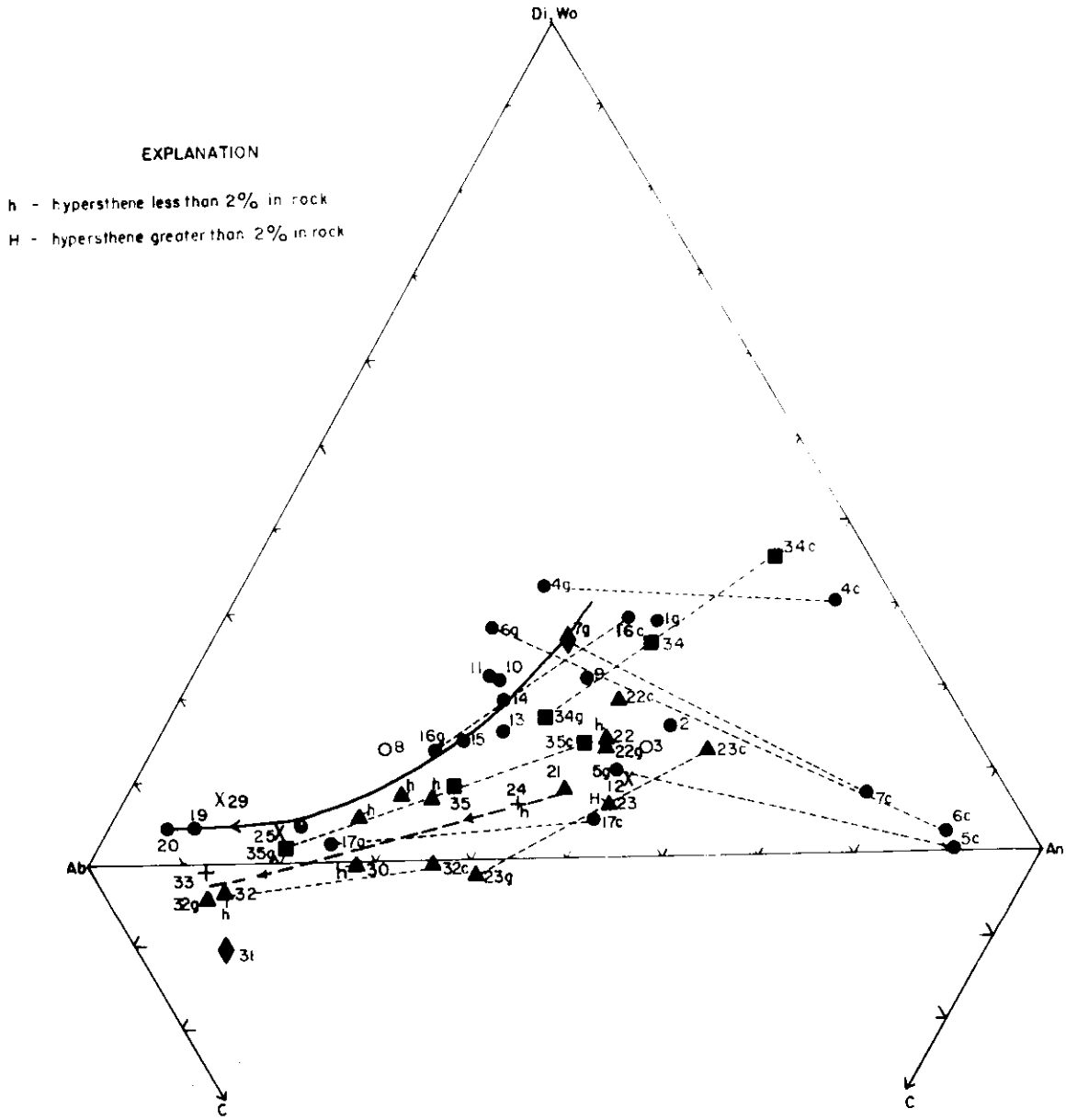

Figure 23.--Double Ternary diagram of rock, crystal (phenocryst), and groundmass compositions with respect to normative Diopside, Albite, Anorthite, and Corundum recomputed to 100 percent. Symbols and numbers within diagram are same as in figure 17.

argillaceous sediments by basaltic magma may have produced a parental quartz dioritic magma containing high alumina. The probable reaction has been suggested by Bowen (1928, p. 206):

$$Al_2SiO_5 + CaMgSi_2O_6 = CaAl_2Si_2O_8 + MgSiO_3$$
(argillite) (clinopyroxene) (anorthite) (hypersthene)

Alumina-enrichment of more siliceous rocks and magmas may possibly be emphasized by fractional crystallization, once a magma has been contaminated with argillaceous sediments. If such a magma differentiates by crystal fractionation with removal of the early-formed, alumina-poor pyroxene phenocrysts, a residual magma can apparently evolve that contains not only excess silica, but also excess alumina over lime and alkalis (Fig. 23). Support of this hypothesis is afforded by both the southwestern Umnak rhyolite dome and granophyre (nos. 32 and 33), which contain normative corundum.

Curves (solid lines, see Fig. 10) representing the liquid line of descent of northeast Umnak magmas strongly suggest that crystal fractionation is the major factor in differentiation, though slight contamination of magmas by aluminous sediments may have played a minor role. A noteworthy feature of the curves of northeastern Umnak magmatic liquids is the strongly curvilinear character of the lime and magnesia curves at the low silica end of the variation diagram (see Fig. 10). These curves dip very steeply, probably owing to rapid removal of lime and magnesia from the liquid in crystals of highly calcic plagioclase (An_{95-95}) and magnesian olivine (Fo_{90-90}) (cf. Bowen, 1928, pp.

96-110). Considerable scatter of the alumina points at the low silica end of the diagram may reflect differences in the quantities of alumina-rich argillites incorporated in the primary basaltic magma. The alumina content may apparently vary in a cooling magmatic liquid (aphanitic lava) within wider limits than the lime content without causing earlier precipitation of plagioclase, although the composition of the plagioclase that eventually crystallizes would have a higher anorthite content.

Crystal accumulates.--Most of the northeastern Umnak porphyritic rocks whose groundmass compositions fall near the inferred liquid line of descent are greatly enriched in olivine or calcic plagioclase phenocrysts--presumably the result of pronounced crystal sorting effected by gravity settling. The dashed lines connecting compositions of these crystals (Nos. 1c, 5c, 6c, 7c, 16c, and 17c, Figs. 17-21) with corresponding groundmasses intersect the inferred curves of liquid line of descent at high angles in all diagrams in which both the mafic mineral components and plagioclase are represented (Figs. 17, 19, 20, and 21). Gravity settling of early-formed augite and olivine from the upper portion of magma chambers has probably played an important role in the crystal fractionation of northeastern Umnak magmas. Large augite phenocrysts up to 1 cm (the analyzed augite of Table 1) are concentrated in the lower part of the anorthite-augite-olivine basalt flow (no. 4, Table 7). One might expect that the mafic crystal accumulates would contain a fair proportion of large phenocrysts up to 1 cm, like the augite phenocrysts of the

anorthite-augite-olivine basalt, but most of the plagioclase-poor mafic basalts, of which the olivine basalt (no. 1) at Cape Idak is an excellent example, contain only small phenocrysts averaging about 0.5 mm and generally not exceeding 2 mm. Possibly the settled mafic phenocrysts may have been partly resorbed in the hotter zones to which they settled. Later cooling induced reprecipitation of smaller crystals. The plagioclase-rich basalts, such as the anorthite basalts (nos. 5 and 6, Table 7, APPENDIX) may have resulted by gravity settling of mafic phenocrysts with passive enrichment in plagioclase phenocrysts. These would likely remain suspended in the magmatic liquid, because of the small density differences between the plagioclase crystals and basaltic liquid.

Primary basaltic magma.--The dominantly basaltic northeastern Umnak lavas suggest a primary basaltic magma such as Daly (1933, pp. 186-204), Kennedy (1933, p. 239) and many others have postulated. The average silica content of the two analyzed aphyric basalts (nos. 10 and 11, Table 7, APPENDIX) is about 52.5 percent. The silica content (not tabulated) was determined on nine interbedded aphyric basaltic lavas of the Okmok formation and was found to be within the relatively narrow range from 51.3 to 53.7 percent. As already noted, however, the groundmass compositions of the porphyritic basalts are quite variable in composition, and the question immediately arises as to which composition might represent the primary basaltic magma. Fortunately a little light on this problem is forthcoming from studies in other areas.

Kuno (1949, pp. 1003-1006) computed the groundmass compositions of porphyritic basalts of Hakone Volcano, Japan and stated (p. 1003): "The most striking fact seen . . . is that the calculated compositions of the groundmasses agree closely with the analyses of the aphyric rocks." While this is more or less true of the porphyritic andesite groundmasses of Hakone Volcano, the groundmasses of the Hakone porphyritic basalts are slightly higher in lime and magnesia than those of the aphyric basalts (Kuno, 1950, p. 1004). Kuno's variation diagram (p. 1007) of the aphyric lavas and groundmasses of porphyritic lavas likewise indicates a pronounced upward swing of lime and magnesia at the low silica end of the series similar to the northeastern Umnak diagram (see Fig. 10). In fact, the low silica end of Kuno's curve at 49.5 percent of silica indicates about 13 percent of lime and 7 percent of magnesia as compared with 13 percent of lime and 9 percent of magnesia at the low silica end of the northeastern Umnak curves (Fig. 10). Iron oxide shows similar behavior except that the groundmass of the northeastern Umnak olivine-rich basalt indicates a more definite downward trend for the iron curve (Fig. 10) than that shown for the iron oxide curve of Hakone Volcano (Kuno, 1950, p. 1007).

Additional information on the behavior of lime, magnesia, iron oxide, and alkali curves at the low silica end of the variation diagrams is provided by C. A. Anderson's study of lavas of the Medicine Lake Highland, California (Anderson, 1941, p. 402). Lime and magnesia rise sharply at the low silica end (47-50 per-

cent), but here in the Medicine Lake diagram we are dealing with essentially nonporphyritic basaltic lavas that approach the compositions of the northeastern Umnak porphyritic basalt groundmasses. At the extreme low silica end of the Medicine Lake diagram the magnesia and lime curves reach $9\frac{1}{2}$ and 12 percent, respectively, whereas total iron as Fe_2O_3 dips from 10 percent at 52 percent of silica to 9 percent at 47 percent of silica. Alumina is higher, than in Umnak lavas, possibly because more argillaceous sediments have been incorporated in the Medicine Lake lavas. Alkali curves are similar to alkali curves in the northeastern Umnak diagram, except that potash is nearly zero in the Medicine Lake diagram at 47 percent of silica. The Medicine Lake basalts of low silica content are slightly porphyritic, but in smoothing the curves Anderson (1941, Fig. 14) has eliminated slight discrepancies introduced by compositions of the porphyritic lavas. These basalts are actually subophitic to ophitic with minor olivine phenocrysts (p. 395) and must have been liquid at the time of extrusion except for the minor olivine crystals. Anderson (1941, p. 403) observes:

> It may be added that the Medicine Lake basalts may have developed by the concentration of plagioclase and olivine, for they are rich in lime, magnesia and alumina. However, the Medicine Lake basic basalts are not porphyritic, with the exception of the Lake basalt, and only this lava has a magnesia content comparable to the Hull porphyritic central type basalt. But the subophitic and intersertal basalts might well represent crystal accumulations of early separated olivine as well as plagioclase, thus accounting for the enrichment of magnesia. Remelting of this crystal differentiate would be necessary for extravasation as lava flows, for the subophitic and intersertal lavas have all the features of fluid lavas with no sign of crystal rupture

such as would be present if they were extruded as a crystal mesh. (Italics supplied by present writer.)

The progressive change in groundmass compositions of the northeastern Umnak porphyritic basalts can probably be explained by simple crystal enrichment from a primary basaltic magma if one assumes subsequent resolution of the phenocrysts in a hotter zone. If the analyzed aphyric basalts of Okmok Volcano (nos. 10 and 11, Table 7, APPENDIX) are regarded as products of a primary magma, they are somewhat richer in alkalis than the average primary tholeiitic magma (Kennedy, 1933, p. 239). The Umnak aphyric basalts more likely are differentiates of a less silicious magma, although their high content of heavy metals (Table 7) indicates they are probably not too far removed from a primary magma. The augite basalt (no. 9, Table 7) approaches the composition of an ideal tholeiitic primary magma, although it is slightly enriched in plagioclase (high lime and alumina), not unlike the most silicious Mull porphyritic central type (Bailey et al., 1924, p. 22).

