Some Effects of Recent Volcanic Ash Falls With Especial Reference to Alaska

By RAY E. WILCOX

INVESTIGATIONS OF ALASKAN VOLCANOES

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PREFACE

In October 1945, the War Department (now Department of the Army) requested the Geological Survey to undertake a program of volcano investigations in the Aleutian Islands and Alaska Peninsula area. The first field studies were made during the years 1946–48. The results of the first year's field, laboratory, and library work were hastily assembled as two administrative reports, and most of these data have been revised for publication in Geological Survey Bulletin 1028. Part of the early work was published in 1950 in Bulletin 974–B, "Volcanic Activity in the Aleutian Arc," and in 1951 in Bulletin 989–A, "Geology of Buldir Island, Aleutian Islands, Alaska," both by Robert R. Coats. Additional fieldwork was done during the years 1949–54. Unpublished results of the early work and all the later studies are being incorporated as parts of Bulletin 1028. The investigations of 1946 were supported almost entirely by the Office, Chief of Engineers, U.S. Army. From 1947–55 the Departments of the Army, Navy, and Air Force joined to furnish financial and logistic assistance. The Geological Survey is indebted to the Office, Chief of Engineers, for its early recognition of the value of geologic studies in the Aleutian region, and to the several military departments for their support.

CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

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By RAY E. WILCOX

ABSTRACT

Most historic and late prehistoric volcanic eruptions of Alaska have yielded a high proportion of fragmental material in the form of ash, whose effects are felt over wider areas than those of lava flows because of the wide distribution of ash by winds. Some 6 cubic miles of fragmental material was erupted during the first 3 days of the spectacular Mount Katmai eruption of 1912, and much of it was spread over large areas of the Alaska Peninsula and Kodiak Island, producing extensive, but not permanent, damage. Less intense Alaskan eruptions were those of Okmok Volcano in 1945, Trident Volcano in 1952, and Mount Spurr in 1953.

Because of the scantiness of records of Alaskan eruptions and their effects, data from several better documented eruptions in other parts of the world are used here to fill in the range of behavior expected of future Alaskan eruptions. The importance of wind directions, wind speed, and rainfall in affecting the distribution of ash fall is illustrated by the eruptions of Hekla in Iceland, Volcán Quizapú in Chile, Gunung Kelud in Java, and Parícutin in Mexico, and by that of Mount Katmai in Alaska. Wind rose diagrams compiled from upper-wind data at selected Alaskan stations enable crude estimates to be made of the probabilities of ash fall from future eruptions in particular Alaskan areas.

Much needless fear of volcanic eruptions can be prevented by a foreknowledge of the range of effects that may be expected. The danger from poisonous gases, for instance, is seldom present, especially at the distances of most Alaskan communities from the potentially active vents. Few historic Alaskan lava flows have extended more than a few miles from their sources, and ash fall from the moderate activity that characterizes the great majority of Alaskan eruptions is commonly less dangerous than it is inconvenient. Nevertheless, volcanic activity in Alaska must command an attitude of respect because of its great potential and because of the chance that great damage will be done by the occasional extraordinarily strong eruption.

A mantle of ash more than a few inches thick over the countryside can radically increase runoff, with accompanying important effects on water supply, transportation, and agriculture, not only during, but also for some time after, the ash fall. Floods and mudflows may damage travel arteries, water reservoirs, and crop land. Ash fall itself may totally destroy growing

crops; but if the deposit is not more than a few inches thick, as at Kodiak Island in 1912, the next few seasons' plantings may result in normal or even improved harvests because of the beneficial mechanical and chemical effects of the ash that is worked into the old soil. Volcanic ashes commonly contain important amounts of calcium, potassium, and phosphorus available for plant nutrition—some are rich enough to encourage their use as fertilizers. The nearly complete lack of available nitrogen in most volcanic ash and the special chemical and physical properties of raw ash impose handicaps to its direct utilization as a soil, however, and these characters must be modified by some means for successful cropping.

The recovery of natural vegetation may make great progress in only a season or two in areas where the ash fall deposit is less than a foot thick and rainfall is adequate, as was shown at Kodiak Island after the eruption of Mount Katmai in 1912. With greater thickness of ash or in drier climate, the rate of recovery may be proportionately slower; the initial lack of available nitrogen in the raw ash appears to be an important obstacle. On bare lava flows the rate of recovery is enormously slower than on ash under similar climatic conditions; it is delayed both by the lack of nitrogen and by the slow rate of breakdown of the lava to a soil. The course of recovery usually does not wait on the formation of a residual soil, however, for plants get a foothold in crevices partly filled by airborne dust. In the case of lava flows covered by ash-fall deposits of the same eruption or by reworked clastic material, the progress of colonization by plants becomes much the same as that on ash fall alone.

INTRODUCTION

More than 250 separate eruptions have been observed from 39 Alaskan volcanoes during slightly less than 200 years of recorded history of the region, and many more eruptions must have gone unobserved in isolated areas. The frequencies of eruption have apparently varied considerably from decade to decade, and according to Coats (1950) eruptions have occurred with greater frequency about the years 1770, 1790, 1830, 1910, and 1930. There have usually been one or two eruptions a year, and no doubt similar behavior may be expected in the future. This paper will present descriptions of several past volcanic eruptions in Alaska, and, with the aid of this and information from certain eruptions in other parts of the world, will attempt to explore the problems that might have to be solved by communities or by organizations operating in the Alaskan region. Although ready solutions are not offered, it is hoped that this discussion will result in an awareness of the nature and scope of the problems that will help in dealing with them when they arise.

The writer is indebted to colleagues in the Geological Survey, especially G. A. Macdonald, for helpful criticism and suggestions in compiling this paper. An early draft of the manuscript was read and criticized by Dr. V. H. Cahalane of the New York State

Museum, and by Dr. W. D. Keller and Dr. E. R. Graham of the University of Missouri, and their help is gratefully acknowledged. Thanks are due Dr. Harry Wexler of the U.S. Weather Bureau for helpful discussion and for making available the date on which the map montages of figures 12 to 15 are based. The Coast and Geodetic Survey kindly furnished copies of the seismic record at College, Alaska, of the period before and during the eruption of Mount Spurr on July 9, 1953.

For the purpose of the present discussion the volcanic phenomena can be divided into two types: (1) lava flows, ash flows, and volcanic landslides; and (2) ash falls and gases. Damage to human habitation by flows of lava and ash has not figured prominently in Alaska, mostly because they extend only short distances from the volcanoes; in inhabited areas, however, the destruction could be complete. Damage by ash falls and gases may extend many miles downwind and be accompanied or followed by damage from floods and mudflows. Most consideration is here given to the effects of ash falls, both because of their more common occurrence and wider extent and because there seem to be more chances to reduce their harmful effects by directed effort.

The present paper does not deal with seismic sea waves ("tsunamis", often incorrectly called "tidal waves") and seiches generated by submarine earthquakes, some of which may be associated with volcanic eruptions. For these phenomena the reader is referred to Gutenberg and Richter (1954, p. 94) for a general discussion and especially to Imamura (1937, p. 126), who discusses them with special attention also to volcanic earthquakes and volcanic eruptions. Also left out of consideration here are the possible indirect effects of volcanic activity on climate. These effects, due perhaps mainly to absorption of sunlight by extremely fine ash blown to great heights in some major eruptions and spread by winds to form a world-wide blanket, have long been the subject of controversy and have recently been discussed by Wexler (1951).

The area seemingly most likely to be affected by volcanic activity includes not only the active volcanic zone itself, extending 1,600 miles from Mount Spurr near Anchorage southwestward out the Alaska Peninsula and westward nearly to the end of the Aleutian Islands chain (pl. 54), but also the adjacent areas that might be reached by ash falls, principally Kodiak Island, the Kenai Peninsula, and even points farther east. Few historic eruptions have been noted in other parts of Alaska, but there are several other areas in which the volcanic activity cannot with certainty be said to be extinct. In point is the late prehistoric eruption that blanketed the White River near the Canadian border with a great ash blanket, possibly about 1,400 years ago, according to Capps (1915). Here, also, should be noted the several mild steam and "smoke" eruptions from Mount Wrangell, suspected puffs from nearby Mount Blackburn and Mount Sanford in the Wrangell Mountains 200 miles east of Anchorage, and finally the very recent volcanic ash deposits around Mount Edgecumbe on Kruzof Island in southeastern Alaska and the Indian legends of its activity. Volcanic rocks and deposits of recent origin in British Columbia and the Yukon have been listed by Hanson (1934), and they indicate the possibility of eruptions from centers in areas adjacent to Alaska.

The geology of the volcanic region is known only in reconnaissance. Spurr's (1900) survey of southwestern Alaska gives most of the meager record of the appearance of the Katmai country before its physiognomy was drastically changed by the eruption of Mount Katmai in 1912. Atwood (1911) outlined the geology from rapid reconnaissance through parts of the peninsula and adjacent islands. Martin and Katz (1912) described the region near Iliamna Volcano, and Smith (1925) and Knappen (1929) briefly described Aniakchak volcano. Capps (1929, 1930, and 1935) described the geology of the southern Alaska Range, including Mount Spurr, the volcano at the extreme northeastern end of the volcanic zone, and furnished notes (Capps, 1934) on the geology of several islands in the Aleutian chain. Volcanic activity in the eastern Aleutians is briefly described by Jaggar (1908) in the account of his 1907 expedition. The volcanological and petrological results of the National Geographic Society's early expeditions to Mount Katmai are admirably reported by Griggs (1918, 1919*a* and *b*, 1922) and by Fenner (1920, 1923, 1925, 1930, and 1950). Finch (1934, 1935) reported on the activity of Shishaldin Volcano and Akutan Peak in the eastern Aleutians.

From 1946–54 the Geological Survey did reconnaissance geologic mapping, together with some geophysical work and observation of volcanic activity at selected localities in the Aleutians. The record of volcanic activity is thus somewhat more complete for this than for former periods, but many gaps exist in the record even after 1946. A list of historic eruptions was compiled by Coats (1950) and a more complete summary of Alaskan volcanoes is being prepared by Coats for the "Catalogue of Active Volcanoes of the World," to be published by the International Volcanological Association. Preliminary reports have been made on various parts of the Aleutians and the peninsula (Simons and Mathewson, 1956; Kennedy and Waldron, 1956; Coats, 1956*a*, *b*, and *c*) and others are in preparation. In 1953 and 1954 the National Park Service, in cooperation with the National Geographic Society and the Department of Defense, sponsored an expedition into the Katmai National Monument to study problems of geology, botany, and zoology arising from the 1912 eruption; the results are being prepared for publication by G. L. Curtis, V. H. Cahalane, and others.

GEOGRAPHY

The backbone of the Alaska Peninsula is the Aleutian Range, a zone of volcanoes and folded and faulted mountains (pl. 54) extending southwestward from the nonvolcanic Alaska Range. Still farther southwestward along the peninsula, the mountains are lower and the peninsula narrower and more indented; it is finally terminated by a saddle below sea level (Isanotski Strait), and the mountain range is continued as the mostly submerged Aleutian chain of island volcanoes. This chain extends westward in a long arc for a thousand miles with generally decreasing size of islands and increasing lengths of open water between. Kiska Volcano, 200 miles short of the western end of the chain, is the westernmost volcano known to have been active in historic time. Buldir volcano, 50 miles farther west, has been active in postglacial time and cannot be said to be extinct. Three hundred miles of open water separate Attu Island, the westernmost of the American Aleutian Islands, from the Russian Komandorskiye Ostrova, which in turn lie 200 miles from the Kamchatka Peninsula, part of a separate volcanic arc.

Northwest of the peninsula, the Bering Sea is quite shallow. The 600-foot depth line runs generally northwest from Unimak Pass and marks the beginning of a relatively steep slope westward down to depths of 12,000 feet. To the north of the middle and western parts of the Aleutian chain, the floor of the Bering Sea is quite flat, mostly at depths about 12,000 feet, broken only by the curving submerged ridge of Bowers Bank, which extends 150 miles northward from Amchitka Island. The south flank of the submerged Aleutian mountain range slopes down to a maximum depth of about 24,000 feet in the Aleutian Trench, thence the bottom rises to the rolling floor of the Pacific Ocean at depths between 15,000 and 20,000 feet. The beautiful geometric plan of the arc and of the trough in front of it has counterparts in the several other island arcs surrounding the Pacific basin; the

Kamchatka-Kurile arc, the Japan arc, and the Philippine arc are examples, which, with the Aleutian arc, undoubtedly reflect major crustal structures. All are volcanically and seismically active, and their volcanoes erupt materials chemically and mineralogically similar. The common structural interpretation is that the troughs mark the traces of major crustal fractures sloping toward the concave sides of the arcs (northward in the case of the Aleutians), and that there has been overthrusting along this fracture. The locus of surface volcanic activity lies some miles inside the trace of this supposed fault zone, presumably above the intersection of the major fracture with molten or potentially molten zones at depth.

The young volcanic rocks of the Aleutian arc are mainly of basaltic and andesitic composition, with minor amounts of rhyolitic or dacitic materials. Chemically they belong to the "calcic" suite of volcanic rocks, that is, one in which the ratio of calcium to alkalies is relatively high for a given silica content. On the peninsula the exposures of young volcanic rocks are subordinate in area to older sedimentary, metamorphic, and plutonic igneous rocks; on the islands the reverse is generally true, and there also much of the sedimentary rock is composed of only slightly reworked volcanic materials.

Most of the civil communities in the neighborhood of the main Alaskan volcanic zone are small and the intervening areas sparsely populated. Chief industries are fishing, cattle and sheep raising, and a limited amount of farming. The small population near the active volcanoes of Alaska is in sharp contrast to the situation in such areas as Java or near Vesuvius and Etna in Italy, where intense agricultural development extends to the bases or even up the flanks of intermittently active volcanoes. As pointed out by Sapper (1926), population density and economic development are important considerations in choosing practical protective measures against effects of volcanic eruptions.

The mainland end of the Alaska Peninsula is forested, but trees are virtually absent southwest of a line through Kodiak Island and the Mount Katmai region. Because the trees along this "timberline" are mostly young and not particularly stunted, Griggs (1934) concluded that the timberline is moving slowly westward under the influence of postglacial reforestation. On the islands a few scrub willows are found in protected valleys, but in general the trees grow and survive only where specially cared for. Even these do not thrive and their seedlings rarely persist (Bruce and Court, 1945). The dominant cover on the islands and the western part of the peninsula consists of grasses, sedges, mosses, and ferns growing on soils that have been designated as "tundra" type by Kellogg and Nygard (1951). Animal life on the islands is limited to mice, shrews, ground squirrels, foxes, rabbits, birds, and a few imported herds of sheep and caribou. Alaskan brown bear are known on Unimak Island, at the end of the peninsula, but not farther west.

CHARACTER OF ALASKAN ERUPTIONS

Much of the material erupted from Alaskan volcanoes during historic time has been pyroclastic, that is, it has been thrown out in a fragmental condition as ash, lapilli, or bombs, to travel downwind various distances depending on its frothiness or fineness and on the intensity of the winds. A minor quantity has been erupted as lava. The large amount of pyroclastic material in the older deposits of the peninsula and the islands attest to much explosive activity in the late prehistoric eruptions also.

The effects of predominantly explosive eruptions are different than those of predominantly effusive (lava-producing) eruptions. The ash of the explosive eruptions may be distributed much farther and over greater areas than the lava of effusive eruptions, and it may be accompanied by reactive gases and fumes and chemicals absorbed on the ash particles. The ash, as deposited, is generally more vulnerable than lava to weathering processes and is potentially more adequate as a soil, mainly because of the greater amount of surface exposure to soil-forming solutions; in addition, it is easily reworked and mixed into old soil, either naturally or artificially, because of its mechanical condition.

Four historic Alaskan eruptions, namely, the 1912 eruption of Mount Katmai, the 1945 eruption of Okmok Volcano, the 1952 eruption of Trident, and the 1953 eruption of Mount Spurr, provide examples of the range of past explosivity and intensity, no doubt comparable to those of the future. The Mount Katmai eruption is justifiably famous for its great intensity and extensive damage. The others were comparatively moderate and perhaps more representative. It is important to note that three of these, Mount Katmai, Trident, and Mount Spurr, had no record of previous eruptions in historic time and to bear in mind that some future eruptions no doubt will come from vents not known to have been recently active.