From the evidence available depth of origin may be an important factor on the composition of the magma--in general the greater the depth the less silicious and more cafemic the magma. Noe-Nygaard (1942) came to the conclusion as a result of his geologic work on the Svartenhuk Peninsula of Greenland that both olivine basalt and tholeiitic magmas were simultaneously present. Walker and Poldervaart (1949, p. 650) aptly remark: "In spite of Kennedy's (1933) conception of two world types, it must be recog-

nized that there is an overlap between them." The composition of the northeastern Umnak primary magma is in general of variable basaltic composition with rather high lime and alumina content typical of the circum-Pacific province. Through a fairly long period of geologic time, several periods of fusion, crystal settling, other relative movements of liquid and crystals, combined with some resolution of accumulated crystals in hotter zones, may have produced the groundmasses rich in lime and magnesia. Crystal settling of mafic crystals may have resulted in a lower depth layer of magnesia-rich olivine and augite overlain by a layer richer in anorthite (cf. Buddington, 1943, pp. 119-140) under most of northeastern Umnak. The dominantly tensional fractures and block faults associated with northeastern Umnak basaltic lavas suggests that tapping of various levels in an already heated orogenic belt may be largely responsible for the variation observed in the basalts.

Quartz-alkali feldspar cotectic.--Leaving the problem of the primary basaltic magma, let us consider the probable composition of the residual granitic magma, which may in part have been derived from fractional crystallization of basaltic magma. The northeastern Umnak sequence of aphyric andesite, latite, and rhyolite (nos. 15, 17, and 19, Figs. 17-21), which occur as small plugs, necks, domes and short, stubby flows, are interpreted as residual liquids resulting from crystal fractionation of basaltic magma in local magma chambers beneath Okmok Volcano. That the relatively small quantities of rhyolite can be generated by

crystal fractionation of northeastern Umnak basalt is confirmed by the fact that the interstitial glass of many northeastern Umnak basalts have indices of about 1.500 (cf. no. 11, Table 8, APPENDIX), only slightly more than the index (1.498) of the northeastern Umnak rhyolite obsidian (no. 19, Table 8).

Plots of the oversaturated Umnak rocks, crystals, and groundmasses on a normative Albite-Orthoclase-Quartz diagram (Fig. 24) suggest a trend toward a quartz-feldspar cotectic for southwestern Umnak rocks at about 38 percent of Quartz, 28 percent of Orthoclase, and 34 percent of Albite. This composition is slightly on the quartz side of the quartz (tridymite)-feldspar cotectic curve (Fig. 24) according to the quartz-feldspar diagram (Schairer and Bowen, 1935, pp. 325-328), recently revised by Schairer (1950, p. 514). The southwestern Umnak rhyolite (no. 32, Fig. 24), however, contains rounded, embayed quartz xenocrysts (see no. 32, Table 8), which at least in part may account for the excess silica above the quartz-feldspar cotectic curve as determined by Schairer. The abundant quartz-feldspar spherulites in the groundmass of the southwestern Umnak rhyolite indicate that the rhyolitic magma was close to the cotectic during final consolidation.

The rhyolite pumice deposited by the 1912 eruption of Katmai Volcano is similar chemically to the southwestern Umnak rhyolite. Fenner (1926, pp. 694-695) found 38.5 percent (by weight) of normative quartz in the Katmai rhyolitic pumice. Fenner remarks (p. 695) that "the ratio" (presumably meaning the

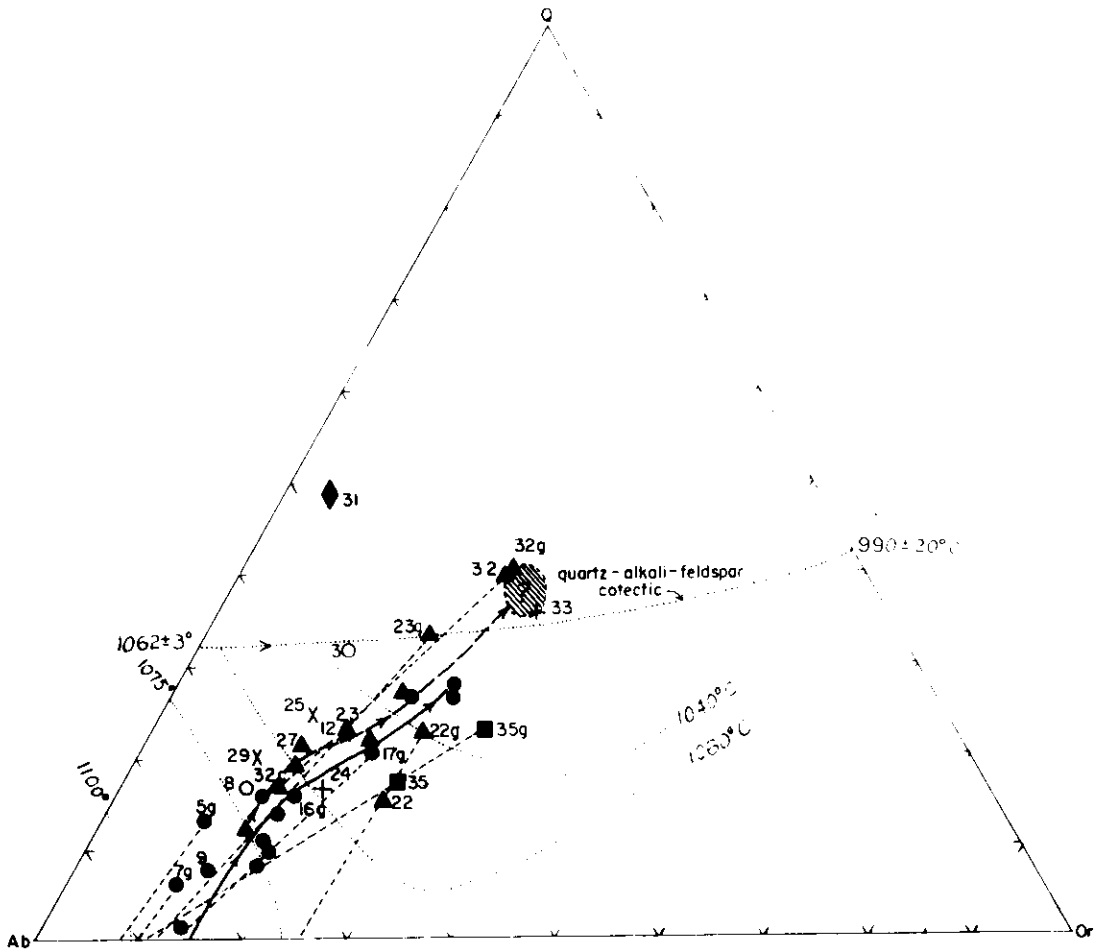

Figure 24.--Ternary plots of oversaturated rocks, crystals (phenocrysts), and groundmasses on the normative Quartz-Albite-Orthoclase diagram. Normative mineral plots recomputed to 100 percent. Dotted lines show quartz-feldspar cotectic curve and isotherms as determined in laboratory dry melt (Schairer, 1950, p. 514). Other symbols and numbers within diagram are same as in figure 17.

high quartz to low feldspar ratio), differs from that commonly held by some writers, presumably Vogt (1904, p. 19), necessary to form the quartz-feldspar eutectic in graphic granites. The Katmai rhyolite like the southwestern Umnak rhyolite contains a little modal quartz as rounded xenocrysts. Both rhyolites contain high normative quartz, owing in part to the presence of xenocrystic modal quartz, but also it seems possible that the presence of volatiles may move the quartz-alkali feldspar boundary curve of dry melts closer to quartz.

The granophyre (no. 33, Fig. 24) with about 35 percent normative Quartz is probably a closer approach to the actual quartz-feldspar cotectic curve. The granophyre contains 76 percent of silica, which according to Bowen (1928, p. 131) is near the maximum silica content attainable by a true magmatic rock. This normative Quartz content in the Umnak granophyre is only slightly above Schairer's quartz-feldspar cotectic (Fig. 23). The agreement of the granophyre composition with the quartz-feldspar boundary curve of the artifically determined system is considered good and supports the thesis that the granophyre was probably derived by fractional crystallization of a less salic magma, presumably a magma similar in composition to the quartz diorite with which the granophyre is associated.

Effects of Other Processes in Addition to Fractional Crystallization

Coexistence of two magmatic liquids.--The intimate contact relationships of certain andesitic and dacitic or rhyolitic

extrusives on Umnak indicate that two magmatic liquids, a salic and a femic, may have coexisted in the magma chamber beneath the erupting vent. Glassy basaltic andesite xenoliths in the rhyolite obsidian of northeastern Umnak (no. 19, Table 8, APPENDIX) appear from textural relationships to have been chilled from once liquid masses in a viscous rhyolitic magma. The rhyodacite pumices (nos. 29 and 30, Table 7) of both Okmok Volcano and Mt. Vsevidof are early, if not the first, effusives of the culminating eruptions of these two volcanoes. They were apparently highly charged with volatiles as indicated by high H_2O and CO_2 or high ignition values. They were later followed at both volcanoes by sharp transitions to welded andesitic agglomerate and andesitic scoria (nos. 13, 18, and 28). From the sequence of eruption it would appear that the rhyodacitic magma existed as a distinct gas-charged phase above a more femic magma just prior to eruption, although the quantity of rhyodacitic magma was much less than the andesitic magma extruded during the caldera-forming eruption of Mount Okmok.

Similar geologic relationships of a femic lava on a salic lava have been observed in many volcanic regions and probably was first recorded in 1844 by Charles Darwin (1890, p. 245). Williams (1942, pp. 145-147) found basic scoria on dacite pumice at Crater Lake, Oregon. Charles A. Anderson (1941, pp. 394-395) has described two Medicine Lake (California) flows in which possibly three magmatic liquids--basaltic, dacitic, and rhyolitic--may have coexisted, although Anderson regards the now solidified

basalt fragments as solid inclusions that were disintegrated by the dacitic liquid. Isolated olivine xenocrysts are present in the decite flows of Medicine Lake as in the northeastern Umnak rhyolite obsidian. Howel Williams (1935, pp. 276-277) likewise has described a composite basalt-rhyolite flow in the caldera of Newberry Volcano, Oregon. He favored intrusion of the basalt by obsidian at or near the surface, although he considered that certain features of the complex could be explained better by mixing of two magmatic liquids. Wilcox (1944, pp. 1060-1069) also puts forth convincing evidence of coexistence of rhyolitic and basaltic liquids in the Gardiner River Basin, Yellowstone Park. At any rate it seems likely that two magmatic liquids, a sialic one over a femic one are not uncommonly generated in magma chambers by melting of two or more extreme rock types within the crust. It seems not unlikely that these two liquids may coexist with a nearly horizontal interface in much the same manner as fresh water can exist for a considerable time over seawater.

Incomplete fusion of crustal rocks and hybrid magmas.--The generation of magmatic rocks by partial and incomplete fusion of older crustal rocks, both sialic and simatic, and the later mixing of these magmas to produce hybrid rocks are closely interrelated. A rock type that is believed to exemplify incomplete fusion of magmas is the hypersthene-bearing labradorite andesite (no. 23, Figs. 17-24) which makes up the bulk of the southeastern Umnak rocks. The quartz-bearing olivine andesite (no. 32, Figs. 17-23) is believed to be the result of partial fusion of a quartz

diorite that later mixed with an olivine basalt or peridotitic magma. The porphyritic lava domes of Bogoslof are of complex origin, probably involving several periods of incomplete fusion and possibly mixing of magmas.

The hypersthene-bearing labradorite andesite flows of Mt. Recheschnoi are believed to be the result of incomplete fusion of quartz diorite at the time of extravasation and solidification. This hypothesis differs from the concept of partial fusion and later squeezing out of an interstitial liquid in that the incompletely fused quartz diorite became a magma that was capable of mobility en masse, including both liquid and suspended crystals. Several lines of evidence point to such a mechanism.

Before considering more direct evidence, some negative or indirect evidence will place these hypersthene-bearing labradorite andesites in their proper framework. As already shown, the chemical and petrographic dissimilarity of the southwestern Umnak hypersthene-bearing labradorite andesite with nearly aphyric andesites of northeastern Umnak is striking (cf. no. 23 and nos. 13-18, Tables 7 and 8, APPENDIX). If, as seems probable, the northeastern Umnak aphyric andesites were derived by strong crystal fractionation of basaltic magma, it seems highly unlikely that exactly the same process alone could produce a vastly different rock such as the hypersthene-bearing labradorite andesite.

Directly bearing on origin, however, is the fact that the hypersthene-bearing labradorite andesite (no. 23, Table 7) is closely similar to the quartz diorite (no. 24) in chemical compo-

sition, except for higher lime and alumina and lower alkalis in the labradorite andesite--differences expressed petrographically by the somewhat more calcic plagioclase of the andesite. Certain minor elements--strontium, barium, and some other lightweight minor elements--differ slightly in these two rocks, possibly owing to their different environments of crystallization. The quantities of heavy metals, however, including copper, vanadium, chromium, and nickel and cobalt, agree closely. The significantly higher nickel and chromium in both the southwestern Umnak diorite and labradorite andesite and the absence or low values of these elements in two northeastern Umnak aphyric andesites (nos. 15 and 16, Table 7, APPENDIX) further suggests that the southwestern Umnak labradorite andesite and quartz diorite were probably not derived by fractional crystallization of basaltic magma, because nickel and chromium are nearly or completely removed from andesitic liquids derived by fractional crystallization through separation and removal of early mafic phenocrysts (Wager and Mitchell, 1951, p. 201).

Further support of the theory that the hypersthene-bearing labradorite andesite is incompletely fused quartz diorite stems from consideration of the variation diagram (Fig. 10) and the triangular diagrams (Figs. 17-21), in which the groundmass composition (23g) falls considerably off the curves of liquid line of descent established not only for northeastern Umnak rocks, but also for aphyric lavas of southwestern Umnak. The groundmass is considerably more rich in femic constituents, silica, and

potash, than other groundmasses and anhyric lavas (see especially Fig. 17). The groundmass (23g) is low in soda and lime. It is suggested that soda-lime feldspar (plagioclase) dissolved less readily in the regenerated liquid than hydrous femic minerals and potash feldspar. Almost 30 percent of the hypersthene-bearing labradorite andesite is composed of calcic labradorite phenocrysts (An_{60-68}) armored by a rim of dust inclusions (cf. Anderson, 1941, Fig. 11c and p. 389; Kuno, 1950, p. 968). Outside the rim (An_{60}) containing dust inclusions a shell equivalent in composition to the groundmass plagioclase (An_{65}) has been deposited. The cores are believed to represent intratelluric plagioclase phenocrysts that were sealed off from reaction with the magmatic liquid just prior to extrusion, by the armor of dust inclusions. Consequently soda and lime that might otherwise have been furnished to the interstitial regenerated liquid were withheld in the calcic plagioclase, and a femic-, potash-rich liquid was formed that was considerably off the line of liquid descent of other Umnak magmas. The minerals of the original quartz diorite that most likely dissolved to form the interstitial liquid are quartz, orthoclase, biotite, and hornblende, all fairly low-temperature (late) minerals in Bowen's reaction series. That biotite was probably one of the minerals to dissolve is confirmed by the presence of normative corundum in the computed groundmass (no. 23g, Table 7; Fig. 23).

The relatively minor anorthite-bytownite phenocrysts in the hypersthene-bearing labradorite andesite (no. 23, Table 8,

APPENDIX) were probably not precipitated by an andesitic magmatic liquid, for a few of these phenocrysts are armored by a thick zone of calcic labradorite. Gabbroic inclusions containing hypersthene, augite (diopsidic?), and bytownite-labradorite are believed to have contributed the isolated phenocrysts of more calcic plagioclase and some of the augite and hypersthene in the southwestern Umnak lavas. Thus a minor quantity of gabbroic rock or magma may have been assimilated or admixed with the quartz dioritic magma. This raises the important question as to whether most intratelluric phenocrysts in the labradorite andesite, with the probable exception of small olivine phenocrysts, are merely remnants of incompletely fused plutonic rock. Verhoogen (1937, p. 291) likewise found abundant gabbro and noritic inclusions intact in the Cascade-type hypersthene andesites of Mt. St. Helens.

The quartz-bearing olivine andesite flow (no. 22, Figs. 17-21), in addition to being possibly the product of mixing of two magmas contains further, perhaps even better petrographic evidence, that incomplete fusion of a quartz diorite has occurred. The three mutually-perpendicular thin sections cut of the analyzed handspecimen all show small, rounded, uniformly distributed blebs of quartz, never larger than 1 mm. Larsen (1938, p. 285) likewise found that quartz crystals are also evenly distributed in quartz-bearing lavas of the San Juan region, Colorado. Many plagioclase phenocrysts in the quartz-bearing olivine andesite flow of Umnak contain dust inclusions similar to those

in the hypersthene-bearing labradorite andesite. A few of the cores are even as sodic in composition as sodic andesine. Hornblende relics, now an opaque oxide-clinopyroxene aggregate, also are present. These features suggest that the quartz-bearing olivine andesite originated in part by fusion of quartz diorite, but that the time between fusion and extrusion was so short that fusion was even less complete than in the hypersthene-bearing labradorite andesite flows. Glomerophenocrysts of andesine-labradorite, ferrosugite with hypersthene cores, and interstitial glass containing apatite needles may represent coherent remnants of the incompletely fused quartz diorite.

It has been shown that a certain stage of partial or incomplete fusion of a plutonic rock such as quartz diorite does not necessarily yield a liquid that falls on the liquid line of descent of magmas but may yield a more femic liquid rich in potash. Such a liquid has the approximate composition of a lamprophyre. Thus, partial fusion over varying periods of time with incomplete reaction is capable of generating magmatic liquids that are off the liquid line of descent characterized by fractional crystallization and, hence may give rise to a different series of liquids than were present when the rock crystallized. Lamprophyre dikes and other rock masses rich both in femic and alkalic constituents may have arisen by partial or incomplete fusion of another rock. A somewhat similar concept has been suggested by Bowen (1928, pp. 269-273), who showed that fractional resorption of hornblende and biotite would give rise to

alkali-femic-rich liquids, which would crystallize as lamprophyres.

In addition to a quartz diorite source a minor amount of mafic magma appears to have been added to a quartz dioritic magma to produce the quartz-bearing olivine andesite. Small glomerophenocrysts of bytownite and diopsidic augite suggest that gabbroic rock also is included. Olivine phenocrysts in the quartz-bearing andesite occur separately and are corroded and embayed by the groundmass. The composition of the olivine, Fo_{86}, suggests a mafic magma such as an olivine basalt or possibly even a peridotite source. All the oxides except alumina in the computed chemical composition of the groundmass of the quartz-bearing olivine andesite fall off the curves of liquid line of descent, in every case on the concave side (see Fig. 10). This effect may be a closer approach to a straight line or rectilinear variation as would be expected in a mixture of two liquids. In the variation diagram (Fig. 11) showing composition of porphyritic rocks, the computed chemical composition of the olivine-free portion of the rock has been plotted and is similar chemically to the quartz diorite. Hence, the quartz-bearing olivine andesite could have been produced by a mixture of about 90 parts of quartz dioritic magma, similar in composition to the analyzed quartz diorite, and about 10 parts peridotic magma. This, of course, is not a unique solution; if the quartz diorite magma were only slightly less siliceous than the analyzed quartz diorite the quartz-bearing olivine andesite could also have been produced by admix-

ture of olivine basalt magma similar in composition to the analyzed olivine basalt of northeastern Umnak (no. 1, Table 7, APPENDIX). It is possible that this magma mixture was generated at the base of quartz dioritic sial where quartz dioritic and olivine basalt or peridotitic magmas could be formed and later find ample opportunity for mixing on the way to the surface. The heat may have been derived in part from orogenic forces--at least indirectly by depressing quartz dioritic sial deeper into the olivine basaltic or peridotic layer.

The two analyzed porphyritic lava domes of Bogoslof Island (nos. 34 and 35, Table 7, APPENDIX) present a more complicated history of several stages of incomplete or partial fusion followed by cooling (crystallization). It is perhaps significant that the earliest known dome extruded in 1796 is a siliceous andesite (no. 35) and the most recent dome extruded in 1927 is a subsiliceous basalt (no. 34). An analysis of the hornblende basalt of Fire Island, which was extruded in 1883, was made by T. M. Chatard for Merrill (1885, p. 33). Chatard's analysis, reproduced as Table 6, suggests that the 1883 dome was intermediate in composition between the 1796 and the 1927 domes (nos. 35 and 34, respectively, Table 7), even though this old analysis (Table 6) is probably of a low order of accuracy. From the meager evidence available it would appear that between the years 1796 and 1927, the extrusive products of Bogoslof have become decreasingly poorer in silica and increasingly richer in cafemic components.

TABLE 6

CHEMICAL ANALYSIS AND NORM OF HORNBLENDE BASALT FROM FIRE ISLAND DOME (NEW BOGOSLOF)

(T. M. Chatard, analyst; in Merrill, 1885, p. 33)

Analysis (wt.%)		Norm (wt.%)	
SiO_2.....	51.54	or.....	14.46
Al_2O_3.....	20.31	ab.....	29.60
Fe_2O_3.....	4.64	an.....	26.91
FeO.....	3.56	ne.....	3.55
MgO.....	3.16	di.....	12.01
CaO.....	9.55	ol.....	3.54
Na_2O.....	4.33	mt.....	6.73
K_2O.....	2.47	il.....	0.61
Ignition.....	0.34	ap.....	1.34
TiO_2.....	0.32		100.75
P_2O_5.....	0.57		
MnO.....	0.32		
Total.....	101.07		

The computed groundmass compositions of the two analyzed Bogoslof lava domes (columns 34 and 35, Table 7) fall off the liquid lines of descent indicated for Umnak magmas (Figs. 10, 17-21). The Bogoslof groundmasses contain much higher lime and potash than the Umnak groundmasses (Figs. 18 and 24). The high

lime in the Bogoslof hornblende andesite groundmass (magmatic liquid) is associated with low iron and titania in contrast to Umnak groundmasses (Fig. 25). This association is believed to account for the development of sphene in the Bogoslof andesite (no. 35) rather than ilmenite. The computed groundmass composition of the 1927 bytownite-salite-hornblende basalt turns out to be almost as subsilicious as the rock itself (cf. no. 34 and 34g, Table 9, APPENDIX), although there is a considerable enrichment in alkalis (no. 34g, Fig. 10), particularly potash. The groundmass orthoclase or anorthoclase that rims plagioclase phenocrysts reflects this potash enrichment. If water and other volatiles were added to the groundmass it would also have the composition of certain lamprophyre dikes, like the groundmasses of the hypersthene-bearing labradorite andesites of southwestern Umnak.

Assimilation or melting of solid rock?--In a youthful volcanic mountain belt where there is nearly an inexhaustible supply of heat and all the rocks are chemically similar, it may be difficult to distinguish between rocks originating by assimilation and rocks originating by fusion with mixing of magmatic liquids. The two processes probably would produce very similar rocks. Unlimited "assimilation" could occur if heat were slowly added to the system though the magma might not be sufficiently heated to eliminate all suspended crystals, because groundmasses of andesitic and basaltic wallrocks of a magma chamber would almost certainly be dissolved before the phenocrysts of suspended