ERUPTION OF MOUNT KATMAI IN 1912

In early June 1912, Mount Katmai, after apparently centuries of quiescence, burst out in an eruption that was the greatest volcanic catastrophe in the recorded history of Alaska. More than 6 cubic miles of ash and pumice were blown into the air from Mount Katmai and the adjacent vents in the Valley of Ten Thousand Smokes. Measurements of thickness of ash by the 1953 Katmai Expedition led Curtis (1955) to conclude that, contrary to previous opinions, almost all the material was erupted from vents in the Valley of Ten Thousand Smokes and that Mount Katmai played only a subordinate role in the eruption. Much of the ash was carried by winds into the southeastern and northern quadrants (fig. 62). Although a great deal of it fell at sea, vegetation was smothered over thousands of square miles on the mainland and on Kodiak Island. The maximum depths of ash fall material in the vicinity of Mount Katmai were more than 50 feet, while 100 miles to the southeast at Kodiak village it was only about 10 inches—enough, however, to cause extreme damage to buildings and crops.

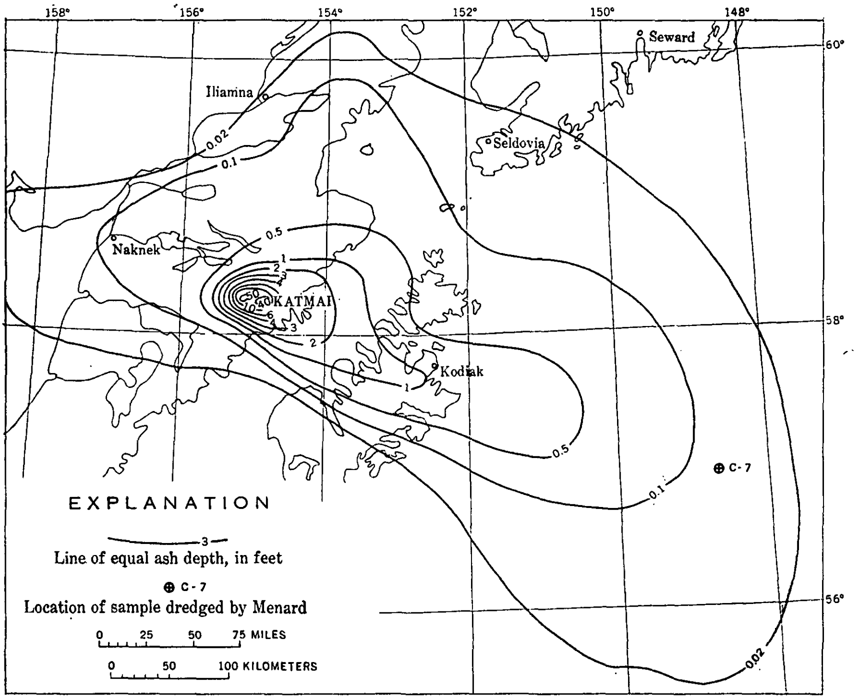

FIGURE 62.—Map of Mount Katmai and the Valley of Ten Thousand Smokes, Alaska showing thickness of ash deposit from the eruption in June 1912 (after Griggs, 1922, and Menard, 1953).

The most complete account of the eruption of Mount Katmai is given by Griggs (1922), who alludes to the lack of definite information about events leading up to the eruption and what was happening during the eruption. As much as 5 days before the eruption, earthquakes began at Katmai village on the Pacific shore some 20 miles from the volcano. The people of Katmai village had become so frightened by earthquakes that, on June 4, they moved 10 miles down the coast to camp at Cap Kubugakli, and when the eruption broke out on June 5, they proceeded another 20 miles along the coast to the village of Cold Bay (now known as Puale Bay). Villagers at Savonoski, about 20 miles northwest of Mount Katmai, likewise were frightened by the preliminary earth tremors but did not begin their move until the eruption started on June 5. Then, with great difficulty, they made their way the 50 miles to the village of Naknek on the north coast of the Alaskan Peninsula.

On the evening of June 5, a supposed eruptive cloud was seen from Cold Bay (now Puale Bay), 40 miles southwest of Mount Katmai, and during the morning of June 6 several large explosions were heard in Seldovia, 150 miles northeast. At about 1:00 p.m. on June 6 the great explosions of the main phase of the eruption began and continued for 2½ days. The major explosions occurred at about 3:00 p.m. and 11:00 p.m. on June 6 and at about 11:00 p.m. on June 7. From what can be made of the fragmentary accounts it seems that fairly strong eruptions continued for several weeks, after which there was a general diminution of the amount of ash being erupted but a continuation of earth tremors and gas-laden explosions for several months.

No seismographs were close enough to record the preliminary earthquakes, of which there were probably many too weak to be felt, but which would have been recordable instrumentally. The quakes accompanying the first few days of the eruption itself, however, were so strong that they were picked up by seismographs at Victoria, British Columbia, and Seattle, Wash. Air shock waves of the explosions were reported to have been seen from Seldovia, 150 miles away, and the noises to have been heard at Juneau, 750 miles away. Curiously, the noises were not reported to have been heard at Kodiak, only 100 miles away; this was attributed to the muffling effect of the ash cloud, presumably already in the air between the volcano and Kodiak Island. It has been suggested also that such phenomena may be due to refraction of sound waves by a layered atmosphere, perhaps in the manner in which Gutenberg and Richter (1931) accounted for the abnormal audibility, at several localities far inland, of naval gunfire off the coast of California.

All the observations of explosions were made from a great distance, and it was universally assumed that the eruptions took place from Mount Katmai. When Griggs and the National Geographic Society party finally reached the scene several years later they found that a huge caldera, 2 miles in diameter, had formed in the summit area of Mount Katmai. In addition, they found a valley extending westward from the western base of the mountain filled with a still steaming mixture of ash and lava lumps that must have moved as a tremendous ash flow from a source near the base of Mount Katmai. They concluded that this material had erupted first, and then been covered by several feet of layered airborne ash from the eruption of Mount Katmai. Actually their observations do not rule out the possibility that almost all the eruptive material came from the valley vents, as suggested by Curtis (1955). The shape of Mount Katmai before the eruption is only imperfectly known and there has been speculation whether a small crater might already have been present in its summit. It seems fairly well agreed that during, or very soon after, the eruption the great caldera formed in its summit, probably by collapse.

ERUPTION OF OKMOK VOLCANO IN 1945

Okmok Volcano is a caldera, 6 miles in diameter, in the broad mountain dominating the northeastern portion of Umnak Island, 200 miles west-southwest of the tip of the Alaska Peninsula. Eight eruptions had been reported before 1945, probably originating from more than one vent in the broad floor of the caldera; the last reported had occurred in 1938.

On June 1, 1945, a sharp earthquake was felt at the Umnak Island army base on the east side of the mountain. Nothing otherwise unusual was noted, and the rim of the caldera was hidden by persistent low clouds. On June 4, pilots reported a column of black ash rising from the southern part of the caldera to a height of 9,000 feet, and that evening the clouds lifted above the rim to reveal red reflections. Attempts to reach the site of eruption were thwarted until June 10 when the weather cleared. On this date ash was being erupted copiously from a small cinder cone near the southwest edge of the caldera floor and lava was flowing from the base of the cone. The lava stream broadened to about 40 feet and flowed at a rate of about 30 feet per minute at the surface. It was flowing in a wide circle to the east and north, undermining a local mass of ice in the southern part of the caldera. The airborne ash, being carried southeasterly at that time, had formed a coarse deposit several feet thick on the ice of the caldera floor and several inches thick on the rim of the caldera. Nine miles southeast only a fraction of an inch of ash was deposited.

The lava flow extended 4 miles in about a month of intermittent, but declining, activity. By late July, lava effusion practically ceased and the amount of ash in the eruptive column generally decreased until only steam was emitted, and that only in weak surges. In December 1945, there was a brief resurgence of activity with a small lava flow and light ash fall. In all, no significant damage was done by the ash fall, and it was apparent at an early stage that any large amount of lava would be effectively confined within the caldera.

ERUPTION OF TRIDENT VOLCANO IN 1952

Trident Volcano, with no record of previous historic activity, broke out in a flank eruption on February 15, 1952. Only about 5 miles southwest of Mount Katmai and 3 miles southeast of the vent area of the Valley of Ten Thousand Smokes, this was the first appreciable eruption in the Mount Katmai area since 1912, although there have been minor ash eruptions from close by Mount Mageik, Mount Martin, and Novarupta, and a few minor outbursts from Mount Katmai itself.

Much ash was ejected from Trident in the initial bursts and reached altitudes near 30,000 feet (Snyder, 1954), but clouds and bad weather prevented immediate identification of the source. The cloud cover persisted for 2 days and aerial observations, limited largely to the material rising above the clouds, indicated that besides Trident, at least one other vent, perhaps Mount Martin or Mount Mageik, must have been contributing to the eruptions of the first several days.

On February 18, the weather cleared to show a gray column of ash and steam rising from a vent at about 3,600 feet on the southwest flank of Trident, but only the usual amount of steam from Mount Martin and Mount Mageik. The Trident vent was apparently just beginning to produce a viscous blocky lava flow about 800 feet in diameter at the vent. Reports of "long streams of molten lava" were obviously erroneous and perhaps had their basis in the mudflows and floods composed of ash and melt water that coursed down the flank of the mountain.

Observation was hampered by the characteristically bad weather of the region at that season of the year, but flights on February 21 and 27 and March 4, 9, and 11 showed much-reduced explosive activity and ash production while the viscous lava built up a dome-shaped lobe three-quarters of a mile broad and a mile long downslope. Explosions recurred briefly on March 24. During the next few months the lava dome grew in height by addition of lava but increased little in length. Sometime before June 2, a landslide carried material from the toe of the lava dome another mile downslope. Brief minor explosions of ash continued through the summer, and another lava flow, apparently of more fluid material, moved out from the source area in a tongue that eventually reached a length of about 2½ miles. Only a few minor ash eruptions were noted during the fall and winter of 1952.

During the period of intense eruption, few observations of directions of ash transport could be made, and the inaccessibility of the area prevented measurements on the ground. On February 18, a blanket of ash was seen to cover the snow west of the vent, but new snow had effectively concealed the pattern of ash distribution of the first 2 days of eruption. All observations until February 27 noted winds carrying ash westward or northwestward, and ash covered the ground as far as 50 miles, around Naknek Lake. Subsequently the ash of subsiding eruptive surges was carried mainly into the southeast and east quadrants.

The volume of the lava erupted before June 1953 was computed to be between 300 and 400 million cubic yards (Snyder, 1954), and later information indicates that the volume of the dome approached 500 million cubic yards by October 26. The volume of ash, most of which was expelled in the early part of the eruption, is estimated to have been between 7 and 70 million cubic yards, making a possible total of 570 million cubic yards on 0.24 cubic mile of material.

ERUPTION OF MOUNT SPURR IN 1953

At 5:00 a.m. on July 9, 1953, a glacier-filled vent on the south flank of Mount Spurr erupted with tremendous violence, shooting a mushroom cloud like an atom-bomb cloud to a height of 60,000 or 70,000 feet in a matter of some 40 minutes. By good chance the eruption was witnessed from its onset by plane pilots whose photos and descriptions provide a valuable record of this type of eruption (Juhle and Coulter, 1955). The bulk of material of the eruption was blown out in only a few brief surges on July 9, and was carried due eastward across the city of Anchorage, 80 miles away. No lava flows occurred, and during the next few weeks the eruption subsided to a weak emission of steam.

The outbreak did not occur at the summit of Mount Spurr, but at a point about 7,000 feet above sea level on the south shoulder of the mountain just above the gorge of the Chakachatna River. No historic record of eruptions of this or other vents on Mount Spurr prior to 1953 are known, except for minor emissions of steam in 1927. Photos of Mount Spurr taken before July 9 show a continuous cover of ice over the area of the July 9 vent, with small glaciers extending down the flank. A mantle of pumice under the turf of the region, noted by Capps (1935, p. 87), indicates a relatively recent eruption from this or nearby vents.

The only premonitory symptom recognized seems to have been an increased fumarolic activity in the peak area noted by pilots during the latter part of May (Fairbanks News-Miner, May 21, 1953, p. 9). The seismic record at College, 300 miles northeast of Mount Spurr, showed that for the evening of July 8, and early hours of July 9, several brief disturbances occurred that may or may not have been connected with the imminent eruption. Because of their relatively short oscillation periods, which is characteristic of volcanic (local) quakes, it seems entirely possible that they may have been precursors of the eruption, although no epicenter distance determinations have been made on the records of these quakes. At a few minutes before 5 a.m. on July 9, the seismograph began recording swarms of confused "microseisms" (vibrations of small intensity and short period compared to those of a normal earthquake), which were quite different in character from normal microseisms.

The following pilots' account of the initial phase of the eruption is quoted from an Air Force press release of July 10, 1953:

> At 05h 05m Lieutenant Metzner noticed a column of smoke 60 miles ahead that was about 15,000 feet high and one-eighth mile wide. As he approached the smoke it was apparent that the eruption causing it was becoming increasingly severe with the smoke growing rapidly in height. At about 25 miles distance, the volcano was recognized as the 11,070-foot high Mount Spurr. Both planes approached the mountain at about 15,000 feet and circled the volcano at about 05h 25m. They noticed the continuing increase in the intensity and size of the column of smoke with lightning flashes through its core every 30 seconds. Smoke issued from the volcano in violent billows at the 7,000-foot level of the mountain caused by huge subterranean explosions. Tremors on the mountainsides were visible from the aircraft and were followed by snow slides on the mountain. The smoke had by now reached the 30,000-foot level, rolling upward and assuming the shape of the atomic bomb mushroom. Clouds of smoke were every shade of gray from black at the crater to pure white at the top. By this time the width had increased to about a mile at the base and 30 miles at its widest part.
>
> About 05h 40m Lieutenant Metzner climbed in order to estimate the height of the mushroom. The top of the stalk, or the bottom of the mushroom, was 30,000 feet and the top of the mushroom had climbed to 70,000 feet. Lightning was now flashing from top to bottom of the mushroom at three-second intervals.
>
> At about 6h 00m volcanic ash began falling from the mushroom on all sides and finally made the entire area hazy. A clear definition of the volcano and the mushroom rapidly faded and the patrol returned to its base.

Thus one gets a picture of a huge mushroom cloud, boiling upward to some 70,000 feet, and the beginning of ash fall as the mushroom spread and turbulence diminished. Wind from the west carried the great sinking ash umbrella due eastward and allowed practically no ash to fall on the west side of the volcano. At 9:00 a.m. a pilot reported ash still being erupted in great quantities, but another observation at noon showed the activity to have greatly decreased. At 3:30 p.m. resumption of strong activity was reported, and other eruptions apparently took place during the afternoon or evening.

The "microseismic" activity recorded at College, Alaska, which had begun in earnest just before 5:00 a.m., increased in intensity until about 9:00 a.m., then diminished rapidly to the normal microseismic level. A similar disturbance began again at about 3:30 p.m., built up to a climax by 5:00 p.m., and thereafter subsided rapidly. The coincidence of times of seismic disturbance and observed periods of strong explosive eruption leave little doubt that this peculiar seismic activity originated at Mount Spurr.

The ash cloud of the first eruptive surges of July 9 moved slowly eastward and by 11:00 a.m. the leading edge of the descending mushroom, by now greatly distorted, had spread out above Anchorage. While ash fell copiously on the northwest shore of Cook Inlet it was not yet falling in Anchorage, and the base of the ash cloud sloped upward to the east in its direction of movement. Fine ash started falling in Anchorage shortly before noon, when darkness caused the automatic switching system to turn on the street lights, and continued to fall copiously until 3:00 p.m. After 3:00 p.m. the rate of ash fall decreased but some continued through the night. By early morning only a pall of dust hung over the area.