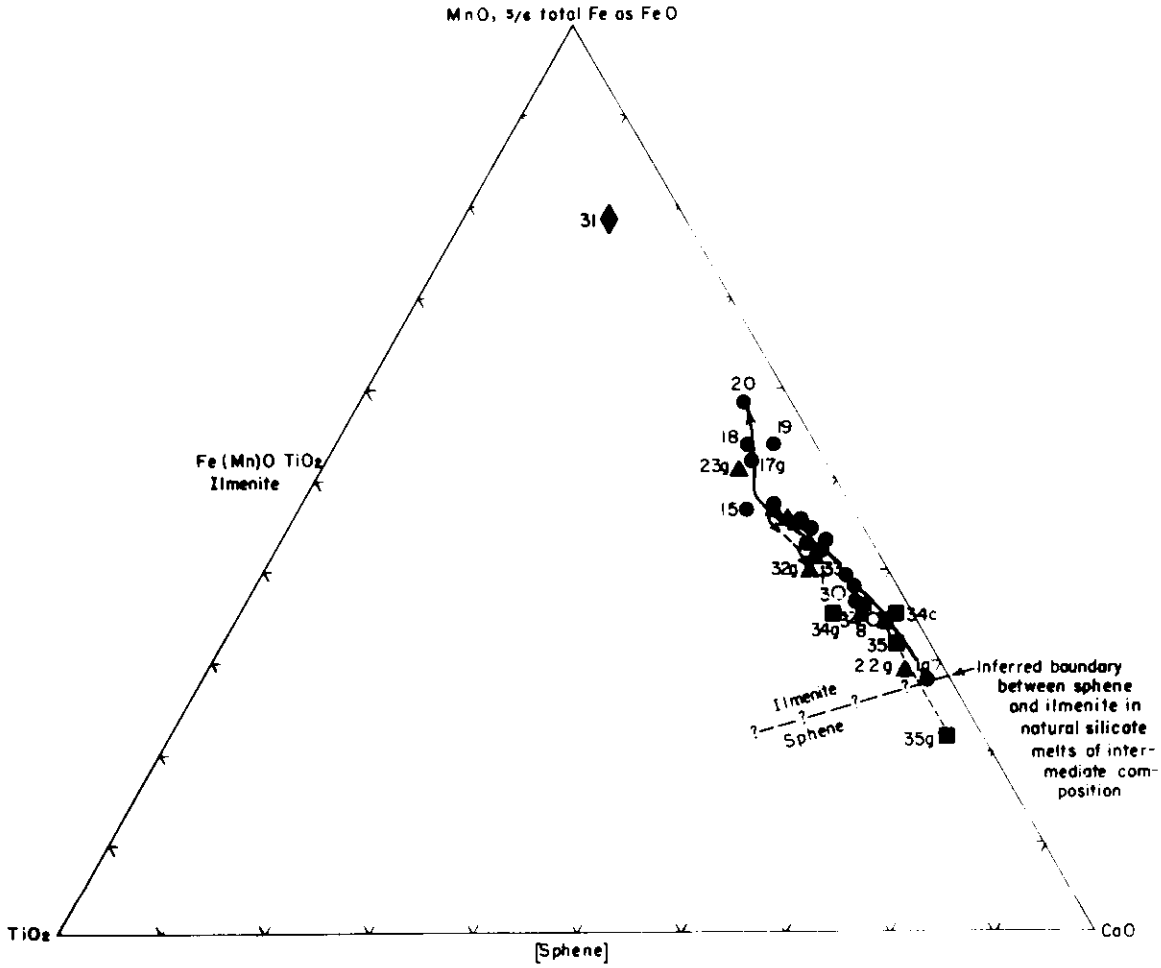

Figure 25.--Ternary plots of rock, crystal (phenocryst), and groundmass compositions with respect to titania, lime, and ferrous oxide in molecular percentages. Five-sixths of the total iron is represented as ferrous (see text), and manganese is included with the ferrous iron. Symbols and numbers within diagram are same as in figure 17.

olivine or anorthite crystals already in the magma. The bulk composition of the magma might be little affected either by assimilation or mixing of magmas of chemically similar wall rocks and both processes would be difficult to demonstrate. That rather siliceous lavas, such as nordmarkite, may contain considerable superheat has been demonstrated at one intrusive body in the Oslo region by McCulloh (1952, pp. 44-47).

Many northeastern Umnak aphyric basalt domes, which contain rare to sparse phenocrysts of anorthite and olivine, also contain irregular, corroded phenocrysts of andesine. The andesine, whatever its source, was in process of dissolving in the melt and probably owes its partial preservation to the viscosity and apparent low temperature of the lava at the time the andesine-bearing rock was included. Such andesitic material may have been completely assimilated by basaltic magma, supplied with heat through convection and from a continuing source (depth), without any petrographic evidence of assimilation. The beds of welded andesitic agglomerate in the Okmok formation contain basaltic xenoliths in all stages of disintegration. The basaltic xenoliths vary in texture from microlitic to intergranular and vary in composition, indicating that they did not originate by chilling of a basaltic magma by an andesitic magma. The welded andesitic agglomerates contain at least two ranges of composition of olivine, augite, and plagioclase phenocrysts; some of the phenocrysts are probably remnants of assimilated xenoliths and others may have been derived from a magmatic liquid somewhat different

in composition from the rock in which they are now embedded. Assimilation of wall rock by a primary magma and mingling of two or more palingenetic magmas may produce the same end result.

Palagonite tuffs.--The palagonitized rocks of Umnak are hydrated andesitic and basaltic pyroclasts, whose palagonitization appears to have resulted from hydration and oxidation at the surface during or immediately following emplacement. The water-free compositions of the Umnak palagonites do not fall on the liquid line of descent for other northeastern Umnak magmatic rocks (Figs. 10, 17, 19, and 21). The palagonites show anomalies in chemical composition that cannot be explained merely by addition of water and by oxidation of the iron. Possibly the original chemical constituents of the palagonites were somewhat reshuffled during palagonitization, possibly involving selective transfer by volatiles. Barth (1950) found that the water-free compositions of Icelandic palagonites agree fairly well with the compositions of the associated plateau basalts. Such is definitely not the case with Umnak palagonites as far as can be learned from two chemical analyses.

Metasomatic Rocks

Hydrothermally Altered (Potash Feldspathized) Rocks

Although direct field evidence is lacking, the hydrothermally altered rocks are probably metasomatized by a volatile fluid phase that escaped during the late stages of consolidation

of the Umnak quartz diorite or a similar plutonic rock. A similar alteration of the quartz diorite borders the granophyre dike (no. 33, Table 7). The typical hydrothermal alteration was the introduction of potassium, boron, and silicon to form adularia(?) tourmaline, and quartz, respectively. Mafic minerals are chloritized, serpentinized, or uralitized. Typical hydrothermal alteration minerals include pyrite, calcite, and two tourmalines that have selectively replaced plagioclase and ferromagnesian minerals, respectively. The presence of the two tourmalines indicates that boron was in the mineralizing fluid, which must have been volatile.

The chemical changes involving some important oxides are shown in the sequence of specimens 12 to 12½, Figures 18 and 19. The completely altered rock, no. 12½, contains the highest potassium content and probably the highest boron and silica of any rock on Umnak Island, though no chemical analyses are available for these latter constituents. Sodium, iron, calcium, and magnesium have been removed from the rock (see Table 3). The process is similar to granitization. Granitic textures were of course not formed, because the metasomatism probably took place at relatively slight depth; possibly within a few miles of the surface, as suggested by many quartz-lined vugs.

Boriferous alkaline chloride thermal springs of southwestern Umnak (Byers and Brannock, 1949, table 7) are believed to be somewhat contaminated remnants of fluid emanations similar to those that caused the hydrothermal alteration. The high

sodium-potassium ratio of the springs is what might be expected if adularia were being precipitated at depth at the expense of plagioclase (cf. Fenner, 1936, pp. 300-301). The silica content of the springs indicate that silicon is being transported also, although gains and losses of this element cannot be computed without additional analyses.

A fluid phase rich in water, boron and other volatiles would separate from the magma as a result of resurgent boiling, owing to high concentration of water in the residual phase, as shown by Bowen and Tuttle (1950, p. 511) and E. Gordon Smith (1948, pp. 539-541). The lack of detectible boron in the southwestern Umnak granophyre (no. 33, Table 7, APPENDIX) suggests that it may have been derived from a granitic residual liquid from which water, boron and other volatiles had already largely escaped. The high boron (0.003 percent) and water (2.2% by ignition content of the southwestern Umnak rhyolite suggests that it was extruded prior to splitting into a siliceous phase and a water-rich phase.

Albitized (Sodium Metasomatized) Rocks

Shaggy oligoclase-andesine cores enclosed by albite in the albite diorite (no. 25, Table 8, APPENDIX) indicate that the sodium (and silicon) was metasomatically introduced into the albitized rocks (nos. 25, 29, and 31, Fig. 18). The sodium metasomatism of the Umnak rocks probably took place at considerably lower temperature than the potassium metasomatism. Eskola,

Vuoristo, and Rankama (1937, pp. 61-69) have shown experimentally that anorthite reacts readily with sodium carbonate solution and silica at temperatures between 264° and 330°C and at about 220 atm. to produce albite and calcite, the minerals commonly observed in the albitized rocks. Silica, either in the form of quartz or an orthosilicate, reacted with soda and anorthite to produce albite. Thus, the experimental evidence suggests that the sodium metasomatism probably took place at a lower temperature than the potassium metasomatism. The sodium-silicon metasomatism may have been introduced by an early far-penetrating sodium-silicon aqueous fluid, which caused low-grade metamorphism at the time of emplacement of the quartz diorite.

However, it seems equally possible that the period of albitization was much earlier than the emplacement of quartz diorite pluton and its associated potassium-boron metasomatism. On the southern shore near the narrow part of Umnak (Pl. 1), potassium metasomatized volcanic rocks of low to moderate dip rest with pronounced angular unconformity on steeply dipping sediments and sills that have been both albitized and potash feldspathized. If the field and petrographic interpretation are correct, the albitization must have preceded the potassium metasomatism by a significant geologic time interval, because after the sodium metasomatism of the older rocks, there was erosion and extrusion of the volcanic rocks prior to potassium metasomatism. Unfortunately, without further detailed mapping on southwestern Umnak and collecting of more specimens for petrographic and chemical

study this relationship cannot be verified.

The argillite and tuff beds of southwestern Umnak have also been albitized and veined with calcite so that the soda, lime and possibly the silica contents of these rocks has been radically changed since deposition. The chemical analysis (no. 31, Table 7) of an argillite is graphically shown in Figures 17-24, and of all the rocks, the analyzed argillite falls farthest from rocks of normal igneous composition.

The problem of the origin of sodium-silicon metasomatism has been reviewed by Gilluly (1935, pp. 225-252; 336-352), who suggests a hydrothermal fluid derived through differentiation of a soda-rich (trondhjemitic) magma to account for keratophyres of Eastern Oregon. Sodium-rich basaltic rocks (spilites) of the Olympic Peninsula in northwest Washington are close to the Pacific basin like the Umnak rocks and are believed by Park (1946, pp. 318-320) to have resulted by rapid, repeated extrusion of thick basalt flows on the sea floor, followed by reaction between basalt and entrapped seawater. No features, such as pillow lavas, suggestive of subaqueous deposition were noted on southwestern Umnak. The meager evidence presently available slightly favors a pervasive sodium-silicon metasomatism of unknown origin; possibly it occurred sometime prior to the emplacement of the main quartz diorite pluton and its associated potassium-silicon metasomatism.

Tectonic Setting and Comparison with Other Circum-Pacific Rocks

Major Structural Alignments Suggested by the Volcanic Centers

A brief examination of Plate I reveals that most of the Recent vents of Umnak Island are grouped along three nearly parallel alignments trending slightly north of east. These three major alignments are the Mt. Okmok group, trending N. 82° E., the Inanudak Bay group, also N. 82° E., and the Southwestern Umnak group, trending N. 77° E. The vents of Bogoslof Island have a N. 15° W. alignment, which may be one end of an arcuate fissure, convex to the east and extending northerly from Cape Tanak on Northeastern Umnak.

The Okmok Volcano alignment, which is most northerly of the three alignments on Umnak Island, has the small cone south of Mt. Idak at its eastern end and extends westerly through several vents, approximately bisecting Okmok caldera. The western extremity is the cinder cone and lava flow of Cape Aslik. This trend is somewhat obscured and is perhaps debatable on account of the great dispersion of vents around Okmok caldera. The Inanudak Bay alignment is 7 miles south of the Okmok Volcano alignment and is marked by four Recent vents extending four miles east of the most westerly vent at Cinder Point in Inanudak Bay. The quartz-bearing olivine andesite vent, 5 miles south of the Cinder Point vent, apparently is not associated with a major alignment, but is intermediate in geographic position between

the Inanudak Bay and southwestern Umnak alignments. The southwestern Umnak alignment, the most southerly, is closest to the Aleutian trench. This alignment is marked at its eastern end by the group of three rhyolite domes, west of the head of Russian Bay (Pl. I), and extends westerly through Recent vents associated with Mounts Recheschnoi and Vsevidof.

One possible explanation for these three en echelon easterly alignments is that they are underlain by large gash fractures, developed between two shear zones within the Aleutian geanticlinal ridge, the southernmost (oceanic) block having a westward component of movement and the northernmost (Bering Sea block) having an eastward component. The major trend of the eastern Aleutians in the vicinity of Umnak is approximately N. 60° E., whereas the vent alignments trend approximately N. 80° E. Topographic expressions of extensive shear zones, approximately parallel to the major trend of the islands, have been noted on the plain south of Mt. Vsevidof. These particular faults (see Plate I) may not be active at the present time, but are probably parallel to northeasterly trending faults south of Umnak. In fact the straight, southwest-trending southern coastline of Umnak opposite Kigul Island southwestward to Cape Sagak and the southern coastline of Samalga Island may be fault controlled. In two other parts of the Aleutian arc, through-going faults parallel to the major trend of Aleutian arc and having large horizontal displacements have been recognized. In both places the block on the Bering Sea side has moved east with respect to the block on the

Pacific Ocean side. In the Aniakchak district, Knepper (1929, p. 207) reports

> The largest faults are thrusts in which the northwestern block has sheared along a general northeasterly line, moving northeastward a considerable distance and overriding the southeastern block to a slight or moderate extent. In other words, the movement has not been purely compressional, or perpendicular to the strike of the fault, but the [Alaska] peninsula has been subjected to shearing forces which tended to move the northwest side northeastward, and the thrusting and overriding have been incidental to a much more extensive horizontal movement.

Similar extensive shear zones have been observed by the writer while a member of Geological Survey party working on Attu Island, where the Bering Sea block has moved eastward relative to the block on the Pacific side. Thus, the through-trending fault or faults of the Aleutian arc appear to have a dominant horizontal component of right lateral movement similar to the San Andreas fault of California (Hill and Dibblee, 1953, p. 447).

Differences in Composition of Lavas Associated with Different Structural Alignments

The main vent alignments, whatever their origin, each are associated with a distinct effusive product, which may be of significance in attempting to correlate petrography with underlying rocks and structural features. The high hypersthene-bearing andesite peaks of southwestern Umnak nearest the Pacific basin contrast sharply with the low-lying, tholeiitic basaltic shield volcano (Okmok) and the flat-lying basalt (Fisk plateau) of northeastern Umnak. The alkali-lime index (Peacock, 1931) of the hypersthene-bearing andesite-rhyolite associated with the south-

western Umnak is 64 in contrast to 59 in the basalt-rhyolite suite of northeastern Umnak. The groundmasses of Bogoslof lavas, 25 miles north of Umnak, have an alkali-lime index of only 56 (see Table 3) and, according to Barth (manuscript in preparation, November, 1951), the lavas of the Pribilof Islands, about 150 miles north of Umnak, are highly alkaline, predominantly nepheline basanites. Thus a band of calc-alkalic and calcic rocks of Umnak and Bogoslof Islands of the Eastern Aleutian Arc are bordered on either side by more basic, alkalic rocks of the Pacific basin and the Pribilof area to the north.

The predominantly basaltic rocks of northeastern Umnak are associated with tensional fractures and cauldron subsidence in contrast to hypersthene andesite volcanic peaks of Southwestern Umnak. Two associations of the hypersthene andesite volcanoes, however, are believed significant; namely, they rest on a visible erosion surface underlain by sediments and plutonic intrusives, and are aligned along a zone that is about 15 miles closer to the edge of the Pacific Basin than the basaltic volcanoes of northeastern Umnak (Plate I). The petrochemical, geologic, and geographic associations of these southwestern Umnak cones suggests to the writer that they may be caused by compressional forces acting at different times on a slightly thicker sialic crust. Downbuckling of the base of this crust into a hotter zone would cause fusion of the base of the crust. The magmatic liquid thus formed would be eruptible during fracturing upon relief of the compressional stresses. Possibly such a

generated magma could be actually squeezed out during compression. The voluminous hypersthene-bearing labradorite andesite of southwestern Umnak is almost the chemical equivalent of the subjacent quartz diorite and may represent a portion of a batholith, albeit a rather cafemic one, that broke through to the surface. During late stages of orogeny, generated quartz dioritic magma, being more fluid than most granitic magmas might reach the surface and be extruded as a volcanic pile.

Similarity of Eastern Aleutian Rocks to Certain Japanese and Cascade Rocks

Volcanic suites somewhat similar to those of Umnak are known elsewhere in the Aleutian arc, in the Cascades of northwestern United States, and in Japan. Volcanoes with well-defined caldera depressions comparable to Okmok include Aniakchak, Fisher, and possibly others in the Aleutians (Coats, 1950, p. 43). These have not been studied in detail. Other Aleutian hypersthene-bearing andesite volcanoes with steep-sided cones similar to those of southwestern Umnak include Pavlof Voncano (Kennedy and Waldron, 1947, p. 18) Akutan Volcano (Byers and Barth, 1949, Table 1), and Kanago Volcano (Coats, 1947, p. 92). There are many other volcanoes which are probably transitional between these two extreme types (Coats, 1950, p. 43).

Williams (1935, p. 297) and Anderson (1941, pp. 404-405) have commented on the differences between the aphyric basalt-rhyolite association of shield volcanoes of the eastern, interior Cascades and the predominantly hypersthene-bearing porphyritic

andesite-dacite association of the more westerly High Cascades. The alkali-lime indices of the basalt-rhyolite association of the eastern Cascade ranges from 58-60½ (Anderson, 1941, p. 401), whereas the alkali-lime indices of the porphyritic andesite-dacite association of the High Cascade ranges from 61.5-63.9. Basaltic shield volcanoes, such as Newberry Volcano of central Oregon (Williams, 1935, p. 266) and the Medicine Lake Highland (Anderson, 1941, pp. 358-360), are further distinguished by large central calderas in contrast to the steep-sided andesite peaks of the Cascades. Thus, the basalt-rhyolite association of the eastern Cascades and the porphyritic andesite-dacite association of the High Cascades are analogous to the northeastern Umnak basalt-rhyolite association and the southwestern Umnak labradorite andesite-dacite-rhyolite association with respect to composition, land forms, geographic position, and possibly tectonics. Tension fractures have probably been operative in developing the Newberry and Medicine Lake Highland calderas.

Evidence is also forthcoming that the lavas of Mt. Ranier of the High Cascades were formed by partial fusion of underlying dioritic rocks. The Snoqualmie granodiorite, which grades into quartz diorite and diorite, forms a part of the basement upon which the Pleistocene Mt. Ranier hypersthene-bearing plagioclase andesites were extruded (Coombs, 1936, pp. 169-180). The lavas contain an earlier generation of large sodic plagioclase phenocrysts (An_{37-52}) with jagged outlines and rounded, resorbed corners (Coombs, 1936, pp. 178-180). The Mount Ranier

lavas, judging from Coombs' description, closely resemble those of Mount Recheschnoi on southwestern Umnak. The present writer, on the basis of the Umnak study, would interpret the corroded plagioclase phenocrysts in the Mt. Rainier lavas as vestiges of plagioclase derived from the partial fusion of an underlying diorite or quartz diorite.

If High Cascade hypersthene-bearing labradorite andesites are actually derived from incompletely fused sial, a plausible way to generate those magmas is by local downbuckling of the sial during an epoch of compression. The thickness of the sialic crust (geosyncline?) may have possibly been greater beneath the High Cascade peaks than beneath the shield volcanoes of the eastern, interior Cascades adjacent to the Columbia Plateaus. Verhoogen (1937, p. 292) has expressed a similar view in accounting for the high alumina lavas:

> Quite typical of these two volcanoes [Mount St. Helens and Mount Shasta] is the high alumina content; it is virtually independent of the silica content, whereas in other lavas the alumina curve falls off rapidly with increasing acidity. Much significance may be attached to this fact. . . . Another possibility is that the alumina content was increased by the assimilation of argillaceous sediments. In this connection it may be of some interest to recall that both Mount Shasta and Mount St. Helens probably rest on a basement of mudstones and shales.

The alumina saturation of Cascade rocks (except those of Lassen peak and a few small cones) is shown by plots of these rocks on a portion of the diamond-shaped (normative) diopside-anorthite-albite-corundum diagram (Fig. 26), already used to illustrate similar relationship of the Umnak rocks. The symbols

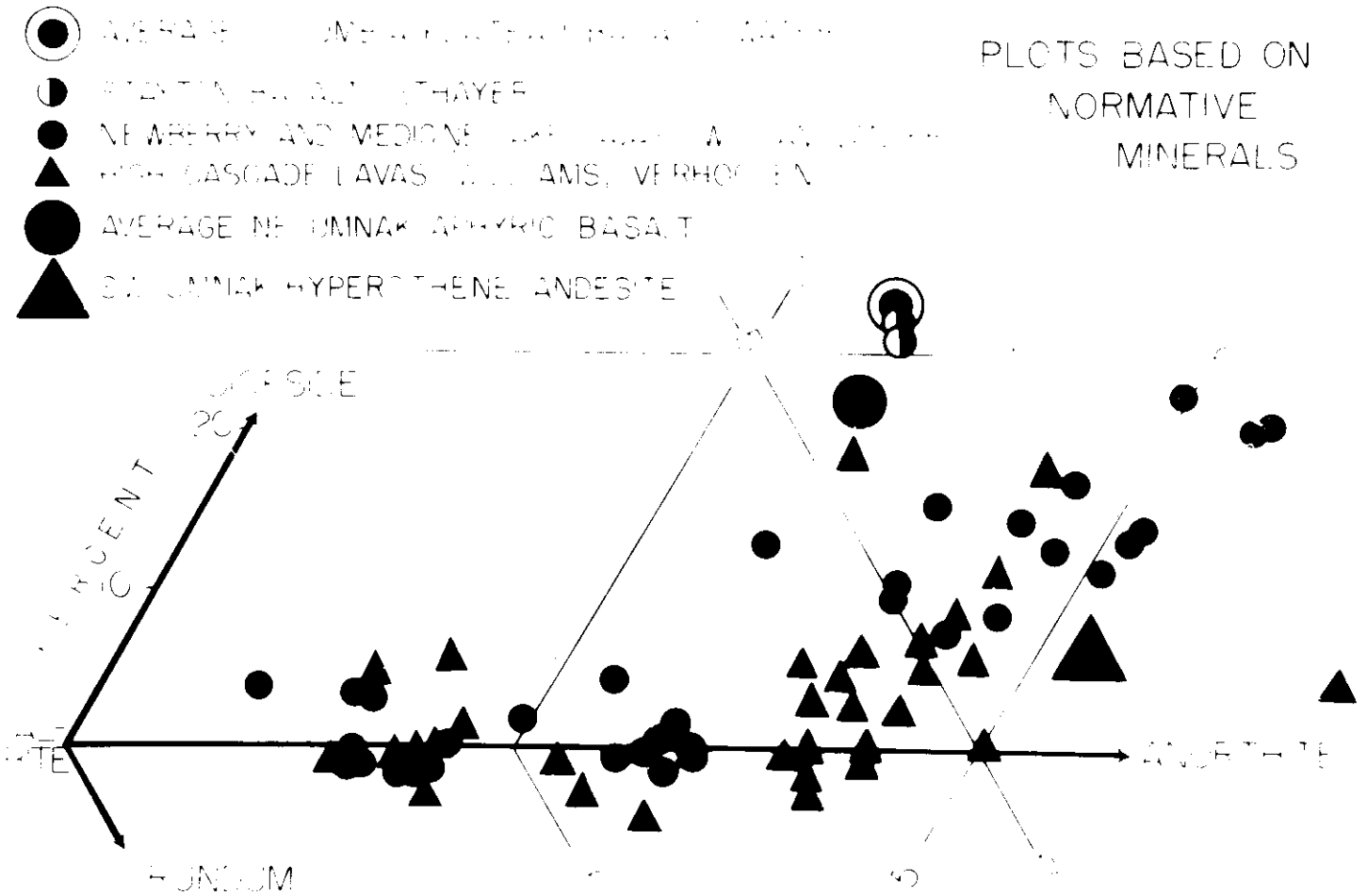

Figure 2. --Portion of normative diopside-wollastonite-acmite-corundum-quartz [illegible] principal Umnak-Bogoslof rock types compared with similar plots of Cascade rocks (Anderson, [illegible]; Thayer, [illegible]; Verbeek, [illegible]; A. C. Waters in Anderson, [illegible]; and Williams, [illegible], 1942). Plots are in weight percent.

used are also analogous to similar Umnak rocks. The plot of the average Columbia plateau basalt as computed by A. C. Waters is taken from Anderson (1941, p. 404). The presence or absence of hypersthene and hornblende in the Cascade rocks plotted in Figure 26 is shown on Figure 27. Where hypersthene and hornblende are absent, a capital "C" indicates Clinopyroxene as the chief mafic mineral, although clinopyroxene is ubiquitous in all Cascade rocks. The presence of hornblende is indicated on Figure 27, because in a few rapidly extruded Cascade extrusives, hornblende, which is lime-poor, formed in the intratelluric environment apparently instead of hypersthene. This diagram illustrates the tendency of hypersthene to occur in Cascade volcanic rocks whose plots fall close to the anorthite-albite join like those of the Umnak rocks. The high alumina in the High Cascade volcanic rocks, as in many of the southwestern Umnak rocks, is probably the principal factor in the separation of hypersthene, according to Bowen's reaction (1928, pp. 550-558).