On July 10 at 5:00 a.m. the vent was only steaming. At 3:30 p.m. an especially strong surge of ash-laden steam rose to 20,000 feet. From July 11–16, according to Juhle and Coulter (1955), the eruption consisted only of white steam clouds rising to maximum altitudes of 20,000 feet and occasional puffs of black dust and rock debris, most of which fell back into the throat of the volcano.

A mudflow or debris-laden flood must have occurred July 9 or 10, for Juhle and Coulter on their arrival at the volcano July 11 found a fresh debris dam across the Chakachatna River just below the Mount Spurr vent and a new lake, 5 miles long. The mudflow may have been caused by the torrential rains of the initial eruption or by melt water from the ice that apparently had filled the vent.

The zone of heavy ash fall covered an area some 25 miles wide extending almost due eastward from Mount Spurr (fig. 63). Thickest ash (and lapilli) deposits were not far from the volcano, and the appearance from the air of bowed-over foliage in the Beluga Lake area indicated a thickness of ash of several inches. At Anchorage the deposit was variously one-eighth to one-fourth inch in thickness, decreasing still more to the eastward where ash fall was reported at Valdez and within 30 miles of Cordova, some 200 miles from the origin. Additional reports of ash fall came from Kenai, Kalgin Island, and as far south along Cook Inlet as Tuxedni Bay, 80 miles south of Mount Spurr, near Iliamna. This ash could have been from a branch of the main cloud of the morning eruption on July 9, or from the clouds of the afternoon eruptions, by which time the winds may have shifted.

ERUPTIVE SEQUENCES

Few generalizations on the behavior patterns of volcanoes are valid, but in most eruptions the eruptive behavior may conveniently be split into three phases: preliminary symptoms, outbreak and climax, and declining phase. From volcano to volcano and from region to region, these phases may bear quite different relations to each other in duration and intensity.

The preliminary symptoms are of great importance, for they often make possible the successful prediction of an impending eruption. They may include earthquakes, slow earth movements (such as tilt of the ground surface), and disturbances in the local magnetic and electrical fields. Until recently, the established volcano observatories, such as that in Hawaii, gave most attention to earthquakes and tilting in their efforts to find bases for prediction of eruptions. Within the last decade, however, enough data on magnetic and electrical effects have become available to suggest that these also may become useful, once the behavior pattern for a particular volcano is established.

The tilting of the land surface near a volcano has been interpreted as being due to a general swelling of the volcanic structure that is brought about by increase of internal pressure or temperature or both. Tilting generally amounts to only a few seconds of arc, and although it may be detected by precise leveling across the volcano flanks, it is much more convenient to record its progress by sensitive tiltmeters placed at strategic points on the flanks. Local earthquakes occur from time to time in most volcanic regions without any apparent direct relation to volcanic eruptions. When the frequency and intensity of quakes originating below a

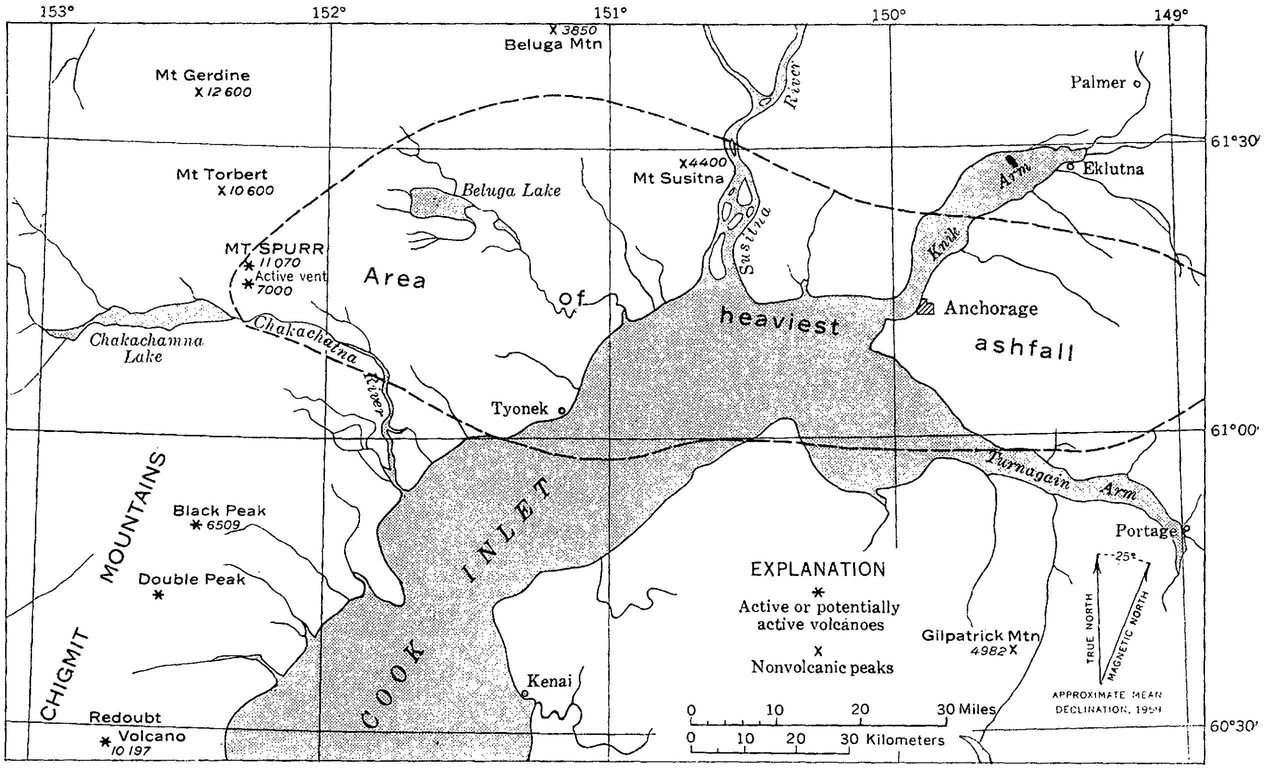

FIGURE 63.—Map of area affected by ash from the eruption of Mount Spurr, Alaska, in July 1953. Approximate area of heavy ash fall is outlined by dashed line.

particular volcano increase, however, it may be suspected that increasing volcanic pressure is causing rock failure and readjustments that may be the forerunners of an actual outbreak. Abnormal changes in the earth's local magnetic field and in local patterns of earth currents have been recorded in several areas, such as in the Japanese volcanic arc, in connection with volcanic eruptions, and observatories in several volcanic zones are making continuing studies of these phenomena in the hope that they will serve as indicators of impending outbreaks.

The actual outbreak of the eruption is usually sudden and may be regarded as the continuing crescendo of energy release that started with the premonitory earthquakes. After the initial outbreak the earthquakes commonly cease or decrease greatly in intensity and frequency. Eruptions commonly build up to a climax in a matter of hours or days and thereafter subside irregularly. Material may be erupted as flowing lava, pyroclastic blebs or fragments, or as both, accompanied of course by various amounts of gaseous products. Part, at least, of the driving force of the eruption must be the pressure of the pent-up gases that, once an exit to the surface has been made, rush toward it pushing the lava along. If the lava is very fluid, the expanding gas can be released quietly at the surface to produce lava fountains and smooth flow, such as are typical of Hawaiian eruptions. If the lava is less fluid, the rapidly expanding gases may disrupt the molten material explosively to produce pyroclastic material, such as was the case with the eruption of Mount Spurr in 1953. It is perhaps more common to find a combination of effusive and explosive activity, as occurred in the eruption of Okmok Volcano in 1945 and the eruption of Parícutin volcano in Mexico.

The declining phases of eruptions commonly continue for periods many times the length of the period from outbreak to climax. They are marked by intermittent resurgences of explosive or effusive activity, successive ones being of generally decreasing intensity and no doubt representing relief of minor pressures built up during readjustment to the new conditions. After the eruption is over and the record is complete, the climax of the eruption can often be pointed out easily in retrospect. During the eruption, however, it is not simple to say when the climax has been reached, for it is often approached in a series of explosions or surges of generally increasing intensity and sometimes increasing frequency. An observer who has witnessed several eruptions of the particular volcano might be better able to estimate when the decline begins, but unfortunately the explosive eruptions of a particular volcano are spaced erratically and often at intervals greater than the life span of the observer. Hence, although the pattern and phase sequence outlined above may be applicable in the general case, the duration of the separate eruptive phases is not commonly predictable and the transition from one phase to the next not always recognizable at the moment.

To be able to interpret the seismic and other preludes to eruptive activity at a particular volcano requires an investment in equipment and research in the area through a period of several eruptions, so that the usual pattern of events preceding an eruption is indicated. Even then, in certain areas or at certain volcanoes, the seismic or other prelude may be too brief to provide sufficient advance warning of the impending eruption. At the present time the lack of funds and difficulties of instrumentation hinder the establishment of a network of stations for studying the behavior of Alaskan volcanoes. The brief record from 1949–53 obtained by the Geological Survey observatory at Adak Island concerning the seismic phenomena and intermittent eruptive activity of the nearby volcanoes of Kanaga and Great Sitkin Islands has been of only limited value in indicating eruptive symptoms. It is now apparent that the task of mapping the behavior patterns of the sporadically active volcanoes of this sparsely populated extensive geographic region in a manner that would be of direct application to the problems of prediction would require a considerable outlay of money as well as a generation or two of human effort.

DISTRIBUTION OF ASH FALL

Because of the high proportion of explosive eruptions from Alaskan volcanoes, the manner of transportation and deposition of the fragmentary products of such eruptions and meteorologic conditions of the area are of interest. As the information on Alaska ash falls is meager, records of several ash falls from volcanoes in other parts of the world—those from Volcán Quizapú in Chile in 1932, Hekla in Iceland in 1947, Gunung Kelud in Java in 1919, and Parícutin in Mexico in 1943–52—have possible applicability to the Alaskan situation. The eruptions of the first three and the eruption of Mount Katmai in Alaska represent predominantly explosive eruptions in which the main bulk of material was ejected in the space of a few days or weeks and the resulting patterns of ash fall were relatively simple. The eruption of Parícutin represents a long-continued eruption through 9 years with complications in the pattern of ash distribution that were due to seasonal changes in wind direction.

MOUNT KATMAI

The ash fall of the Mount Katmai eruption in Alaska in 1912 was mainly in the quadrant east-southeastward across Kodiak Island, with a minor lobe to the north (p. 417). The map of ash fall thickness (fig. 62) is taken chieffly from Griggs' (1922) detailed book on the eruption, with slight modification of the isopachs (lines of equal thickness) in the Gulf of Alaska, where a dredged sample by Menard (1953) indicated somewhat thicker ash on the sea bottom than was inferred by Griggs.

According to Griggs (1922, p. 26) an area of 3,000 square miles was covered by ash a foot or more deep, and 30,000 square miles by more than an inch of ash. Small ash falls were also recorded at Fairbanks (550 miles distant), Juneau (750 miles) and in the Puget Sound region (about 1,500 miles). Griggs estimated that the total volume of ash fall was about 4¾ cubic miles, not counting the ash flow of the Valley of Ten Thousand Smokes.

Appreciable amounts of extremely fine ash blown into the stratosphere remained in suspension for months and caused spectacular red sunsets in many parts of the globe. The effect of the suspended ash on infall of solar energy, and thus on climate, has been discussed at length in several papers (Griggs, 1922, p. 33–44; Wexler, 1951).

At the village of Kodiak, 100 miles east-southeast, the ash began falling about 5:00 p.m. on June 6, following the unusual occurrence of thunder and lightning. Five inches of coarse ash were deposited during the night and some 6 inches of finer ash during the following two days. Subsequently very little ash fell there.

"Acid rains" were common at many localities, usually along with ash fall. This is spoken of in most reports as "sulfuric acid" although few actual determinations seem to have been made. According to newspaper accounts, on June 11 a "corrosive" rain fell at Seward, 250 miles from Mount Katmai, and at Cordova, 360 miles distant, painfully burning some persons and damaging vegetation and exposed metal. Fumes near Cape Spencer, 700 miles distant, were strong enough to tarnish freshly polished ship's brass in 15 or 20 minutes. On July 12, at Vancouver, British Columbia, 1,500 miles away, laundered linen goods of many housewives were reported to have been decomposed by the acid fumes. Curiously, no mention of damage to fabrics at points closer to the volcano was made by Griggs (1922), nor does he mention acid rains and fume damage at all at Kodiak. Perhaps the other effects of the ash fall were so strong as to overshadow those of acids and fumes.

HEKLA

Much specific data and pertinent discussion on ash falls and their effects are furnished in a series of papers on the 1947 eruption of Hekla volcano in southern Iceland, published by the Museum of Natural History at Reykjavík (Thorarinsson, 1951, 1954; Einarsson, 1949a and b, 1950, 1951; and Kjartansson, 1951). Hekla had been dormant since 1845 and had come to be regarded by some as extinct. Precursory earthquakes to the eruption of March 29, 1947, were too faint to be recorded at the nearest seismograph, 70 miles away at Reykjavík, but a few nearby residents had noted peculiar rushing noises for several nights prior to the eruption, without having been aware of their origin. Several residents were awakened in the early hours of the 29th by brief tremors that rattled windows, and the vibrations increased notably during the last half hour before the outbreak. All these phenomena would probably have produced records on a seismograph in the immediate vicinity.

The visible eruption cloud started from a single crater at 6:40 a.m. and rose very rapidly. To the accompaniment of earthquakes at 6:50 a.m. nearly the whole ridge line of the mountain split open, and eruptions spread along 2 miles of the fissure. By 7:00 a.m. a white umbrella cloud condensing above the eruptive mushroom had reached a height of 85,000 feet and by 7:10 a.m. a height of some 88,000 feet with the top of the darker eruptive material not much lower. This singular-appearing white umbrella had nearly disintegrated by 7:40 a.m. while winds of 40 to 60 miles per hour at the intermediate levels rapidly pushed the darker eruptive cloud southward. The material being erupted at this time was only reaching heights of some 30,000 feet (the base of the stratosphere), and in midafternoon it was only reaching to about 18,000 feet where it was maintained for 2 days.

Most of the fragmentary material was erupted during the first hour: about 60,000 cubic yards of solids at a rate of some 16,000 cubic yards per second (Einarsson, 1949a). Most of the lava probably flowed out in the first 10 hours, and the total of both lava and pyroclastic material ejected by the eruption, which continued at a much reduced rate for a year, is estimated at some 520 million cubic yards. The lava flows covered a relatively small area, estimated at 18 square kilometers (7 square miles) on the slopes and at the base of the volcano.

The chemical composition of the erupted material changed progressively during the eruption. The initial outburst was of brownish-gray material containing 62 percent silica and 9 percent total iron oxide; the later material was darker and contained 54 percent silica and 13½ percent iron oxide (Einarsson, 1950). The Hekla eruptions of 1845, 1766–68, and 1693 behaved similarly. The initial material is apparently dacite and later material andesite near basalt in composition.

Closely associated with the eruption were minor flash floods and mudflows, the water of which was thought by Kjartansson (1951) to have come from condensed volcanic steam and melted snow and ice. The largest floods came from a series of tongues of water pouring down the north face of the elongate volcano, probably not more than a few minutes after the eruptive outbreak. The total volume of the floodwaters was estimated at 3½ million cubic yards of water. After gathering at the headwaters of the Ytri-Rangá they rushed down the 40 miles to the sea as one simple wave less than 3 feet high, taking only a couple of hours to pass. On the volcano flanks steam issued from the multiple flood streams, and many persons noted the tepid character of the water along the lower reaches of the streams.

The ash cloud at first moved southward and laid down a mantle of ash, whose thickness varied as shown in figure 64. Some ash fell on ships at sea and as far away as Scotland and Finland. Thorarinsson (1954) carefully reconstructed the probable path of the eruptive cloud from reports of the ships and Finnish geologists, and from prevailing meteorological conditions; his map (fig. 65) shows that the cloud followed a curved path about 2,400 miles long and travelled at an average speed of about 50 miles per hour, based on its arrival time at Finland. Across Finland the ash fall was quite thin and was restricted to a zone only about 40 miles wide—surprisingly narrow considering the length of the trip from Iceland.