The distinction between rocks of the eastern interior Cascades (Medicine Lake Highland and Newberry Volcano) and rocks of the High Cascades (Fig. 26) is not as readily apparent as from a consideration of the variation diagrams (Williams, 1935, pp. 295-300), because both the Medicine Lake and Newberry rocks contain hypersthene-bearing intermediate rocks with high alumina, and conversely the basal lavas of the High Cascades contain hypersthene-free basaltic andesites of moderate alumina content. Part of the overlap of these two Cascade suites is believed due

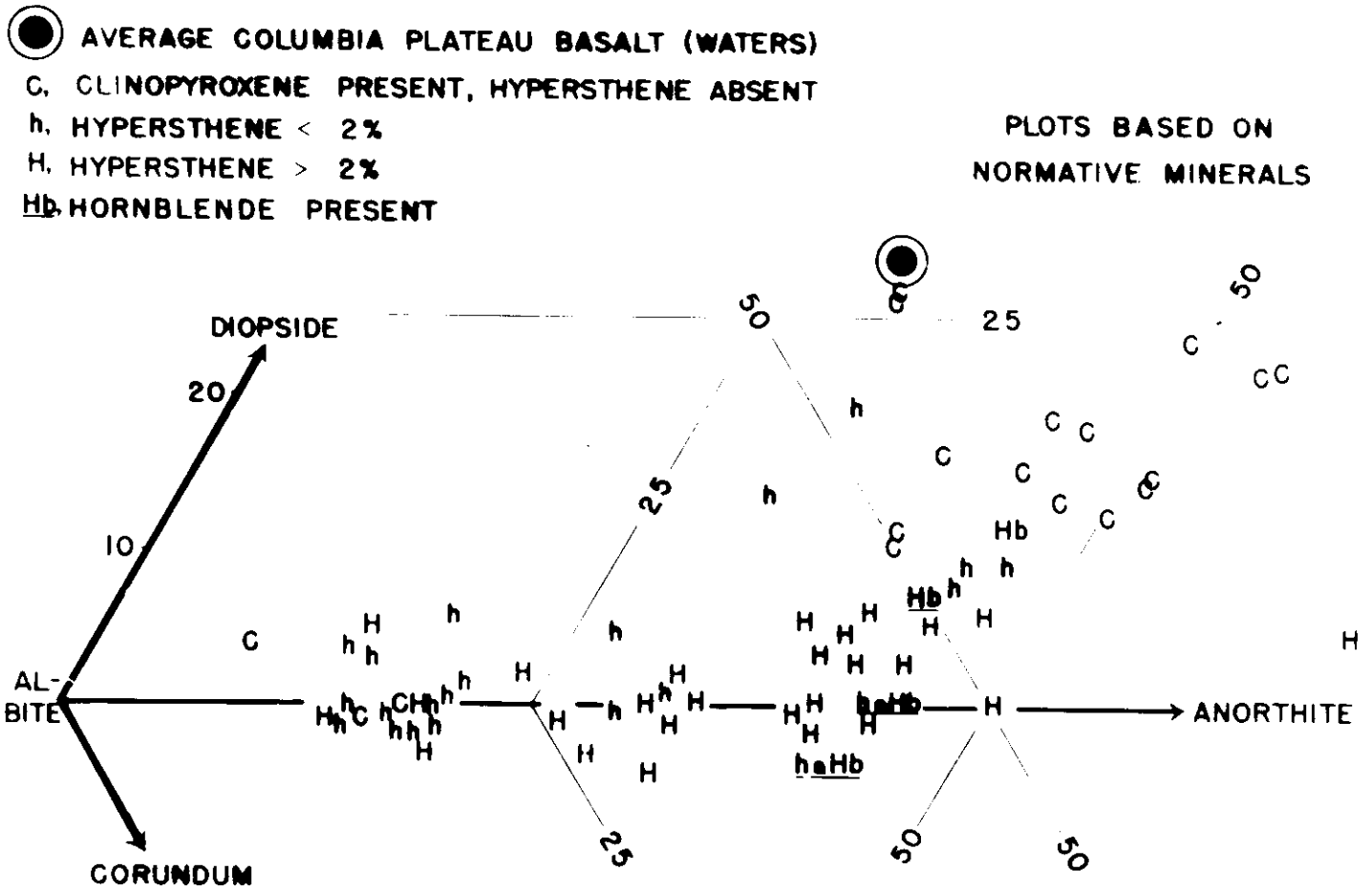

Figure 27.--Portion of normative diopside-anorthite-albite-corundum diagram showing presence or absence of hypersthene and hornblende in Cascade rocks whose plots are shown in figure 26.

unsatisfactory determinations of alumina in the chemical analyses. More likely, however, the distinctly continental environment of the Cascade Range would presuppose a thick sialic root, which may be nearly as thick under Newberry and Medicine Lake Volcanoes as beneath the High Cascades. Probably depth of origin of the magma is a greater factor in determining composition of Cascade lavas than geographic location. The average Columbia River basalt, however, is distinctly lower in alumina saturation than all Cascade lavas (Fig. 26) and furthermore, Aaron C. Waters (personal communication, 1952; Campbell, 1950, p. 76) has never observed hypersthene in any lava that he regards as a true Columbia River basalt. There is evidence that the sialic crust beneath the Columbia Plateau is not thin; ancient folded mountain ranges with plutonic masses trend into the western edge of the Columbia Plateau (Waters, 1933, p. 260). Hence, the source of the Columbia River basalts, possibly like basalts of northeastern Umnak, are probably derived from a deeper source and therefore are "uncontaminated" by alumina-rich sediments.

The Stayton basalts, as noted by Thayer (1937, p. 1647), closely resemble the typical low alumina plateau basalt of the Columbia River basalts, but, strangely enough, they are found on the western slope of the Cascade Range. The Stayton basalts are similar to the Columbia River basalts in age and possibly were extruded under the same tectonic environment.

A somewhat similar analogy to the two types of Umnak lavas is described by Kuno, 1950, pp. 982-995, at Hakone and Izu

volcanoes, Japan. Kuno distinguished a "pigeonitic rock series" and a "hypersthenic rock series" that are somewhat analogous to the northeastern Umnak and southwestern Umnak lavas respectively. The porphyritic hypersthene-bearing andesites of the "hypersthenic rock series" very closely resemble those of southwestern Umnak and are believed by Kuno (1950, p. 995) to represent assimilation of volatile-rich granitic and related rocks. The two rock series, however, are not separated as distinctly in space as the two Umnak rock types.

There are many features that seemingly contradict the concept of two idealized rock types. For example, Thayer (1937, pp. 1642-45) has shown by mapping a part of the Oregon Cascades that many of the High Cascade peaks of porphyritic andesite are underlain by much more voluminous basalts, although many of Thayer's so-called "basalts" would be regarded by the present writer as "basaltic andesite" because of their high alumina (ca. 18 percent) and silica (ca. 54 percent). Also a caldera-forming eruption has occurred not only at the basaltic shield volcano of northeastern Umnak, but also a somewhat similar type of eruption has occurred in the High Cascade porphyritic andesite-dacite volcano, Mt. Mazama (Williams, 1942, pp. 99-101). Furthermore, the rhyolite flows and domes around Newberry Volcano (Williams, 1935, p. 260) are much more voluminous than the single known rhyolite dome of northeastern Umnak. Could all these domes have been immediately derived by fractional crystallization in an underlying basaltic magma chamber? The silicious rhyolite dome flanking

the hypersthene-bearing labradorite andesite of southwestern Umnak is apparently a more silicious differentiate than any yet recognized from the High Cascade porphyritic andesites. Finally, the plagioclase in the Umnak basic rocks is in general much more calcic (An_{60-95}) than plagioclase in Cascade Rocks of similar composition and approaches the high lime plagioclases of Japanese basic rocks.

Some of these enigmas can perhaps be attributed to the more cafemic, less silicious composition of the sialic crust beneath Umnak. Possibly, the hypothesis outlined by Bucher (1950, p. 504) and others that the sialic crust of continents has grown through sedimentation and orogeny out from a central core finds some support in the more cafemic sialic crust of the continental border at the eastern Aleutian Islands.

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Northeastern Unmak

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Mode (volume percent):																				
Mimic fragments	—	—	1	—	—	—	—	—	—	—	—	—	1.1	—	—	0.6	—	—	1	
Crystals (largely phenocrysts) > 0.2 mm:	—	—	—	—	—	—	—	—	a/	—	—	—	—	—	—	—	—	—	—	
Plagioclase	—	36	1	20.8	30.2	28.9	16.8	a/	68.5	2.0	0.1	8.2	1.8	0.9	0.2	2.6	4.7	5.2	5.6	
Augite	—	0.1	< 0.1	12.5	0.2	1.1	1.1	a/	20.6	0.2	—	2.3	1.1	0.1	0.1	1.6	0.3	0.2	0.2	
Olivine	22.2	6	0.1	6.8	0.7	0.9	1.5	—	1.8	0.1	< 0.1	a/ 0.5	< 0.1	0.05	0.01	< 0.1	< 0.1	0.2	0.2	
Opaque oxides	0.05	—	—	—	—	—	—	—	4.5	—	—	—	0.1	—	0.1	0.1	0.2	0.2	0.2	
Groundmass or intersertal material	77.7	58	a/ 98	59.9	74.8	69.1	80.6	a/ 95	4.6	97.8	99.8	a/ 89	95.9	98.9	99.6	b/ 93.1	94.7	94.6	93.2	
Composition of less calcic plagioclase crystals	—	An_{65-90}	An_{70-80}	An_{87-94}	b/ An_{90-95}	An_{89-93}	An_{78-93}	An_{45-50}	An_{34-93}	An_{83-92}	An_{78-87}	An_{60-86}	An_{43-50}	An_{90-94}	An_{50-66}	An_{43-60}	An_{43-58}	An_{40} (?)	An_{43-58}	
Composition of more calcic plagioclase crystals	—	An_{77}	An_{75}	An_{91}	b/ An_{93}	An_{91}	An_{84}	An_{47}	An_{75}(?)	An_{88}	An_{83}	An_{68}	An_{70-90}	An_{91}	An_{60-85}	An_{51-67}	An_{51}	An_{70}	An_{51}	
Estimated average composition of less calcic plagioclase crystals	—												An_{46}		An_{58}(?)	An_{55}				
Estimated average composition of more calcic plagioclase crystals	—												An_{80}		An_{87}	An_{84}				
Approximate composition of groundmass plagioclase (± An_5)	An_{75}	An_{55}	—	An_{70}	An_{65}	An_{70}	—	—	—	An_{65}(?)	An_{60}	An_{60}	An_{42}(?)	An_{75}(?)	—	—	—	—	—	
Average β of augite crystals	—	—	—	1.695	1.703	1.698	1.695	—	1.697	1.706	b/ 1.699	—	1.696	—	1.700	b/ 1.710	—	1.705	1.703	
Average 2V of augite crystals	—	—	—	54°	55°	54°	54°	—	48°-54°	—	b/ 35°	—	—	—	—	—	—	—	—	
Composition of less magnesian olivine crystals	Fo_{81-90}	Fo_{69-78}	—	Fo_{76-86}	Fo_{68-75}	Fo_{76-80}	Fo_{75-78}	—	Fo_{59-71}	Fo_{70-75}	Fo_{60-69}	—	Fo_{68-73}	—	Fo_{50-70}	Fo_{23-29}	Fo_{30-35} (pseudomorphs)	$Fo_{28-?}$	Fo_{27-31}	
Composition of more magnesian olivine crystals	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	b/ Fo_{55-61}	—	—	—	
Estimated average composition of less magnesian olivine crystals	—	Fo_{75}	—	Fo_{84}	Fo_{71}	Fo_{78}	Fo_{77}	—	Fo_{65}	Fo_{73}	Fo_{66}	—	Fo_{70}	—	Fo_{60}(?)	Fo_{26}	Fo_{33}	—	Fo_{29}	
Estimated average composition of more magnesian olivine crystals	Fo_{86}	—	—	—	—	—	—	—	—	—	—	—	—	—	—	Fo_{72}(?)	—	—	—	
Refractive index of groundmass or intersertal glass	—	—	1/ 1.575	—	—	—	—	1/ 1.560	1.50	—	1.500	—	—	1.515	—	—	1.511	1.520	1.517	

Southwestern Unmak

Bogoslof

	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
Mode (volume percent):															
Crystals (including phenocrysts) > 0.2 mm:	—	—		a/	a/	a/	—	a/	a/	—	—	—	—	—	a/
Quartz	—	1.2	—	10.2	4	—	—	—	9	—	—	0.6	28.7	—	—
Potash feldspar	—	—	—	5.9	13	—	—	—	5	—	—	—	24.7	—	—
Less calcic plagioclase	1.2	7.6	29.1	64.9	71	0.3	1.9	3.8	72	1.8	—	3.3	43.7	< 0.1	26.5
More calcic plagioclase		1.3	2.5								—	0.1	19.6	19.6	3.0
Biotite (and minor chloritic alteration)	—	—	—	8.4	10	—	—	—	10	—	—	0.8	a/ 0.3	—	—
Amphibole (includes decomposed amphibole)	—	b/ 0.7	—	3.2	—	—	—	—	—	—	—	0.1	0.1	a/ 3.5	6.1
Clinopyroxene (epidote in column 33)	—	2.7	6.2	5.4	0.7	0.1	1.2	0.1	2	0.2	—	—	2.6	10.6	2.0
Orthopyroxene; hypersthene	—	0.4	2.9	0.2	—	< 0.1	0.2	0.5	—	0.2	—	< 0.1	—	—	—
Olivine	0.1	7.6	0.3	—	—	—	0.01	—	—	—	—	—	—	—	—
Apatite (includes 0.2 sphene in column 35)	—	—	—	0.3	0.2	—	—	—	0.1	—	—	—	0.01	—	0.3
Opaque oxides	—	0.3	0.1	1.5	1.1	—	0.2	0.3	2	0.2	—	< 0.1	0.1	1.9	1.2
Groundmass or intersertal material	98.7	78.2	58.9	< 0.1	—	99.5	96.5	95.3	—	97.6	100.0	95.1	—	62.3	60.9
Composition of less calcic plagioclase crystals	An_{78-84}	An_{35-55}	An_{60-68}	An_{27-59}	b/ An_{20-40}	An_{30-35}	An_{46-62} (?)	An_{48-60}	b/ An_2 (absent)	An_{48-55}	An_2 (absent)	An_{30-40}	An_{6-16}	An_{30-42}	An_{25-50}
Composition of more calcic plagioclase crystals		An_{78-84}	An_{88-92}			An_{48-55}	An_{78-88}					An_{55-68}		An_{78-94}	An_{78-94}
Estimated average composition of less calcic plagioclase crystals	An_{81}	An_{50}	An_{65}	An_{40}(?)	b/ An_2	An_{33}	b/ An_2	An_{54}	b/ An_2	An_{52}	An_2	An_{33}	An_{10}	An_{38}	An_5
Estimated average composition of more calcic plagioclase crystals		An_{80}	An_{90}		An_{30}	An_{52}	An_{93}	An_{40}(?)	—			An_{60}		An_{55}(?)	An_5(?)
Approximate composition of groundmass plagioclase (± An_5)	An_{75}	An_{60}	An_{65}	—	—	—	An_{45}(?)	—	—	—	—	—	—	—	—
Gamma index of biotite crystals	—	—	—	1.66	1.64	—	—	—	—	—	—	1.68	—	1.70	1.73
Beta index of amphibole crystals	—	—	—	1.67	1.674	—	—	—	—	—	—	1.68	1.64	—	—
Beta index of ferriferous c/ clinopyroxene crystals	—	1.710	1.708	1.697-1.705	1.700	1.710	—	1.705	1.701	1.705	—	—	—	1.705	1.707
Beta index of calciferous d/ clinopyroxene crystals	—	1.698	(present?)			1.704	—				—	—	—		
2V of ferriferous clinopyroxene crystals	—	50°	47°	54°	—	—	—	50½°	48½°	48°	—	—	—	57°	57½°
2V of calciferous clinopyroxene crystals	—	53°	—		—	—	—				—	—	—		
Composition of hypersthene crystals	—	En_{54-64}	En_{60-64}	—	—	En_{55-58}	—	En_{57-63}	—	En_{57-61}	—	En_{50-55}	—	—	—
Average composition of hypersthene crystals	—	En_{57}	En_{63}	—	—	En_{57}	—	En_{60}	—	En_{59}	—	En_{52}	—	—	—
Composition of olivine crystals	Fo_{69-77}	Fo_{84-88}	Fo_{68-78}	—	—	—	Fo_{67-72}	—	—	—	—	—	—	—	—
Average composition of olivine crystals	Fo_{74}	Fo_{86}	Fo_{71}	—	—	—	Fo_{70}	—	—	—	—	—	—	—	—
Refractive index of groundmass or intersertal glass	—	—	—	—	—	1.543	1.505	1.499	—	1.514	—	1.498	—	—	—

a/ Minimum size of crystals about 0.1 mm; modes of intrusive rocks include somewhat smaller crystals.

b/ Visual estimate. Rare hypersthene also present.

c/ "Ghosts" of olivine, now antigorite, penninite, quartz, and magnetite.

d/ Includes palagonitised glass, zeolites, etc.

e/ Includes 0.6 percent of calcite and 2 percent of chlorite, antigorite, quartz, and zeolites.

f/ Includes 0.1 percent of zeolite-filled vesicles.

g/ Includes felsic groundmass with microvesicles of quartz, zeolite, and magnetite.

h/ Based on optical determination of refractive indices; partial analysis for alkalis (Na + K = 1.14%) indicates composition of An_{24}.

i/ Data on groundmass augite.

j/ Micropoidic augite (β = 1.696) also present; probably xenocrysts.

k/ At least two distinct olivines, probably xenocrysts, with overlapping compositions.

l/ Data on unpalagonitized clear glass (siderovelane).

m/ Bleached biotite; probably a chlorite.

n/ Entirely decomposed to opaque oxide-clinopyroxene aggregate.

o/ Largely decomposed to secondary minerals: opaque oxide rims, clinopyroxene, fibrous green mica and amphibole, zonic plagioclase, brown glass with opaque needles, and carpholite(?).

p/ Determination by refractive indices (α = 1.527 - 8; γ = 1.538) indicates nearly pure albite.

q/ A few plagioclase crystals are zoned through entire range, An_{50-88}.

r/ Includes ferriferous augite and ferrosalite following classification of Poldervaart and Hess (1951, p. 474).

s/ Includes diopsidic augite, salite, and ferrosalite following classification of Poldervaart and Hess (1951, p. 474).

TABLE 9

RECALCULATED MOLECULAR OXIDES AND NORMS OF UMNAK - BOGOSLOF ROCKS a/, CRYSTALS b/, AND GROUNDMASSES REDUCED TO ONE METAL ATOM PER OXIDE c/

Northeastern Umnak

	1	1g	2	3	4	4c	4g	5	5c	5g	6	6c
Major oxides (water-free, recomputed to 100 percent)												
SiO_2	41.2	44.7	45.1	52.0	44.9	41.3	47.5	46.6	41.8	46.9	47.0	41.7
Al_2O_3	13.6	18.8	20.7	18.8	17.6	19.5	16.1	25.1	26.7	19.9	21.6	35.2
Fe_2O_3	3.1	3.4	2.9	3.7	2.0	0.4	3.0	1.8	—	2.7	1.2	0.1
Fe(Mn)O	4.6	2.5	5.0	3.3	4.8	3.6	5.8	4.3	0.6	6.0	5.5	[illegible]
MgO	24.5	12.6	9.1	6.6	13.2	19.4	8.9	5.0	1.5	6.6	6.4	[illegible]
CaO	9.2	12.6	11.0	8.9	12.7	14.7	11.2	11.6	17.5	8.9	11.9	17.3
Na_2O	2.9	4.0	4.5	4.4	3.5	0.9	5.4	4.4	1.8	5.4	4.9	1.7
K_2O	0.5	0.8	0.6	1.2	0.6	0.1	1.1	0.6	0.1	0.7	0.7	0.1
TiO_2	0.3	0.5	0.8	1.0	0.5	0.1	0.8	0.5	—	0.8	0.7	—
P_2O_5	0.1	0.1	0.2	0.1	0.1	—	0.2	0.1	—	0.1	0.1	—
CO_2	—	—	—	—	—	—	—	—	—	—	—	—
Norms												
Q	—	—	—	12.9	—	—	—	2.2	—	4.5	—	—
Or	2.5	4.0	3.0	6.0	3.0	0.5	5.5	3.0	0.5	3.5	3.5	0.5
Ab	14.5	20.0	22.5	22.0	17.5	4.5	27.0	22.0	9.0	27.0	24.5	8.5
An	25.8	35.0	39.0	33.0	33.7	46.2	24.0	50.2	87.0	34.5	40.0	83.5
Di	15.2	21.8	11.6	8.4	23.2	22.0	24.4	5.6	0.40	7.2	14.8	2.4
Di Wo	7.6	10.8	5.8	4.2	11.6	11.0	12.2	2.8	0.2	3.6	7.4	1.2
Di En	6.8	10.6	4.4	4.0	9.2	9.4	8.8	1.8	0.14	2.2	4.6	1.0
Di Fs	0.8	0.4	1.4	0.2	2.4	1.6	3.4	1.0	0.06	1.4	2.8	0.2
Hy	5.0	6.6	15.8	9.8	8.6	0.8	12.2	13.0	0.40	15.5	13.4	0.6
Hy En	4.4	6.4	12.2	9.2	6.8	0.7	8.7	8.2	0.28	11.0	8.0	0.5
Hy Fs	0.6	0.2	3.6	0.6	1.8	0.1	3.5	4.8	0.12	4.5	5.4	0.1
Ol	31.5	6.3	1.5	—	9.6	25.2	0.3	—	2.7	—	0.3	4.2
Ol Fo	28.2	6.1	1.2	—	7.8	21.6	0.2	—	1.9	—	0.2	3.5
Ol Fa	3.3	0.2	0.3	—	1.8	3.6	0.1	—	0.8	—	0.1	0.7
Mt	4.6	5.1	4.4	5.6	3.0	0.6	4.5	2.7	—	4.0	1.8	0.2
Il	0.6	1.0	1.6	2.0	1.0	0.2	1.6	1.0	—	1.6	1.4	—
Hm	—	—	—	—	—	—	—	—	—	—	—	—
Ap	0.3	0.3	0.5	0.3	0.3	—	0.5	0.3	—	0.3	0.3	—
Cc	—	—	—	—	—	—	—	—	—	—	—	—

	6g	7	7c	7g	8	9	10	11	12	12A (partial analyses)	12B (partial analyses)
Major oxides (water-free, recomputed to 100 percent)											
SiO_2	48.7	47.1	42.8	48.2	52.3	48.5	49.3	49.7	50.6	(For weight percents	
Al_2O_3	16.0	19.8	30.2	17.2	17.2	18.6	17.0	16.6	20.6	see table)	
Fe_2O_3	1.7	2.1	0.1	2.6	4.8	2.3	4.2	2.7	3.2	(d)	(d)
Fe(Mn)O	7.4	5.4	1.9	6.2	1.5	5.3	5.5	7.2	2.6	4.3	2.5
MgO	9.0	7.7	7.0	9.0	[illegible]	7.6	5.8	5.6	4.9	4.2	0.45
CaO	10.0	11.4	15.3	10.6	9.2	10.3	8.8	8.7	9.5	5.0	0.45
Na_2O	5.9	4.9	[illegible]	5.4	8.7	5.4	5.4	6.4	5.1	4.2	3.5
K_2O	1.0	0.6	0.2	0.7	1.5	0.9	1.5	1.5	1.7	3.5	7.0
TiO_2	0.2	0.8	—	0.9	0.7	0.9	1.1	1.3	0.7	....	....
P_2O_5	1.0	0.2	—	0.2	2.0	0.2	0.3	0.3	0.2	....	....
CO_2	—	—	—	—	—	—	—	—	0.9	....	....
Norms											
Q	0.2	1.1	—	2.0	10.0	2.5	4.6	3.4	9.9	....	....
Or	5.0	3.0	1.0	3.5	7.5	4.5	7.5	7.5	8.5	....	....
Ab	29.5	24.5	12.5	27.0	43.5	27.0	32.0	32.0	25.5	....	....
An	22.7	35.8	68.7	27.7	17.5	30.7	22.7	21.8	34.2	....	....
Di	20.8	15.6	6.4	19.2	9.4	15.4	15.2	15.2	6.0	....	....
Di Wo	10.4	7.8	3.2	9.6	4.8	7.8	7.6	7.6	3.0	....	....
Di En	6.2	5.4	2.6	6.4	4.6	5.4	5.4	4.2	2.8	....	....
Di Fs	4.2	2.4	0.6	3.2	—	2.2	2.2	3.4	0.2	....	....
Hy	16.6	14.8	1.6	14.4	—	14.2	8.6	12.6	7.4	....	....
Hy En	9.8	10.0	1.2	9.6	—	9.8	6.2	7.0	7.0	....	....
Hy Fs	6.8	4.8	0.4	4.8	—	4.4	2.4	5.6	0.4	....	....
Ol	—	—	9.6	—	—	—	—	—	—	....	....
Ol Fo	—	—	7.6	—	—	—	—	—	—	....	....
Ol Fa	—	—	2.0	—	—	—	—	—	—	....	....
Mt	2.6	3.1	0.2	3.9	1.8	3.4	6.3	4.1	4.2	....	....
Il	2.0	1.6	—	1.8	1.4	1.8	2.2	2.6	1.4	....	....
Hm	—	—	—	—	3.6	—	—	—	—	....	....
Ap	0.5	0.5	—	0.5	5.3	0.5	0.2	0.6	0.5	....	....
Cc	—	—	—	—	—	—	—	—	1.8	....	....