The relative amounts of particles of different sizes in the ash deposit control the manner in which the mantle will absorb subsequent rainfall and are important factors in the rapidity of soil development and release of inorganic nutrients to plants. Studies have therefore been made of the size characteristics of the ash from a number of volcanoes, and the report of Thorarinsson (1954) on Hekla is one of the most informative. Thorarinsson made many determinations on the range in size of ash particles at various distances and directions from Hekla, and his results for stations at intervals downwind for 100 km from the volcano are summarized in figure 66. The maximum diameter of ash particles

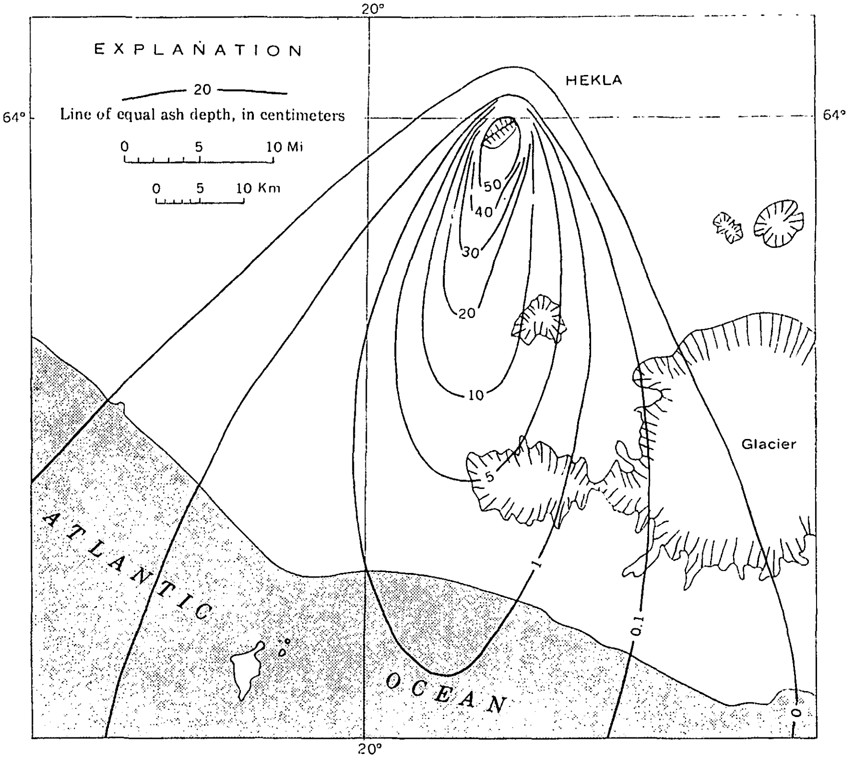

FIGURE 64.—Map of Hekla volcano in Iceland showing thickness of ash deposit from the eruption in March 1947 (after Thorarinsson, 1954).

at the vent is too large to be shown on this graph. It was about 6 centimeters at a distance of 3 kilometers downwind, 1.5 centimeters at 30 kilometers and 0.2 centimeters at 70 kilometers. The median diameter decreases similarly. While the maximum and median diameters give an idea of the range in size, more meaningful information may be conveyed by plotting the size range of the middle 80 percent of the material. Thus, in figure 66, at 3 kilometers from the volcano 80 percent of the material is between 0.15 and 5.0 centimeters diameter, whereas at 30 kilometers, 80 percent is between 0.05 and 0.50 centimeter diameter. It is shown here in this manner to emphasize that not only do the maximum, average and median sizes decrease at greater distances but that necessarily the size range of material must decrease also. The salient effect of the lower absolute size and smaller range of size of particles at greater distance is to decrease the permeability of the mantle to rainfall and hence to increase the possibility of excessive runoff and erosion out to the point where the thickness

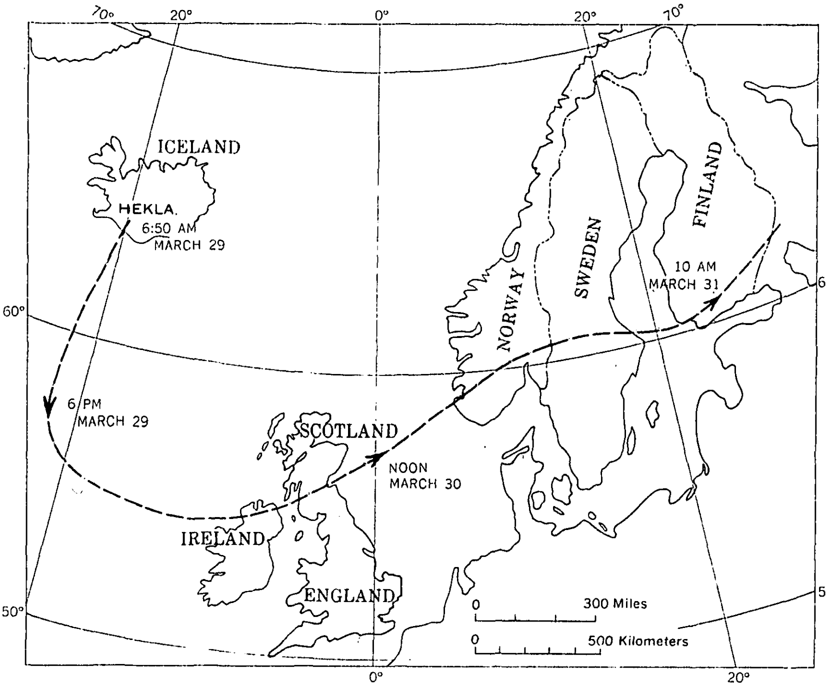

FIGURE 65.—Map of route of airborne ash from the eruption of Hekla volcano in Iceland, across Scotland and Finland, on March 29–31, 1947 (after Thorarinsson, 1954).

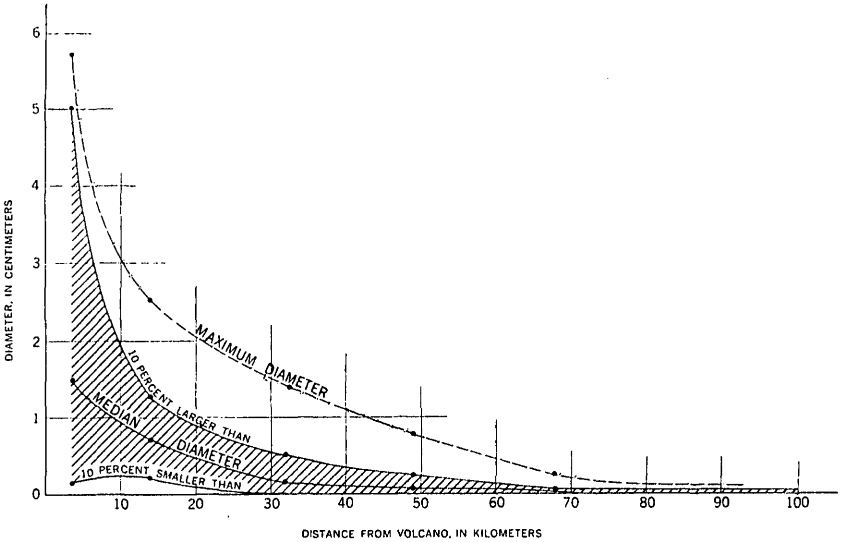

FIGURE 66.—Graph showing size range of ash fall in 1947 at increasing distances downwind from Hekla volcano in Iceland. At a particular distance 80 percent of the material is of sizes between the upper and lower solid curves (from data of Thorarinsson, 1954).

of the mantle becomes so small as to furnish little material to the runoff water.

VOLCÁN QUIZAPÚ

A brief, but catastrophic eruption of Volcan Quizapú in the Chilean Andes on April 10, 1932, projected a great quantity of ash to heights of about 45,000 feet to be carried eastward by strong winds and deposited in a belt across the whole width of South America. According to Brüggen (1932) and Vogel (1932), the strong explosions apparently began about noon on April 10, reaching a climax in the late afternoon. The eruption continued through the night and the next several days with decreasing intensity. Because of the heavy cover of ash and pumice in the source areas, it could not be determined subsequently whether there had been minor amounts of lava erupted also.

The large area of ash fall on land provided an exceptional opportunity for investigation of the pattern of ash distribution, and Larsson (1937) made a careful and detailed study of ash samples that had been collected along the path of the ash cloud and augmented it with the many published descriptions of the ash fall at various points. Larsson's map of the times of beginning of ash fall, reproduced in figure 67, indicates that the ash cloud

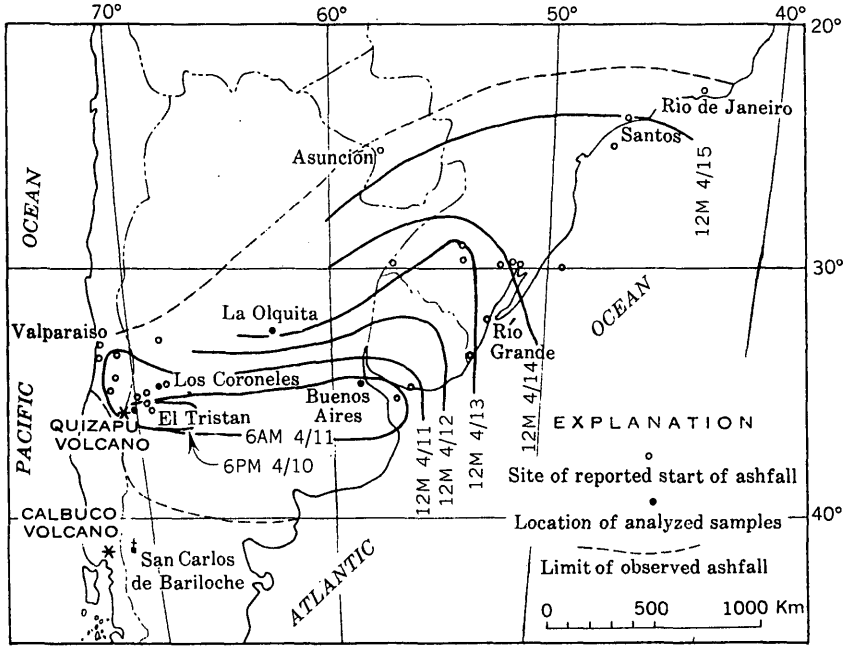

FIGURE 67.—Map of successive positions of ash front from the eruption of Volcán Quizapú in Chile, in April 1932 (after Larsson, 1937).

moved eastward at high speed but along a remarkably narrow front. Its arrival at Buenos Aires, Argentina, 700 miles to the east at 6:00 a.m. on April 11 implies an average speed of about 40 miles per hour in this direction. From Buenos Aires the ash fall front swung around and moved more slowly northeastward along the Atlantic coast, reaching Rio de Janeiro, Brazil, a distance of 1,850 miles from the volcano, shortly after noon on April 15.

Because of the uniformity of wind directions in the levels through which the ash settled, the zone of appreciable ash fall is quite narrow, as shown by figure 68, Larsson's (1937) map of lines of equal thickness of ash deposit. The general decrease in thickness with increasing distance downwind from the volcano is interrupted by a subordinate maximum greater than 10 centimeters (4 inches) some 350 miles downwind. The zone within the line of 5 centimeters (2 inch) thickness, is only some 60 miles wide but stretches for 600 miles downwind, almost to Buenos Aires. North and south of this narrow zone the thickness of ash fall decreases rapidly so that the zone of ash fall that is thicker than 0.1 centimeter ($\frac{1}{25}$ inch) is only about 400 miles wide, and of

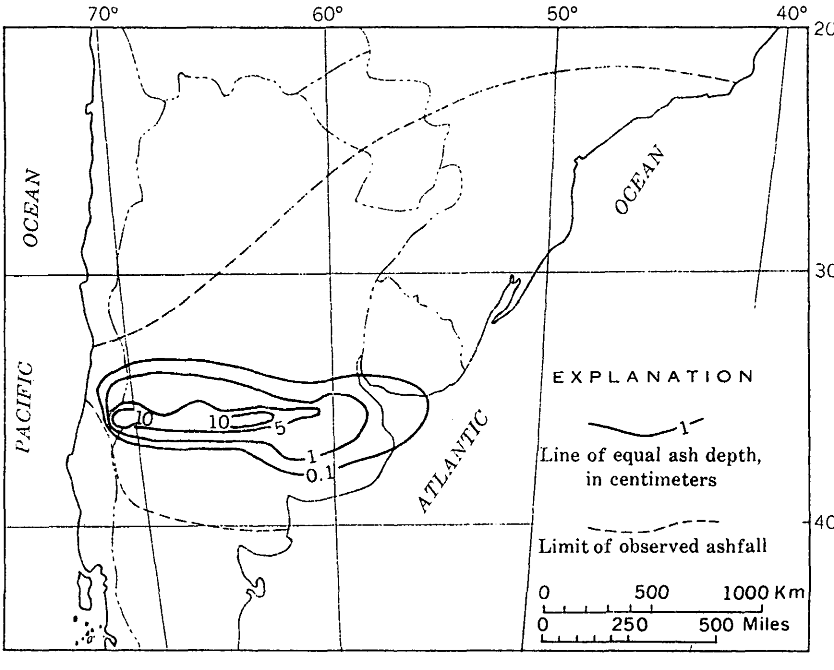

FIGURE 68.—Map showing the thickness of ash deposits from the eruption of Volcán Quizapú, Chile, in April 1932 (after Larsson, 1937).

fairly uniform width from the vicinity of the volcano to the far side of Buenos Aires.

The material erupted was andesitic or dacitic with about 64 percent silica, 16 percent alumina, and 4 percent total iron oxides. The detailed data of Larsson's study made it possible for him to demonstrate that progressively greater differences existed between the bulk composition of the material as initially erupted and the material falling at greater distances from the volcano. Thus ash at 100 miles distance had 67½ percent silica, that at 500 miles had 70¼ percent silica, and that at 700 miles had 69¾ percent silica, a general increase of some 6 percent silica with concomitant changes in other oxides, compared with the erupted material near the vents. This change Larsson accounts for simply as a result of the early settling out of the heavy low-silica mineral constituents, such as pyroxenes and calcic plagioclase, leaving the remaining ash enriched in silica, a characteristic of ash falls noted by several previous workers, among them Murray and Renard (1884). He further reasons that the material falling quite near the volcano should be enriched in these heavier mineral constituents giving a bulk composition lower in total silica than that of the material as initially erupted. Larsson lacked samples to confirm this relationship but it seems to be borne out in the 1919 eruption of Gunung Kelud in Indonesia.

GUNUNG KELUD

Gunung Kelud, a volcano 5,678 feet above sea level in central Java, is an example of an explosive volcano, where the hazard of its eruption is increased greatly by the presence of a crater lake in its summit, for such a volcano may furnish not only quantities of airborne ash, but also destructive mudflows and floods. Ten thousand persons are said to have been killed in its eruption in 1587 A.D., and 5,110 persons in its eruption of 1919.

The eruption in 1919 took place on the night of the 19th and 20th of May. The crater lake, containing about 40 million cubic yards of water, was ejected along with somewhat more than this volume of volcanic debris and ash. In less than an hour 104 villages and many plantations were partly or completely destroyed (Mohr and Van Baren, 1954, p. 224).

The eruption of Gunung Kelud illustrates still another pattern of ash distribution brought about by a specific meteorological situation. The eruption took place during the season when winds below 20,000 feet were from the west while those above were from the east. The ash blown to high levels was carried westward at fairly high speed, and as it settled into the lower zone it was

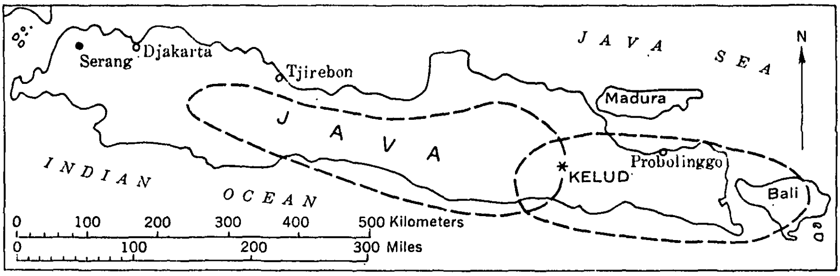

FIGURE 69.—Map of Java, showing bilateral distribution of ash fall from the 1919 eruption of Gunung Kelud volcano. Dashed lines enclose areas of ashfall. (Mohr and Van Baren, 1954, fig. 38a, after Kemmerling, 1921).

carried eastward, but at slower speeds so that the bulk of it fell to the ground west of the volcano (fig. 69). That portion of the ash thrown to heights less than 20,000 feet was carried only eastward to form another lobe of the ash deposit that extended as far as Bali. The composition of ash fall material at various distances east and west from the volcano follows closely the pattern of ash fall eruption of Volcán Quizapú in Chile in 1932, (Larsson, 1937). Figure 70 has been constructed with data selected by Mohr and Van Baren (1954, p. 233) from Baak (1949, p. 38) and shows that the material that fell very near Gunung Kelud is somewhat less silicic than the bulk composition as erupted, though that which fell at great distances is more silicic.