	13	14	15	16	16c	16g	17	17c	17g	18	19	20
Major oxides (water-free, recomputed to 100 percent)												
SiO_2	51.0	51.1	51.9	53.9	47.4	54.2	59.4	47.7	60.1	63.5	67.5	68.2
Al_2O_3	18.2	17.4	16.7	17.1	[illegible]	16.9	17.7	27.1	17.2	16.0	15.1	14.6
Fe_2O_3	2.1	3.0	2.0	1.4	0.9	1.5	1.0	0.9	1.0	1.5	0.4	1.0
Fe(Mn)O	6.4	5.3	7.3	6.3	5.1	6.4	4.1	2.7	4.2	3.2	1.9	1.2
MgO	4.7	5.6	4.2	4.1	7.5	3.9	1.7	1.7	1.7	0.7	0.1	0.1
CaO	8.1	8.3	7.3	6.8	13.6	6.4	3.8	10.2	3.4	2.9	1.5	1.2
Na_2O	6.7	6.4	6.9	7.2	5.0	7.3	8.3	8.3	8.3	8.0	8.4	8.5
K_2O	1.6	1.5	1.4	1.8	0.2	1.9	3.2	0.6	3.3	3.7	4.9	4.9
TiO_2	0.9	1.1	1.8	1.1	0.3	1.1	0.6	0.9	0.6	0.5	0.15	0.15
P_2O_5	0.3	0.2	0.5	0.3	—	0.3	0.2	—	0.2	0.1	0.04	0.04
CO_2	—	—	—	—	—	—	—	—	—	—	—	—
Norms												
Q	1.5	6.3	7.6	7.9	—	8.3	13.6	—	14.6	20.9	23.5	25.7
Or	8.0	7.5	7.0	9.0	1.0	9.5	16.0	3.0	16.5	18.5	24.5	24.5
Ab	33.5	32.0	34.5	36.0	25.0	36.5	41.5	40.5	41.5	40.0	42.0	42.5
An	24.8	23.7	21.0	20.2	37.0	19.2	15.5	46.0	14.0	10.7	4.5	3.0
Di	10.4	13.2	9.2	9.2	24.8	8.4	1.6	4.0	1.2	2.4	2.2	2.00
Di Wo	5.2	6.6	4.6	4.6	12.4	4.2	0.8	2.0	0.6	1.2	1.1	1.0
Di En	2.8	4.4	2.2	2.2	7.8	2.0	0.3	1.2	0.2	0.4	0.1	0.16
Di Fs	2.4	2.2	2.4	2.4	4.6	2.2	0.5	0.8	0.4	0.8	1.0	0.84
Hy	13.0	10.0	12.8	12.6	7.2	12.8	8.6	0.8	9.0	4.0	2.3	0.3
Hy En	6.6	6.8	6.2	6.0	4.6	5.8	3.2	0.5	3.2	1.0	0.2	0.04
Hy Fs	6.4	3.2	6.6	6.6	2.6	7.0	5.4	0.3	5.8	3.0	2.1	0.26
Ol	—	—	—	—	3.0	—	—	2.4	—	—	—	—
Ol Fo	—	—	—	—	1.9	—	—	1.4	—	—	—	—
Ol Fa	—	—	—	—	1.1	—	—	1.0	—	—	—	—
Mt	3.2	4.5	3.0	2.1	1.4	2.2	1.5	1.4	1.5	2.3	0.6	1.5
Il	1.8	2.2	3.6	2.2	0.6	2.2	1.2	1.8	1.2	1.0	0.3	0.3
Hm	—	—	—	—	—	—	—	—	—	—	—	—
Ap	0.8	0.5	1.3	0.8	—	0.8	0.5	—	0.5	0.3	0.1	0.16
Cc	—	—	—	—	—	—	—	—	—	—	—	—

Southwestern Umnak

	21	22	22c	22g	22-ol	23	23c	23g	24	25	26	27	28	29
Major oxides (water-free, recomputed to 100 percent)														
SiO_2	51.0	51.5	43.6	54.0	53.5	53.6	46.8	58.7	53.4	56.8	[illegible]	[illegible]	[illegible]	60.9
Al_2O_3	19.8	16.9	11.5	18.6	18.8	19.9	25.2	16.3	19.1	17.0	[illegible]	[illegible]	[illegible]	15.4
Fe_2O_3	1.2	1.4	1.4	1.4	1.6	1.5	0.3	2.3	1.6	1.9	1.5	1.8	1.5	3.1
Fe(Mn)O	6.3	3.8	7.2	2.6	3.2	4.0	4.4	3.7	4.1	4.5	4.8	4.3	3.3	1.8
MgO	5.3	12.1	26.7	7.6	7.1	5.6	5.3	5.9	5.3	2.8	[illegible]	3.1	1.7	2.8
CaO	7.9	7.6	6.3	8.0	8.4	7.7	12.7	4.0	6.9	3.5	3.6	5.6	4.2	2.8
Na_2O	6.2	4.3	3.1	4.7	4.7	5.3	4.9	5.4	6.5	9.8	8.3	7.7	8.2	10.9
K_2O	1.2	1.9	0.1	2.4	2.1	1.7	0.3	2.6	2.0	2.6	2.0	1.9	3.1	1.8
TiO_2	0.9	0.4	0.1	0.5	0.5	0.6	0.1	0.9	0.8	0.7	0.7	0.8	0.6	0.5
P_2O_5	0.2	0.1	—	0.1	0.1	0.1	—	0.2	0.3	0.3	0.3	0.1	0.2	0.1
CO_2	—	—	—	—	—	—	—	—	—	0.1	—	—	—	—
Norms														
Q	5.0	5.4	—	10.1	9.9	10.4	—	19.7	8.4	8.7	[illegible]	[illegible]	[illegible]	16.0
C	—	—	—	—	—	—	—	0.9	—	—	—	—	—	—
Or	6.0	9.5	0.5	12.0	10.5	8.5	1.5	13.0	10.0	13.0	10.0	9.5	15.5	9.0
Ab	31.0	21.5	14.5	23.5	23.5	26.5	24.5	27.0	32.5	49.0	41.5	[illegible]	41.0	54.5
An	31.	26.8	21.5	28.8	30.0	32.3	50.0	18.5	26.5	11.5	[illegible]	[illegible]	[illegible]	6.7
Ne	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Di	[illegible]	8.0	8.4	8.0	8.8	4.0	10.8	—	4.4	2.4	5.2	[illegible]	[illegible]	[illegible]
Di Wo	2.6	4.0	4.2	4.0	4.4	2.0	5.4	—	2.2	1.2	2.6	[illegible]	[illegible]	2.6
Di En	1.4	3.2	3.4	3.4	3.4	1.4	3.0	—	1.5	0.6	[illegible]	[illegible]	[illegible]	2.6
Di Fs	1.2	0.8	0.8	0.6	1.0	0.6	2.4	—	0.7	0.6	[illegible]	[illegible]	[illegible]	—
Wo	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Hy	17.6	25.5	24.0	14.2	13.6	14.6	9.8	15.2	13.4	10.2	[illegible]	[illegible]	[illegible]	[illegible]
Hy En	9.2	[illegible]	19.2	11.8	10.8	9.8	5.6	11.8	9.1	5.0	[illegible]	[illegible]	[illegible]	3.0
Hy Fs	8.4	[illegible]	4.8	2.4	2.8	4.8	4.2	3.4	4.3	5.2	[illegible]	[illegible]	[illegible]	—
Ol	—	—	[illegible]	—	—	—	2.7	—	—	—	—	—	—	—
Ol Fo	—	—	23.1	—	—	—	1.5	—	—	—	—	—	—	—
Ol Fa	—	—	5.4	—	—	—	1.2	—	—	—	—	—	—	—
Mt	[illegible]	2.1	2.1	2.1	2.4	2.2	0.5	3.4	2.4	2.8	2.3	2.7	2.3	3.9
Il	1.8	[illegible]	[illegible]	1.0	1.0	1.2	0.2	1.8	1.6	1.4	1.4	1.6	1.2	1.0
Hm	—	—	—	—	—	—	—	—	—	—	—	—	—	0.5
Ap	0.6	0.3	—	0.3	0.3	0.3	—	0.5	0.8	0.8	0.8	0.3	0.5	0.3
Cc	—	—	—	—	—	—	—	—	—	0.2	—	—	—	—

Southwestern Umnak (continued) and Bogoslof

	30	31	32	32c	32g	33	34	34c	34g	35	35c	35g
Major oxides (water-free, recomputed to 100 percent)												
SiO_2	61.8	66.1	71.8	56.5	72.5	71.6	43.7	41.0	45.8	56.5	45.6	64.7
Al_2O_3	17.4	13.0	14.5	21.5	14.1	14.2	20.4	21.0	20.0	20.2	23.8	17.5
Fe_2O_3	1.5	1.6	0.3	1.6	0.3	—	4.3	5.5	3.4	2.7	5.2	0.8
Fe(Mn)O	2.8	5.0	0.6	0.8	0.6	1.0	4.1	5.6	2.9	1.0	2.1	0.2
MgO	1.0	5.5	0.3	3.0	0.1	0.1	7.6	7.0	7.9	1.5	3.4	0.1
CaO	3.5	1.0	1.2	5.1	1.0	0.9	12.0	16.9	8.8	6.4	11.2	2.8
Na_2O	7.7	6.5	6.4	8.9	6.2	[illegible]	4.8	2.1	6.4	7.6	7.3	7.9
K_2O	3.4	0.6	4.7	2.0	4.8	5.7	1.9	0.3	3.0	3.5	0.6	5.6
TiO_2	0.6	0.5	0.1	0.6	0.2	0.1	1.0	0.6	1.3	0.4	0.7	0.1
P_2O_5	0.2	0.1	0.1	—	0.1	0.02	0.3	—	0.4	0.2	0.1	0.3
CO_2	0.1	—	—	—	—	—	—	—	—	—	—	—
Norms												
Q	19.9	34.0	35.9	10.6	37.5	[illegible]	—	—	—	11.2	—	19.8
C	0.1	4.3	1.4	0.4	1.5	0.4	—	—	—	—	—	—
Or	17.0	3.0	23.5	10.0	24.0	28.5	9.5	1.5	15.0	17.5	3.0	28.0
Ab	38.5	32.5	32.0	44.5	31.0	[illegible]	20.5	8.5	29.0	38.0	36.0	39.5
An	15.5	4.0	5.0	25.5	4.0	[illegible]	34.2	46.5	26.5	22.7	39.8	10.0
Ne	—	—	—	—	—	—	2.1	1.2	1.8	—	0.3	—
Di	—	—	—	—	—	[illegible]	18.8	30.4	[illegible]	5.6	12.0	0.4
Di Wo	—	—	—	—	—	[illegible]	9.4	15.2	5.8	2.8	6.0	0.2
Di En	—	—	—	—	—	[illegible]	8.2	11.4	5.6	2.8	6.0	0.2
Di Fs	—	—	—	—	—	[illegible]	1.2	3.8	—	—	—	—
Wo	—	—	—	—	—	—	—	—	—	—	—	0.4
Hy	4.8	18.4	1.2	6.0	0.7	[illegible]	—	—	—	0.1	—	—
Hy En	2.0	11.0	0.6	6.0	0.2	[illegible]	—	—	—	0.1	—	—
Hy Fs	2.8	7.4	0.6	—	0.5	[illegible]	—	—	—	—	—	—
Ol	—	—	—	—	—	—	5.8	2.5	7.7	—	0.6	—
Ol Fo	—	—	—	—	—	—	5.2	1.9	7.7	—	0.6	—
Ol Fa	—	—	—	—	—	—	0.6	0.6	—	—	—	—
Mt	2.3	2.4	0.5	0.6	0.5	—	6.4	8.2	4.8	1.5	4.2	0.3
Il	1.2	1.0	0.2	1.2	0.4	0.2	2.0	1.2	2.6	0.8	1.4	0.8
Hm	—	—	—	1.2	—	—	—	—	0.2	—	2.4	0.6
Ap	0.5	0.3	0.3	—	0.3	0.05	0.8	—	1.1	0.6	0.3	0.8
Cc	0.2	—	—	—	—	—	—	—	—	—	—	—

a/ Numbers of columns correspond to those in table 7; c, crystals; g, groundmass; -ol, minus olivine crystals.

12A and 12B are partial analyses of hydrothermally altered (potassium metasomatized) rocks similar to No. 12.

b/ Phenocrysts and xenocrysts > 0.1 or 0.2 mm (See table 8).

c/ After Niggli, 1936, pp. 295-317, and Barth, 1945, pp. 11-13.

d/ Total iron as FeO.