PARÍCUTIN

Prolonged eruptions are not common, and indeed it is uncommon for significant ash eruption to last more than a few weeks or months. Parícutin, the volcano that started at a point where no vent had been known previously, was an exception, and its 9 years

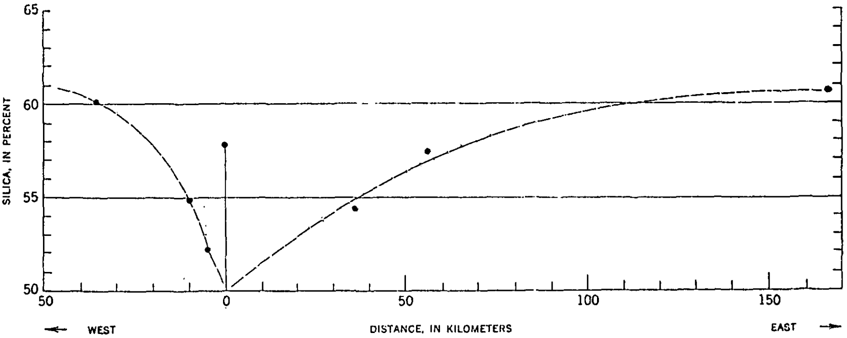

FIGURE 70.—Graph showing variation in silica content of ash fall of Gunung Kelud in Java, in 1919, with distance east and west of the volcano (from data listed by Mohr and Van Baren, 1954, p. 233).

of continuous eruptive activity permitted investigation more extensive than usual. During these years there were 18 changes of seasonal wind directions in the waxing and waning ash column, so that the resultant distribution of ash became much more complicated than that of the more common brief eruptions. A detailed account of the first 3 years of activity, during which the major part of material was erupted, is given by Foshag and Gonzales (1956).

The preliminary seismic disturbances began several weeks before the outbreak and built to such a crescendo of intensity and frequency that the villages in the area were thoroughly aroused to impending disaster. The outbreak, when it came on the afternoon of February 20, 1943, was not from any of the many cinder cones that dotted the countryside, but from a flat, cultivated area. At first only ash, bombs, and gases were thrown out of the newly opened fissure. Then, during the second night, a lava flow started, and from that time onward for 9 years there were few, if any, periods when lava was not being erupted, although there were periods, some of them weeks in length, during which eruption of ash remained small.

The first several weeks were marked by particularly strong ash eruptions. According to Fries (1953) some 83 million cubic meters (110 million cubic yards) of bombs, lapilli, and ash were erupted from February 20 to March 6, a rate of some 5,930,000 cubic meters per day. Thereafter the daily rate dropped consistently to the end of 1947 and remained well below 100,000 cubic meters per day until the latter part of 1951 when volume increased again, much like a dying gasp, before finally ceasing entirely on March 4, 1952.

The measurements of ash thickness given by Segerstrom (1950) for the deposits in 1946 are approximately those at the end of the eruption, for the bulk of ash had been erupted before 1946 (fig. 71). The ash mantle extends radially from the volcano with decreasing thickness, and because of the many changes of wind direction as well as vacillations in strength of the eruption, the deposit is made up of many discontinuous layers of ash and lapilli varying in grain size.

The winds of the dry season (winter and spring) in this region of Mexico are prevailingly from the west, and those of the wet season (summer and fall) from the east, accounting in large part for the east-west elongation of the distribution pattern. According to Segerstrom (1950) the area of ash deposit thicker than 25 centimeters (10 inches) was 233 square kilometers (about 9,500

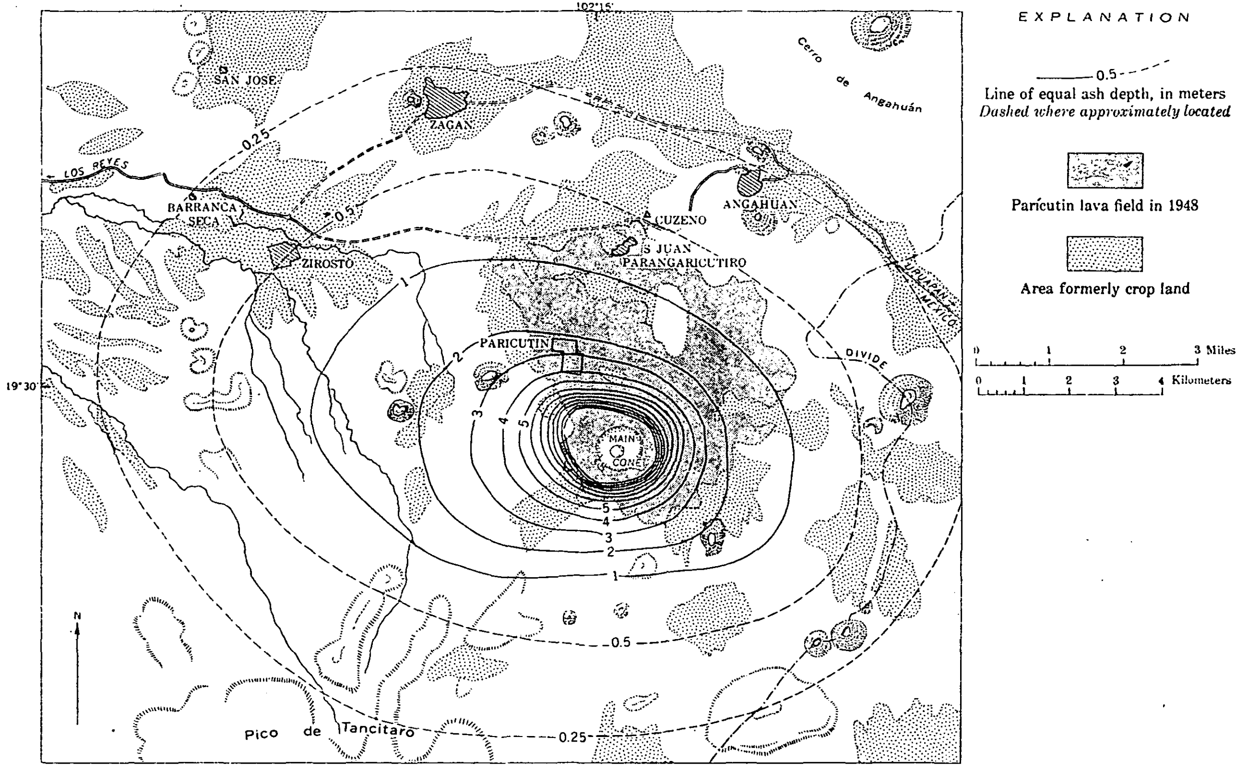

FIGURE 71.—Map of the vicinity of Parícutin in Mexico (from Segerstrom, 1950, pl. 3), showing thickness of ash deposit in 1946 from the eruption of the volcano, the area covered by lava flows in 1948, and the area that was crop land before the beginning of the eruption in 1943.

acres), and this land was covered too deeply by ash to enable early reclamation, especially in the face of continued threat of more ash fall. Consequently this zone of bare ash-covered fields and dead forests remained desolate through the 9 years of the eruption.

METEOROLOGICAL FACTORS IN ALASKA

Important factors that affect the pattern of distribution of ash fall from a given explosive eruption include height of eruption, particle size and density, behavior of wind, and occurrence or nonoccurrence of rainfall. Knowing these factors and making several compromises in the interest of simplifying the problem, the area where ash fall will occur may be determined and even the relative amounts falling at different areas may be indicated roughly. Similar calculations have been made with varying degrees of precision to determine fall-out patterns in atomic bomb tests (Air Weather Service, 1952). But for most volcanic eruptions the calculations become impractical because the necessary data are not available at the moment of eruption, much less in advance, and because the height to which material is thrown varies widely during the course of the eruption. Little can be said of the characteristics of the particles except that a great range of size may be expected and a range of density, from very compact material to very frothy material. Wind directions and speeds are not only likely to be quite different at different levels through which the particles settle, but also may change as the eruption continues. About the only aspect of the problem that encourages exploration is that of the probability of ash fall in given areas on the basis of general behavior of winds.

The map montages of plates 55 to 58 have been compiled to show the wind directions and average speeds at different elevations and seasons from series of observations at four Alaskan stations. The location of each map area is given in plate 54. These montages permit a very rough estimate of the probabilities of ash being carried across a given area from the eruption of a given volcano. They imply nothing, of course, as to the probability of an eruption occurring.

The data on which plates 55 to 58 are based were obtained from daily soundings during the period May 1948 to April 1953, the total number of successful observations for most levels and seasons varying from 350 to 450. The observation was attempted at 0300 G.c.t. each day, and, if unsuccessful, a usable value was sometimes furnished by measuring wind direction and speed from the upper air chart for that particular observation time. The data were averaged and tabulated by the U.S. Weather Bureau for the Aerological Branch of the U.S. Navy for the seasons of the year and for five isobaric levels corresponding approximately to elevations of 5, 10, 20, 30, and 40 thousand feet above sea level. The map montages were compiled by the writer from these tabulations, centering the wind roses for upper levels at representative volcanoes rather than at the station where the observations were made. Such shifting of wind roses by a hundred miles or so seems permissible, at least for the upper levels, because of the similarity of the wind rose patterns from station to station along the 1,200-mile arc from Anchorage to Adak Island. The 850 millibars (5,000 feet elevation) wind roses are not confidently applied except in the immediate vicinity of their station because of orographic effects.

In addition some information on wind behavior at levels above 40,000 feet may be obtained from the mean monthly maps (for instance, Air Weather Service 1953). An "average" wind direction and speed can be scaled off the map of a particular month and level above the geographic point in question, and such determinations for four representative months are shown in the following table. A disadvantage of such a representation for the present purpose is that no idea can be obtained of the variability of the winds nor the percentage of time the wind direction is in each quadrant.

To illustrate the use and limitations of such a map montage an estimate of the probability of ash fall at Whittier, 140 miles to

Four-year-average directional tendency of upper-air wind

[Inferred from "Mean monthly maps of 300-, 200-, 100-, 50-, and 25-millibar surfaces over North America," Air Weather Service, tech. rept. 105-107 April 1953, Washington, D. C.]

Place	Level (millibars)	Approximate elevation (feet)	Directional tendencies, in degrees clockwise from north, for indicated midseason months			
			January	April	July	October
Anchorage	25	70,000	65	350	315	55
	50	60,000	65	10	320	60
	100	50,000	[1] 75	[1] 20	340	55
	200	40,000	[1] 60	45	325	30
	300	30,000	50	45	[1] 35	[1] 55
Kodiak	25	70,000	65	[1] 15	320	80
	50	60,000	65	20	310	80
	100	50,000	[1] 65	[1] 45	[1] 0	90
	200	40,000	[1] 55	55	0	55
	300	30,000	50	60	[1] 50	[1] 60
Dutch Harbor	25	70,000	95	[1] 105	(?)	85
	50	60,000	85	65	300	90
	100	50,000	[1] 65	[1] 70	[1] 90	95
	200	40,000	[1] 60	85	80	75
	300	30,000	60	75	[1] 70	[1] 70

[1] Weak tendency.

the east, can be made from a hypothetical example of a winter eruption at Redoubt Volcano in which a brief explosion throws material to a maximum height of 45,000 feet. As a first approximation, the percentage of time that the wind at each level is directed from Redoubt Volcano toward Whittier may be listed, as in the following table, and the average made of the whole. This is 11.5 percent, a very crude indication that winds would be favorable about that percentage of the time to carry ash from Redoubt Volcano to, and beyond, Whittier. Although the winds in the upper levels have the greater velocities and, for precision, should probably be given more weight in the calculation, it alters the result in the normal case only slightly, certainly not enough to cause concern in view of the many other imponderable and uncertain factors.

Percent of time wind blew from Redoubt Volcano toward Whittier and Homer, Alaska

Level (feet)	Whittier		Homer	
	Winter	Summer	Winter	Summer
35,000 to 45,000	18	12	8	7
25,000 to 35,000	12.5	11	10	5
15,000 to 25,000	8.5	8	8	4
5,000 to 15,000	7	5	7	3
Average	11.5	9	8.3	3.8

It is well to remember, however, that the "average" situation dealt with here does not necessarily represent an actual situation at a particular time. The assumption in the foregoing discussion that the 18 times out of a hundred when winds at 40,000 feet are directed from Redoubt Volcano toward Whittier also includes the 12, 8, and 7 times that the winds, at 30-, 20-, and 10-thousand feet respectively were in that direction, but winds seldom are in exactly the same direction at all levels. To fall at Whittier, ash starting its journey at 45,000 feet might start in a southeastern or northeastern direction and be carried by a somewhat circuitous route to Whittier by an appropriate combination of winds at lower levels.

Similar qualitative estimates of the situations for other volcanoes and localities in the area could be made from plate 55, or of still other situations illustrated in the map montages of the Kodiak Island, Dutch Harbor, and Adak Island areas (pls. 56–58).

In a general way, ash may be carried great distances by the stronger winds at higher levels, and the wind directions at these higher levels are more consistent than those at low levels. Thus for the Anchorage and Kodiak areas in the winter, spring, and summer, winds above 20,000 feet blow toward the eastern quadrant most of the time, but in the fall they blow into the northern and northeastern quadrants, and for the Dutch Harbor and Adak Island areas, the upper winds blow into the eastern quadrant most of the time in all seasons. Probably the distribution of ash from major explosive eruptions (hence in general the more damaging eruptions) can be predicted more confidently than that of the weak eruptions, because the ash of the major explosions will be projected to upper levels where wind directions are more consistent.

Rainfall may have a great influence, not only in limiting the area of ash fall, but also in determining the action of the ash and its associated water-soluble chemicals on the vegetation and in the buildup of floods and mudflows (p. 449). The simple smooth distribution of ash fall downwind by gravitational settling can be greatly modified by a heavy rainstorm, bringing down in a small area most of the ash remaining in the erupitve plume and forming an abnormally thick accumulation there and an abnormally thin one farther downwind. Very favorable conditions for production of torrential rains are found in the immediate vicinity of the eruptive column (Finch, 1930) and under the "elbow" where the eruptive plume extends downwind from the vertical eruptive column. Moisture-laden low-level air has been dragged upward and mixed into the rapidly cooling gases of the eruptive column, which contains a certain amount of steam as well as abundant solid particles to act as condensation nuclei. Conditions likewise favorable for producing rain exist to a diminishing degree downwind in the extremely turbulent eruptive cloud.

EFFECTS OF ERUPTIONS

It would be quite impossible to anticipate all the effects, direct and indirect, that might result from volcanic eruptions in Alaska or to set them down in their proper relationship. But here to be considered are the range of effects on public health and safety, utilities, transportation, communication, and agriculture, based on the limited recorded experience in Alaskan eruptions and on several somewhat better documented eruptions in other parts of the world. Several points are worth noting at the outset: first, the major damage and human suffering from a volcanic eruption often may be due less to physical than to psychological factors, such as panic and fear of the unknown, and usually such suffering is entirely unnecessary; second, eruptions are short-lived, and, although they produce physically uncomfortable or inconvenient situations, actual danger is usually quite absent at a reasonable distance from the vents; and third, explosive eruptions usually bring long-range benefits, such as improvement of soil and crop production as an after effect of ash fall.

PUBLIC HEALTH AND SAFETY

Of immediate concern to the individual are his own personal health, safety, and continued efficiency. Many people at once associate the ash from volcanic eruptions with noxious gases and poisonous chemicals, and the terms "sulfurous fumes" and "toxic gases" are used more often than warranted in descriptions of eruptions. It is true that the odors of certain acid gases are frequently detectable in areas of falling ash, but at a distance from the vent the concentrations are usually only temporary and no more than met with in an adequately ventilated chemical laboratory, in which atmosphere the chemist works year after year with no ill effects.

Some of the materials erupted as vapors, such as water, quickly condense in large part to liquids, while others such as carbon dioxide and sulfur dioxide may remain as gas for some time and gradually become diluted by mixing with the atmosphere. The odor characteristic of volcanic eruptions, frequently ascribed simply to "sulfur," may often be due to burned sulfur, that is, sulfur dioxide, less often sulfur trioxide, or to hydrogen sulfide, but it is rarely justifiable to presume that other gases are not present. In many cases where "sulfurous" fumes have been noted by sense of smell, it has been found by analyses that several other gases are in equal or greater quantities. These other frequently-present gases include hydrochloric acid, hydrofluoric acid, carbonic acid (carbon dioxide), and ammonia.

All these gases may be harmful if inhaled in sufficient concentration for a sufficient length of time. The accompanying list gives the maximum concentration of industrial gases considered permissible for workers in steady contact (Sax, 1951), but somewhat greater concentrations of some of the gases can be tolerated for short periods of time. Thus, while 10 parts per million of sulfur dioxide is regarded as the maximum allowable concentration for continuous exposure, as much as 50 to 100 parts per million can be tolerated for exposures of half an hour to one hour duration. Ammonia, although perhaps common at the vents of some volcanoes, may be expected to quickly form less harmful compounds by reaction with one or more acid gases usually present in excess. Carbon dioxide is harmful only in very high concentrations, when it acts as a diluent of oxygen. Its density causes it sometimes to collect in low places where it may be a hazard, especially because of its lack of warning odor.

Most of the other common volcanic gases are acidic, and have similar injurious effects, that is, irritational injuries to the eyes (conjunctivitis) and to the respiratory system (lung or bronchial edema). It is not possible to prescribe complete protective measures for all volcanic situations, and a properly fitted industrial gas-mask with acid-type filter is best. In the common case where such special equipment is lacking, it has been found a practical expedient to breathe through a dampened folded cloth, and if the eyes smart, to wear airtight-type goggles. As the action of the damp cloth is to trap the acidic gas in the moisture of the cloth, it is advisable to renew the effectiveness of the cloth at intervals by rinsing.

Effects of industrial gases on humans

[Generalized from Sax, 1951]

Gas	Initially detectable odor (ppm)	Maximum allowable continuous exposure (ppm)	Effects of overdose
Ammonia	53	100	Conjunctivitis, retention of urine, lung edema.
Carbon dioxide	Odorless	5,000	Coma, asphyxiation.
Carbon monoxide		100	Headache, dizziness, nausea, asphyxiation.
Chlorine	3.5	0.35	Conjunctivitis, lung edema.
Fluorine		1 mg/cu M	Conjunctivitis, skin irritation, bone degenration, lung inflammation.
Hydrochloric acid		5	Conjunctivitis, edema or spasm of the larynx.
Hydrofluoric acid		3	Eye irritation, blindness, skin burns, lung edema.
Hydrogen sulfide		20	Photophobia, inflammation of cornea and respiratory tract.
Sulfur dioxide	1	10	Conjunctivitis, lung edema, lung paralysis.
Sulfur trioxide	1	2	Irritation of mucous surfaces, inflamation of lungs.
Sulfuric acid (aerosol)		1	Skin burns, lung damage (wide variation in individual susceptibility to respiratory effects).

The sulfur-derivative gases deserve special attention because of the complexity of their relationships and the variety of effects under different conditions. In a strongly reducing environment the sulfur derivative may come forth as hydrogen sulfide, recognized by its well-known odor of rotten eggs. In a strongly oxidizing environment, the sulfur derivative may be sulfur dioxide, recognizable as the odor of a flaring match. It happens not infrequently that the conditions are neither strongly oxidizing nor reducing, and the product then may be a mixture of both gases. In the air their conversion to the stable sulfur trioxide or sulfuric acid goes on only slowly, in spite of the readily available oxygen, and in the absence of a catalyst the two original gases may persist for many miles downwind, with the concentration of the much-blamed "sulfuric acid" actually remaining quite low. This is not to say that sulfuric acid is rare or unimportant in volcanic products, for it no doubt comes out ready-formed in many eruptions. Its potency as a respiratory irritant is certainly decreased in this situation, however, by its existence not as a gas but as aerosol droplets which tend to take on moisture from the air to further dilute themselves and grow to sizes more likely to be filtered out of the inhaled air.

The solid products of an explosive eruption, that is, the ash particles themselves, are largely composed of rock-forming silicate minerals and silicate glass. Small quantities of such material inhaled usually have no harmful effect. The filtering mechanism in the human nose and upper air passages is remarkably efficient, and only a very small proportion of particles of ash-laden atmosphere entering these passages actually reaches the lungs. The length of exposure to such ash-laden air is relatively short—usually not more than a few hours or days—and quite ineffective in comparison to the months and years of daily exposure required in certain dusty occupations to develop the condition known as silicosis or pneumonoconiosis. Nevertheless during an ash fall from a volcanic eruption, it is usually easy and convenient to hold a damp folded handkerchief over the face, or, if both hands must be free, wear a dust mask, either ready-made or improvised. These can give nearly complete prefiltering action against dust and also give the wearer added comfort by relieving the nasal passages of a large part of the filtering work.

The health hazard of breathing ash, while never great if simple precautions are observed, should be guarded against, particularly among those whose occupations may expose them to airborne ash for protracted periods. Long intermittent exposure to low-level concentrations of finely divided ash could possibly have more harmful and insidious effect on the individual than the brief exposure to very high concentrations that may have occurred during the ash fall proper. For weeks or months after an eruption there may be brief flurries of ash caught up by winds, and these are of no harm nor great inconvenience to persons in most occupations. However, those persons continually exposed, such as in the clearing of the ash from traffic arteries, should wear dust masks.

Many of the public and private water supplies of Alaska are from streams and reservoirs exposed to ash fall in the event of a nearby volcanic eruption. While an ash fall will not necessarily spoil a stream or reservoir supply, such supplies need close attention during and after the eruption to confirm potability of their water. In extreme cases, also, the actual storage capacity of a reservoir may be greatly reduced by ash brought in with runoff water.

During an eruption the ash particles commonly act as nuclei for the condensation of water, which dissolves a certain amount of acidic and other gaseous coproducts of the eruption. The water may persist as raindrops or as thin films until it reaches the ground, or it may evaporate, leaving an acid residue on the particle. The acid constituents in solution in the drop or film react slowly with the ash particle, and in time the solution will return to a nearly neutral condition. Should a large amount of such ash fall into a stream, lake or reservoir before reaction is complete, the initial effects will be increased turbidity and acidity of the water. Within a few hours after cessation of the ash fall, however, the water may again become neutral or slightly alkaline, owing to reaction of the acid with the ash or other suspended material. The final condition will be a somewhat greater content of dissolved solids.

An instructive example of effect on water supply is furnished by the ash fall in Anchorage from the eruption of Mount Spurr on July 9, 1953. Between one-fourth and one-eighth inch of fine ash was deposited in the environs of Anchorage in a period of about 6 hours. Early tests of water samples from a reservoir showed pH values near 4.5 (moderately acidic); yet a few hours later when the ash fall had abated, the pH was again back to its normal value of slightly over 7. In the laboratory, measured amounts of dry ash placed in distilled water likewise produced only temporary increase in acidity. Thus, an acidic water that may have entered the public distribution system must have been neutralized long before reaching the consumer.

Turbidity of the intake water at the Fort Richardson treatment plant is normally less than 5 parts per million. On July 9, the day of the ash fall, it rose sharply to 290 parts per million and then decreased to below 5 again by July 15 (Whetstone, 1955). At the times of the rains mentioned below the turbidity again rose to low maxima of 10, 12, 36, and 70 parts per million. It was necessary to add much more of the chlorinating agent than normal at the Anchorage treatment plant to maintain the required level of chlorination during the initial period of high turbidity and presumably the extra chlorinating agent was consumed by reaction with the suspended ash.

An investigation of the effects of the ash fall on the chemical character of water from Ship Creek and other water sources in the Anchorage area was made by Whetstone (1955). During a normal period, such as July 1949, the average sulfate concentration stayed close to 16 parts per million, decreasing, as did the content of total dissolved solids, during periods of high discharge of the streams. Immediately after the ash fall of July 9, 1953, the sulfate content was 28 parts per million, considerably higher than would be expected at this time of year. For a few days thereafter the sulfate content ranged between 27 and 29 parts per million, then increased to 36 parts per million on July 17–19, coincident with the first rainfall since the eruption and accompanying increase in stream discharge. The sulfate concentration then decreased gradually to 23 parts per million by the end of July. Subsequently maxima of 28, 35, and 38 parts per million occurred immediately after rains of August 1–2, 5–10, and 21–28 respectively. Less complete sampling of other creeks in the area indicated similar concentrations.

It is quite apparent from these results that soluble sulfate brought down with the ash particles caused the abnormally high concentrations in the surface runoff. This occurred not only at the time of the ash fall but also at times of subsequent rainfall and high stream discharge. Although the amounts of sulfate involved in this case are far below that considered harmful to drinking water, harmful or disagreeable amounts of soluble constituents, such as sulfates, chlorides, fluorides, borates, or combination of these, might be furnished by other eruptions. It would seem advisable therefore to determine the potability of a threatened water supply by repeated tests during and for a reasonable period following an ash fall.

Attention is directed also to similar effects on smaller water supplies, such as reservoirs, tanks, open wells, and springs serving only small groups of people or those on farms. With small or moderate amounts of ash falling into a well, the undesirable effects of turbidity and dissolved solids may be cleared up simply by prolonged pumping to bring in normal water from the aquifer. In other cases, such as during the eruption of Parícutin volcano in Mexico, springs and small gathering areas may silt up so badly that removal of ash becomes necessary. According to Segerstrom (1950, p. 25), the ash fall from Parícutin affected such local water supplies in a variety of direct and indirect ways.

BUILDINGS

In some volcanic areas, during eruptions there is an immediate danger of roof collapse due to heavy loads of ash. This danger is especially frequent in tropical countries where the construction of roofs for dwellings and other buildings is typically somewhat flimsy, providing only for protection from sun and rain. Least trouble of this kind is experienced with steep-pitched roofs, which permit the load of ash to slide off before an excessive amount collects. For instance, ash fall material did not accumulate on the steep shingled roofs of the Tarascan Indian homes in the neighborhood of Parícutin volcano, Mexico, in 1943 and 1944, whereas much not only collected on the low tile roofs of the Spanish style buildings but was difficult to remove because of their fragile construction. It is interesting to note that the distinctive steep-roofed Tarascan architectural style is found in a region that probably was subjected to relatively frequent ash falls during the last few thousand years and that the steepness of roofs may thus be more than a coincidence.

Roofs of Alaskan houses and many public buildings possess high bearing strength and are purposely steep as a measure of protection against overload by snow. Although almost a foot of ash fell at the village of Kodiak during the 1912 eruption of Mount Katmai, Griggs' account makes little mention of roof collapse due to overloading except for one photo of a low-angle shed roof on a barn on Long Island, just off the village of Kodiak (Griggs, 1922, p. 16). While the possibility of roof collapse due to excessive loads of volcanic ash thus may not be acute during an Alaskan eruption, nevertheless it should not be disregarded, and attention should be given especially to those roofs of weak construction or low pitch. The point of failure of a roof will be approached with a much thinner deposit of ash than of snow because of the greater density of volcanic ash, and the point of failure will be even more quickly approached with wet ash.

UTILITIES, TRANSPORTATION, AND COMMUNICATION

The community electric power is affected by both the potential of the generating plant and by the changing load or demand. Both factors operated to disadvantage during the ash fall at Anchorage on July 9, 1953, from the eruption of Mount Spurr. At the time one generator was already shut down for normal summer overhaul, when the peak power demand usually is lowest, and thus the available standby power was below normal. The darkness preceding and accompanying the ash fall caused the city street-lighting system to come on automatically at 11 o'clock in the morning, and with the lights of residences and office buildings being turned on also, an unanticipated peak load resulted. The crisis was passed without serious breakdown by means of prompt radio appeals to consumers to economize on the use of power.

At the same time, Anchorage telephone facilities were greatly strained because of the rush of phone calls between neighbors, friends, and relatives wishing to compare notes on the extent and meaning of the unprecedented fall of ash. Again radio appeals to the subscribers were successful in reducing the load and prevention of choking of the system. It is fairly obvious that for a community of this size one of the most effective means of communicating with the populace during an emergency is by way of the operating radio stations.

Transportation at first may be made difficult, chiefly owing to decreased visibility, but seldom because of deterioration of engines during the short period of ash fall. The ash, if dry, may form a haze, nearly opaque for all practical purposes to headlights of surface traffic. To this are added difficulties due to ash coatings on windshields and headlights and scratching of windshields, if windshield wipers are used incautiously. Even if the rate of ash fall is not great, much fine ash may be churned into the air by traffic and by winds, giving greatly decreased visibility. The damp ash or mud rain, which commonly falls, adheres even more persistently than dry ash to windshields and headlights, and the driver may or may not find improvement by leaning outside, where he must face the same barrage as the windshield. Traction becomes a problem with greater depths of ash on streets and highways, and it may become necessary to begin large-scale ash-removal operations at once.

Air traffic may become completely impracticable during the ash fall because of the decreased visibility. In a heavy ash fall the ceiling is zero for all practical purposes, and the attrition effects of the ash particles may cause damage to the plane and engine if exposure is more than momentary. Operation of plane traffic during light ash fall does not seem to have serious consequences.

For some time after eruption and fall of ash has declined, the danger of floods, mudflows, and even landslides may continue; they constitute the main threats to continuous operation of public utilities, transportation, and communication. Additional hazards may exist to a minor degree owing to wind-raised dust clouds in and around the desolated region.

Although it might appear at first that ground covered with the porous and fluffy ash mantle should readily absorb large quantities of rainfall and thus hold back runoff, generally it can hold back only a fraction of what would have been retained were the ground still covered with normal vegetation (Lowdermilk, 1947). The rainwater quickly saturates the interstitial space of the ash, then begins to run off its surface and erode the already saturated ash and the soil beneath. The very fineness of particle size of the ash at the surface—the portion that settled out most slowly—decreases the permeability and is a major factor in increasing runoff and erosion. Only slight oversaturation of slope ash is needed to increase the bulk volume and lubricate the mass movement of water-saturated ash, so that the situation is ideal for triggering floods and mudflows, which in so many cases have followed volcanic eruptions and caused more loss of life and property than the eruptions themselves.

The probability of floods and mudflows, besides being dependent on the quantity of loose ash deposited, is dependent on the weather, and heavy rains during or following heavy ash fall will practically guarantee the occurrence of destructive floods and mudflows. This probability must be assessed by the civil authorities with the aid of meteorologists, and provision should be made for evacuation of citizens from vulnerable areas. Too often there is no period of grace, for, once started, the flood and mudflow fronts move with astonishing rapidity, and to be safe, personnel must be out before the flow starts. Ash avalanches and landslides, while an extension of the features of mudflows, are likely to be of importance only in areas very deeply covered by new ash, that is, in zones quite near the volcano.

The effect of floods and mudflows on transportation can be sudden and calamitous. Floods of volcanic derivation often carry much greater suspended loads than ordinary floods, and because of this, carry the threat not only of destruction of bridges and washouts of subgrades in some areas but likewise of "fill-ins" along other portions of the flood course. The latter can be in the form of burial of stretches of highway or railroad tracks or choking of established water courses. Following the intense early ash eruptions of Parícutin in Mexico, for instance, the first heavy rains of the wet season sent great debris-laden floods down valley to choke the intricate system of irrigation ditches with ash (Lowdermilk, 1947).

Machinery in power-generating plants, often located not far above normal stream level, can be especially vulnerable to volcanic flood waters. Besides the hazard of submersion, there is the added danger of abrasion of moving parts of turbines by the ash-laden water. Power lines as well as communication lines are vulnerable to breakage by floods, mudflows, and avalanches.

To forestall as much as possible the damage of floods and allied catastrophies, the work of clearing the ash from main arteries of travel should be started as soon as possible after the climax of eruption. In the city, attention should also be given to prevention of clogging of storm sewers and other vulnerable installations. Several types of ash-removal machinery may be pressed into service, and the most effective type will depend on the depth of ash to be removed and the degree of completeness of removal. The 1953 ash fall in the Anchorage area, for instance, was effectively removed by two makeshift devices: at the airports, jet engines were used to blow ash from runways, and in the city streets, graders with thick rubber lips attached to their blades were able to scrape all but a small residue of ash from the streets.

AGRICULTURE AND RELATED ACTIVITIES

Perhaps the most lasting effects of volcanic eruptions from the viewpoint of humans are found in agriculture. Lava flows destroy land for agricultural purposes, usually for many generations, unless covered in turn by volcanic ash or water-deposited sediments. Ash falls may destroy the crop at hand and impose severe handicaps to livestock grazing and to obtaining normal crops for several seasons. As the ash becomes mixed into the old soil, however, it may contribute benefits that are felt for many seasons or generations. The details of the after effects of eruptions on soils and crops are not yet well understood, and there is need for investigation of ways to ameliorate the harmful effects and ways to make the beneficial effects of the ash available soon after an eruption. The agricultural effects of volcanic eruptions may be classed as the immediate effects and the long-range effects. The immediate effects are in the main spectacular and destructive, while those felt over a longer period (several years or generations) include many that are beneficial. The lack of fundamental information on which more definite conclusions could be based is due in large part to the fact that the opportunities for clear-cut investigation presented by actual eruptions are scattered, both geographically and in time, and that only in a very few instances have studies, started with the eruption, been carried through systematically to an ultimate fruition.

IMMEDIATE EFFECTS OF ASH FALL

Plants are relatively vulnerable to damage by volcanic eruptions, and there is a wide range of susceptibility among plants of different types. The mechanical overloading of ash on broadleaf trees and plants is common, leading to breaking of limbs and stems and to many casualties. Needle-leaf trees such as pines, while less vulnerable to overloading, appear to be quite susceptible to damage by such common volcanic gases as sulfur dioxide—damage that may not show up for several days or weeks after exposure. Fruit blooms exposed to volcanic gases and ash may be killed outright or may survive to produce malformed or blighted fruit.

A sufficient depth of ash smothers pasture grass and low foliage. If only an inch or thereabouts of ash is deposited, subsequent rainfall probably will wash out enough for the grass and other plants to continue growth the same season, provided chemical damage to the leaves has not been too great. If the deposit is much deeper, new growth may break through the ash mantle or reappear when the ash mantle is removed by erosion. A depth of ash-fall deposit of several inches is sufficient to smother many types of grasses, and if somewhat thicker it is enough to weigh down and smother low bushy growth. For higher bushes and trees the main damage may be from breakage of branches. With orchard trees and other trees of special value, damage from this source may be prevented in large part by frequent shaking of foliage during the ash fall.

During the eruption there are marked meteorological effects near the vent. Low-level air laden with moisture is dragged upward to mingle with moisture- and dust-laden air of the eruptive cloud (Finch, 1930), with the result that strong downpours, variously loaded with ash and dissolved chemicals, are common in the vicinity of the vent and immediately downwind. The eruptive plume—that is, the horizontal train of eruptive gas and ash moving downwind—is extremely turbulent and has the required conditions not only for rainstorms but also for destructive hailstorms, which have been noted on occasion in zones under the eruptive plume. The heavy rainstorms on ash-covered terrain may result in excessive runoff and disastrous floods (p. 449).

While very little quantitative information is available on damage of vegetation by volcanic gases, a relatively large amount is available about damage by various industrial gases, some that find their counterparts in the fumes emitted from volcanoes. The data in this field have been summarized by Thomas (1951) and are listed in a somewhat generalized form in the following table for those gases common to both industrial and volcanic activity. It may be noted that the "threshold concentration" given here is roughly similar but not exactly analogous to the "maximum allowable concentration" listed for human experience on page 443. It is necessary also to emphasize that the threshold value may vary greatly, not only from one type of plant to another, but also that the susceptibility of a given plant may increase drastically, for instance, during periods of higher humidity and more active growth. An additional factor of possible importance in the problem of volcanic damage is the effect of combinations of one or more of the harmful gases, a situation that apparently also exists in the smog of modern cities and is claiming the attention of many investigators.

Effects of gases on plants

[Generalized from Thomas 1951]

Gas	Threshold concentration (ppm)	Effect of overdose
Ammonia	10	"Cooked" green appearance becoming brown upon drying.
Carbon dioxide		No marked effect.
Carbon monoxide	500	Epinasty, chlorosis, shedding of leaves.
Chlorine	1	Marginal and intravenal leaf lesions.
Fluorine	0.1	Marginal leaf lesions, shedding of leaves.
Hydrochloric acid	10	Marginal and intravenal leaf lesions.
Hydrofluoric acid	Variable	Marginal leaf lesions, shedding of leaves.
Hydrogen sulfide	50	Scorching, especially young leaves.
Sulfur dioxide	1	Chronic: Yellowing and bleaching of leaves. Acute: Collapse of marginal and intercoastal areas, drying to ivory or brownish red.
Sulfuric acid (aerosol)	Variable	Scorching or charring depending on moisture content, size of aerosol droplets.

The complexity of the problem of natural volcanic gases increases by the common involvement of aerosol mists and larger droplets composed of water solutions of one or more of the harmful compounds. Thus, while an aerosol of pure sulfuric acid liquid may not be particularly harmful, one of a water solution of sulfuric acid of medium strength may have a strong scorching effect. Many of the "charred forests" and "burnt" vegetation of past volcanic eruptions, attributed to red hot ash falls or to high-temperature blasts, must rather be suspected of having been produced at low temperatures simply by the oxidizing action of sulfuric acid associated with the ash fall, or by the action of strong doses of sulfur dioxide gas, the effect of which may not be distinguishable from that of sulfuric acid by untrained observers. The action of soluble acid gases, such as hydrochloric and hydrofluoric acids may likewise be expected to vary greatly in water solution aerosols, and not necessarily to show a maximum effect in concentrated solution nor a constant decrease of effect upon dilution.

The wide range of possible concentrations leading to differing chemical and pathological activity of these substances can be appreciated by considering the variety of meteorological situations in which they might be involved. Aerosol droplets of sulfuric acid, for instance, passing through an atmosphere of high relative humidity would be quickly diluted owing to the strong affinity of sulfuric acid for water. Other acids in gaseous form might form aerosols under similar circumstances, and rain drops falling through or forming in an eruptive fume cloud dissolve some of the available nonatmospheric gases or aerosols. Duration of exposure is an important factor, and if the toxic droplets are removed quickly from the plants (rinsed off for instance by a nontoxic rain), there may be no harmful effect.

The gaseous and liquid constituents also exist as absorbed films on ash particles in the eruptive cloud and are brought down with the ash fall or mud rains. The harm they do to vegetation is probably largely conditioned by different meteorological situations, as discussed above. Finely divided ash, especially the glassy portion, may slowly react with the acid solution of the adsorbed film and, if contact is of sufficient duration, the acid may be neutralized before it begins reacting with the vegetation, or shortly thereafter, thus reducing the direct toxic effect.

Near Mount Katmai, the destruction of plants by the 1912 eruption was extreme. Griggs (1915) went ashore in 1913 at Russian Anchorage, about 25 miles east-southeast of Mount Katmai volcano, and found extensive devastation by the 3-foot mantle of ash, but also many indications that the process of recovery had already begun. Whereas the vegetation of the preceding season had been reported as completely wiped out, Griggs found that the alders on slopes facing away from the volcano were green and luxuriant. Those on the slopes facing toward the volcano had shriveled buds and were without leaves, although their woody parts were still pliable and new shoots were being sent up from the roots. From the description it appears that gases or fumes, rather than the high-temperature blasts suggested elsewhere, could have defoliated the alders. Smaller plants on the fairly level areas had been buried completely, yet where ash had been removed, vegetation seemed to be starting again vigorously.

At Kodiak, 100 miles east-southeast of Katmai volcano, the 10-inch ash fall destroyed all low-growing vegetation. The damage to such plants, according to Griggs (1915), was not by any poisoning effect but simply by the smothering action of the ash blanket. Trees were weighted down by the ash, but on the conifers the effect was possibly little worse than from the periodic loads of winter snow. Griggs found no evidence of chemical blight on the coniferous trees. Materials of landslides and mudflows, together with material washed off slopes by running water, were deposited at the base of slopes to fill in ponds and swamps and bury their vegetation.

In the 1943–52 eruption of Parícutin in Mexico, agriculture in the immediate neighborhood came to a virtual halt, and effects of the eruption were felt many miles down the main valley where ash-laden floods covered fields, clogged the irrigation ditches of the rich sugarcane lands of the Los Reyes flood plain, and washed out the several power dams of the valley. Close to the volcano, foliage and blooms of fruit trees were destroyed, and at distances of several tens of miles sporadic ash falls caused damage to fruit blooms. Widespread loss of cane harvests at Los Reyes during 1944 and early 1945 was the result of a plague of cane borers, who thrived apparently because of the extermination of a natural insect enemy of the borer during the ash fall. Yet in the same area the productivity of mangos and guavas increased after the onset of the eruption, reportedly because of the eradication of a destructive fruit fly by the ash fall (Segerstrom, 1950, p. 22). Also the ash fall may have killed certain insects that otherwise would have fertilized blooms and thus may have interrupted the reproductive cycle of some plants.

As long as the eruption continued there seemed little to be done to ameliorate the situation in regard to cultivated crops near Parícutin. If such plantings as were attempted in the ash were able to survive subsequent ash falls, washouts, or burials by runoff sediment, they withered and died before maturing. Consequently there was much discouragement, and the few who obtained harvests were able to do so only by great effort, such as planting corn in individual holes in the ash where the roots could reach the old soil. It should be emphasized here, however, that Parícutin's continuation of activity through several growing seasons is exceptional behavior for volcanoes and that agricultural destruction by most volcanic eruptions takes place mainly in a brief period, after which rehabilitation and return to normal can proceed with only moderate chance of interruption by further eruptive activity.

The logging industry may suffer owing to widespread killing of forests by ash fall, to distorted growth of trees following nonfatal damage, or to insect infestations brought about with the ecological imbalance. At Parícutin prior to the 1943 eruption, pine forests had been the source of lumber, fuel, and turpentine (Segerstrom, 1950, p. 23). Most trees within the 1-meter line of ash thickness were killed, while most outside the half-meter thickness survived. Many men of the nearby villages, no longer able to plant crops, turned to wood cutting for a living, with the result that not only were damaged trees logged off, but also many more of the undamaged trees than was good for the region as a whole. The turpentine industry had to be given up for the duration of the eruption because of the intermittant contamination of the pine sap by ash falling into the collecting cups.

The effect of ash fall on livestock is frequently quite serious, and the present writer has found no complete explanation of the mechanism of the effect, except where starvation has been caused by burial of pastures. In situations where the cattle are able to graze on ash-laden pasturage, they have frequently been seen to sicken and die in a very bloated condition, and this has been presumed, without much trained investigation, to be due mainly to indiscriminate consumption of ash along with the grass, perhaps resulting in ultimate overloading of the digestive system with mechanically irritating rock material or with poisons such as fluorides or ammonium chloride. At Kodiak in 1912 so much concern was felt for the herd of Galloway cattle at the Agricultural Experiment Station that it was shipped to the States and only returned two years after the eruption when pastures had revived. Other cattle were supported by imported ensilage (Griggs, 1922, p. 44). At Parícutin about 4,500 cattle, 550 horses, and dozens of sheep and goats died from the effects of the ash falls during the early weeks of the eruption in 1943 (Segerstrom, 1950, p. 23), and many more were saved only by removing them in time to unaffected areas. A study of the effects of ash fall on livestock is anticipated as a part of the series on the 1947–48 eruption of Hekla in Iceland (Thorarinsson, 1954) and promises to be of value.

Damage to fishing grounds and to marine life in general appear to be very temporary, judging from the scanty information found in the literature. Little directed study seems to have been made of the problems, probably because of the erratic occurrence of eruptions and the difficulties introduced by lack of controlled conditions. However, it is not possible to say that important and long lasting effects do not result from some eruptions.

The effect of the eruption of Mount Katmai on marine vegetation was discussed briefly by Rigg (1914), who had examined the near-shore vegetation along the south coast during the summer of 1913. He found that larger plants, such as kelp, that had been reported as dead soon after the eruption, were once again growing in the littoral zone, and he concluded that damage had been apparently from four causes:

> (1) the grinding effect of floating pumice;
> (2) actual burial of plants by the deposit of ash;
> (3) burial by ash of rocks which had furnished anchorage for marine algae;
> (4) the effect of poisonous gases on plants growing in the littoral zone or whose distal portions are kept at the surface of the water by floats.

Rigg further concluded that the damage was temporary and that the kelp beds, which serve so well as a warning of shallow rocky bottoms to navigators, as well as a source of potash fertilizer for the vegetable gardens of the natives, should regain most of their original distribution shortly. He did not discuss the effects of the ash fall on the food supplies of the near-shore or off-shore fauna or possible direct effects on the fauna.

In discussing the 1947 eruption of Hekla in Iceland, Thorarinsson (1954, p. 62) remarked on the reports of complete disappearance of cod from the fishing area between the islands of Vestmannaeyjar and the south coast of Iceland (map, fig. 4) for two days following the outbreak and ash fall. Fishing boats operating still farther south and outside the zone of ash fall reported an apparent increase of cod in the deeper water, as if they had temporarily fled the area of ash fall. No further information was furnished.

LONG-RANGE EFFECTS OF ASH FALL

Moderate ash falls usually are ultimately beneficial to agriculture, especially if the area affected escapes excessive erosion, for most soils are improved, both chemically and physically, by admixture of fresh rock material. This is strikingly shown in many tropical and subtropical areas of concentrated agricultural development, as remarked upon by van Bemmelen (1949, p. 224) for Indonesia, by Rigotard (1934) for areas of recent volcanic activity in Italy, and by others. Application of volcanic ash to soils as a slow-acting fertilizer has been cogently suggested by Keller (1948). In regions of low temperatures and low rainfall the beneficial effects of volcanic ash falls are not felt as soon perhaps, but nevertheless have been amply demonstrated, as noted, for instance, by Griggs (1922) in describing the remarkable recovery of vegetation at Kodiak Island following the eruption of Mount Katmai. Leōn and Polle (1956) found that only potash was available in adequate amounts in the 1955 ash fall of Volcán Nilahue in southern Chile. Whereas the phosphorous-fixing capacity of this ash was low, that of somewhat older ash soil was already appreciably developed.

The physical characteristics of fresh volcanic ash differ markedly in some respects from those of the usual soil, particularly in its granularity, sharp angularity of particles, general paucity of ultrafine particles, and extreme lack of cohesion under some conditions, yet too great cohesion under other conditions. If the fresh ash deposit is greater than plow depth, these physical characteristics lead to distinct behaviors when its use as a soil is attempted, for they affect not only workability, permeability, and erodability, but also ability to function as a nutrient medium for the soil flora and fauna.

The bulk chemical composition of raw volcanic ash may be similar to that of a normal soil, except for abnormally low content of chemically combined water and organic material. Silica content of most volcanic ash lies between 45 percent and 75 percent. The following table shows, for example, that the ash of the Mount Spurr eruption of 1953 had a fairly low silica content, about 55 percent, whereas that of the Mount Katmai eruption of 1912 ranged from 57 to 76 percent, an extraordinarily wide range for ash of a single eruption. An ash mantle several inches thick would contain large absolute amounts per acre of such mineral nutrients as potash, lime, and phosphorus, even though the percentages of these constituents in the ash is low. However, the total bulk analysis does not give the very important information on how much of the mineral nutrients are available to the plants.

Whether the ash will be suitable as a supporting "soil" is determined by its response to the demands of the plants. A variety of chemical tests have been devised to measure the approximate amounts of plant nutrients that may be expected to become available from a normal soil during the growing season. These tests

Bulk chemical compositions, in percent, of some Alaskan volcanic products

	1	2	3	4
SiO_2	55.2	57.99	68.00	76.53
Al_2O_3	17.2	17.39	14.58	12.31
Fe_2O_3	3.1	2.76	1.66	.46
FeO	4.2	4.75	2.75	.96
MgO	3.7	3.42	1.65	.00
CaO	7.4	7.49	4.07	1.01
Na_2O	3.4	4.03	3.92	4.15
K_2O	1.0	1.06	1.98	3.05
H_2O+	.24	.36	.13	.25
H_2O-	.93	.07	.42	.87
TiO_2	.74	.81	.53	.17
CO_2	None	...	...	...
P_2O_5	.30	.22	.14	.05
MnO	.16	.15	.07	.04
S	.60	.07	.02	.01
Cl	...	.07	.13	.23
SO_3	1.5	...	...	...
BaO	...	.05	.05	.07
Total	100	100.69	100.10	100.16

1. Ash, Mount Spurr, eruption of July 9, 1953, collected at Anchorage, Alaska. Analysts: F. S. Borris, Katrine White, and H. F. Phillips, U.S. Geol. Survey.
2. Ash, Mount Katmai, eruption of 1912, layer in a series. Analyst: C. N. Fenner (1950, p. 616).
3. Same at 2.
4. Same as 2.

commonly involve a rapid leaching of a measured soil sample with a given amount of weak acid solution, such as hydrochloric or citric acid and comparing the results with those obtained from leaching a similar soil, whose nutrient content was shown to be adequate by actual plant growth tests. Unfortunately few controlled plant growth experiments have been made on fresh volcanic ash, and, because ash is so different in many respects from normal soil, certain reservations must be held on the use of arbitrary chemical tests that have been calibrated only against plant-growth experiments on normal soil.

Such chemical tests are to some extent indicative nevertheless, and the results of tests on the 1953 Mount Spurr ash are given below. Although calcium is "high" in these tests, nitrogen (both as nitrate and as ammonia) and phosphorus are unavailable, and potash is "low." This ash in itself would therefore seem

Results of soil tests on ash sample from the Mount Spurr eruption in 1953, collected at Anchorage, Alaska.

[Tests made July 10, 1953, by Paul Martin, Alaska Agr. Expt. Sta., Palmer, Alaska, using Morgan soil-testing system, (Lunt, Swanson and Jacobson, 1950). pH = 6.8 (paste of 1 part ash to 1 part distilled water)]

NO_3	None	Mn	Trace	B	Trace
P_2O_5	None	NH_4	None	Mo	None
K_2O	Low	Cu	Low	Zn	Trace
CaO	High	SO_4	Medium	Hg	Trace
MgO	Trace	Cl	Trace	Pb	None
Fe	Medium	Si	High	As	None
Al	Medium	CO_3	None		

to be a poor medium for plant growth. As its thickness in the Anchorage area was only about a quarter of an inch or less, however, its available nutrients should not greatly influence the total available through the plow depth, in this case. The available phosphorus test showing of "none" is somewhat surprising in view of the quite normal amount of total P_2O_5 in the Mount Spurr ash (p. 458, analysis 1). This total phosphorus can probably be assumed to be in the glassy portion or in the mineral apatite, or in both, as found in similar ash from other volcanoes, which do show a certain amount of phosphorus in the available form.

The first examination of the Mount Katmai ash of 1912 was apparently made by Fry (1912) of the U.S. Department of Agriculture. Three samples of ash, representing the successive ash falls of June 6–8 at the village of Kodiak were found to consist predominantly of glass shards with varying amounts of crystalline minerals. Considering them from the agricultural standpoint, he stated:

> There is every reason to anticipate that these glasses, as well as the definite minerals, would dissolve, hydrolize, and behave as would ordinary soil minerals . . . , and on the whole these falls will probably serve ultimately as an enrichment of the preexisting soil, although it by no means follows that the immediate effects will be satisfactory.

A very few data on the availability of nitrogen in the ash of eruption of Mount Katmai are furnished by Shipley (1919a), and are summarized in the following table. From them it may be concluded, first, that the raw ash has a very low content of nitrogen, or none at all in the case of the ash flow from Katmai volcano, and second, that there was a measurable amount of nigrogen in ash around springs in which algae were growing, and a much higher content of nitrogen in reworked river-bottom ash in which seedlings were thriving. None of these media contained anything near the amount of nitrogen found in the normal tundra soil. Shipley gives no data on available potash and phosphorus although he recounts a few tests for apparent soluble salt content, made by an electrical resistance method, which showed great differences from the tests on normal soils.

Some of the volcanic ash of the Mount Katmai area not only did not support vegetation but appeared to have toxic effect on germinating seedlings. Shipley (1919b) concluded that the effect was probably due to the high content of ferrous sulfate (0.081 and 0.300 percent sulfate ion in two samples), which would handicap the functioning of the nitrifying bacteria.

Results of tests for nitrogen in ash of 1912 eruption of Mount Katmai

[Shipley, 1919a]

Location and description of sample	Nitrogen in parts per million		
	as NH_3	as NO_2	Total N
Mount Katmai volcano:			
Upper layer of ashfall	Trace	0.0004	0.8
Ash flow	None	None	None
Section 8 miles south of Mount Katmai crater:			
1. Ash, wind-deposited layer 4 in. thick	None	None	
2. Ash, top-dust layer 2 in. thick	None	None	
3. Ash, yellow 10 in. thick	0.01	None	
4. Ash, grey 32 in. thick	.01	None	
5. Ash, terracotta 16 in thick	.01	None	
6. Ash, lower gray 18 in. thick	.02	None	
Mixed sample of whole section			.05
Observation Mountain:			
Ash, along stream that contained living algae	.02	.0004	
Ash, dry top layer	.04	None	
Ash, moist top layer	.04	.004	
Katmai River:			
Ash, river-deposited, seedlings growing	.4	.004	32.0
Ash, river-deposited, seedlings dead	Trace	Trace	32.0
Kashvik Bay:			
Tundra at 6 in. depth	2.4	.012	
Tundra, 12 in. thick			4320

According to Griggs (1922, p. 46), ash at Kodiak village showed "available potash (K_2O) 0.05 percent" and a "small amount" of phosphoric acid. He concluded from pot tests on ash alone and with varying added chemical fertilizers that, although wheat would germinate and start to grow in the raw ash, some addition of nitrogen, phosphorus, and potash was necessary to prevent their early death. It was found at Kodiak that addition of nitrate alone to the ash covered fields produced fair harvests of ensilage during the 1913 season.

The low ion-exchange capacity of fresh volcanic ash can no doubt be attributed to the absence of clay minerals, organic matter, and other ultrafine material. Baak (1949, p. 55) emphasized that in typical Indonesian eruptions, the amount of material smaller than a half micron is always less than 1 percent by weight, and this generalization is no doubt valid for most freshly erupted volcanic ash of other parts of the world. The initial pH of suspensions of volcanic ash may be quite acidic, owing mainly to absorbed soluble acid constituents, as discussed in the section above on public health. These suspensions commonly revert to a neutral or slightly alkaline condition as the ash itself gradually makes contributions to the solution, and a similar situation may arise in the ash layer in place on the ground as well as a flushing out of the soluble acidic constituents by percolating water.

Weathering and soil-forming processes begin immediately after the deposition of the ash in those portions exposed to the air and ground water. The ultimate product is a material stable in this environment, normally a soil rich in clay minerals. Volcanic ash, especially the glassy portion, is unstable, and it weathers to clay at a much more rapid rate than dense crystalline rocks, both because of the relative vulnerability of the glass to chemical attack and because its granular character permits easy access of altering solutions. Yet in terms of the human life span, it requires much time. Fifty years after the 1883 eruption of Krakatau volcano, for instance, the surface ash seemed to show no discernible development of clay minerals (Mohr and van Baren, 1954, p. 214), in spite of an abundant growth of new vegetation. No doubt the rate of weathering in the Alaskan and Aleutian climates can be presumed to be even slower than in the tropical climate of Pulau Krakatau. Dickson and Crocker (1954), studying the soil on a 1,200-year old volcanic mudflow from Mount Shasta, Calif., found only a thin opaque coating on the glass fragments as indication of weathering. Crystalline fragments such as plagioclase, pyroxene and amphibole showed no apparent effects after 1,200 years of exposure to weathering agencies.

The mechanisms of weathering of natural minerals and glasses are only poorly understood, and much more observational data under controlled natural conditions are needed. Fieldes and Swindale (1954), investigating soils of Pacific islands and New Zealand list five groups of materials in order of increasing resistance to weathering: (1) olivine, pyroxene, and hornblende; (2) basic volcanic glass and zeolites; (3) mica; (4) acid volcanic glass and feldspars; and (5) quartz. They conclude that basic volcanic glass (glass high in iron, magnesium, and calcium) weathers first to amorphous hydrous oxides of iron, aluminum, and silicon, then to allophane or gibbsite and finally to kaolin or montmorillonite, depending on whether hydrogen ions or calcium ions predominate, respectively. The acid volcanic glasses with which they dealt weather first to amorphous hydrous oxides of aluminum and silicon and then to allophane or kaolin.

The gradual breakdown of volcanic glass and crystalline material during weathering is accompanied by release of elements to ground solutions, and among these elements are calcium, potassium, phosphorus, and certain trace elements important in plant nutrition. Thus plant food is made available at a slow rate, which perhaps becomes even slower as residual decomposition products form mantles on the original particles. The very slowness of release of these food elements may be an advantage in some circumstances, however, as pointed out by Keller (1948), who advocates the application of certain natural rock materials, among them volcanic ash, to the land as fertilizers to provide a steady supply of plant food over many growing seasons. For similar reasons McIntyre (1954) and Nestle (1955) have proposed artificially compounded silica-glasses as advantageous vehicles for furnishing minute but steady supplies of certain "trace element" nutrients, such as boron, copper, zinc, manganese, and molybdenum, to the plants over a period of years.

RECOLONIZATION BY NATURAL VEGETATION

The problem of natural recovery of plants in an area devastated by volcanic activity is very complex, and discussion is handicapped by lack of information. The problem has interested botanists and ecologists for many generations, yet the few results, often quoted, are based on studies that were discouragingly incomplete. Most frequently mentioned perhaps are the discussions of the recolonization of the islands devastated by the catastrophic eruption of Krakatau in 1883, and this recolonization has indeed become a classic example, owing to the work of Verbeek, Treub, Ernst, and Doctors van Leeuwen. Some disagreement has been expressed with the assumption by other investigators that the eruption resulted in total destruction of plant life and that all new-appearing plants must have come from outside by seed or spores. The problem is summarized briefly in a recent paper by Went (1949).

The recovery of vegetation after the 1912 eruption of Mount Katmai was the subject of a series of papers by Griggs and his coworkers, and the papers offer, perhaps, more useful data than the series on Krakatau, especially as applied to the Alaskan situation. Mount Katmai's eruption was nearly as intense as that of Krakatau, although it apparently caused no loss of human life. (In contrast, 28,000 persons were killed by Krakatau's outburst and its accompanying seismic sea waves.) The ash deposits from the Mount Katmai eruption were of two types: those of material transported through the air and those of material that moved along the ground surface as ash flows. The ash-fall deposits were several tens of feet thick in the vicinity of the volcano, thinning to less than a foot at Kodiak, a hundred miles south. The ash flow deposits extended only a few miles but ranged in thickness from several feet to several hundred feet.

The recovery of vegetation on Kodiak Island, according to Griggs (1918*a*, 1922), was faster than had been expected in view of the initial desolation in June 1912, and more than bore out the prediction of Fry (1912) quoted above. The 10-inch deposit of ash had smothered all low vegetation and weighted down branches of pine and deciduous trees. By September 1912 the ash had compacted somewhat, and shrinkage cracks as much as 2 inches wide had formed in it; some vegetation had already started and shoots were developing along these cracks. In 1913 it was found that most trees around Kodiak village had survived, having lost much of their burden of ash by this time and replaced the foliage that had been destroyed. There was still little or no undergrowth and other low vegetation, however, and only a few lupine, fireweeds, and other perennials had come up through the ash blanket. A strong detriment to survival of young plants, and one that has been noted in many other areas devastated by ash fall, was the cutting effect of wind-blown ash.

In 1915, when Griggs next visited Kodiak Island, the whole area was once again green with a vegetative cover. Tree seedlings had begun to appear and persisted through the following winter season. The grasses not only had recovered, but they and other small plants were thriving as never before. The ash mantle had decreased somewhat in thickness, owing mainly to compaction and local erosion, and most of the new growth had come, not from new seeds sprouting in the ash layer, but from old roots in the original soil. A species of field horsetail (*Equisetum arvense*) was able to send up shoots from old roots through two or more feet of ash cover, and this plant spread rapidly in the absence of competition from other plants, acting as an effective deterrent to wind and water erosion. Grass seed planted in the ash layer was able in places to subsist but did not flourish. The detrimental effect of sand blast by blowing ash appeared to be decreasing from season to season as more and more of the area was protected by the encroaching vegetation.

The beneficial effects of the ash to plant growth on Kodiak Island after the initial setback was amply demonstrated. According to the inhabitants the pasture grass and garden vegetables were growing more vigorously a few seasons after the ash fall than they had previously. A spectacular, though not entirely typical, example is a tree cut several seasons after the ash fall (Griggs, 1922, p. 48) showing yearly growth rings after 1913 five times thicker than those formed before the eruption. Griggs (1922, p. 47) concluded that the increased growth rate of most plants was due, not to the effect of added plant nutrients, but to the mulching effect of the ash when mixed in old soil and to the destruction of competing plants. This conclusion was based, however, on limited tests of the plant nutrients that might be available in the ash, and it is felt that the conclusion perhaps should be held in abeyance.

On the mainland in the vicinity of Mount Katmai and the Valley of Ten Thousand Smokes, where the thickness of the ash was on the order of feet rather than inches, the recovery of vegetation was markedly slower than at Kodiak Island, and even today, almost a half century after the eruption, there are large areas on the great ash flow of the valley that, to all appearances, remain without vegetation. Griggs first examined the damage on the peninsula briefly in the summer of 1913 while engaged in kelp studies for the Bureau of Soils of the U.S. Department of Agriculture (Griggs, 1915), and returned for more extensive studies in 1915, 1916, and 1917 at the head of the National Geographic Society expeditions (Griggs, 1918*b*, 1919*a* and *b*). He landed in 1913 at Russian Anchorage, 25 miles east-southeast of Mount Katmai, where he found that alders and most birch trees on slopes exposed toward the volcano had no leaves, although many of their twigs were flexible and the interior wood was green. In sites sheltered from the volcano the alders were in full foliage. Elderberry and devilsclub foliage showed some blight, as if from fumes during the 1913 growing season. A vigorous growth of horsetails, as at Kodiak Island, was found locally, in gullies partly cut through the 3-foot deposit of ash.

Following the more extensive studies in subsequent years in the vicinity of Mount Katmai, Griggs (1919*a*) divided the whole of the affected region into six areas on the basis of the type of plant damage: (1) the outermost zone where plants were locally affected by acid rains but otherwise undamaged; (2) Kodiak and Afognak Islands where ash fall had greatly damaged small plants but had very little effect on trees and bushes; (3) areas of slight injury on the mainland; (4) zone where trees had been killed but grasses had recovered; (5) zone of heavy ash fall where trees were killed and herbage buried; and (6) Valley of Ten Thousand Smokes and Katmai Pass where all vegetation had been incinerated by the incandescent ash flow. The last four of these zones are indicated on the map of figure 72, taken from Griggs (1919*a* and *b*).

A zone in which many trees were killed but herbage had recovered extended as a curving band 5 to 10 miles wide from Katmai village on the south coast around west of Novarupta, generally between the 1-foot and 3-foot lines of ash depth and interrupted

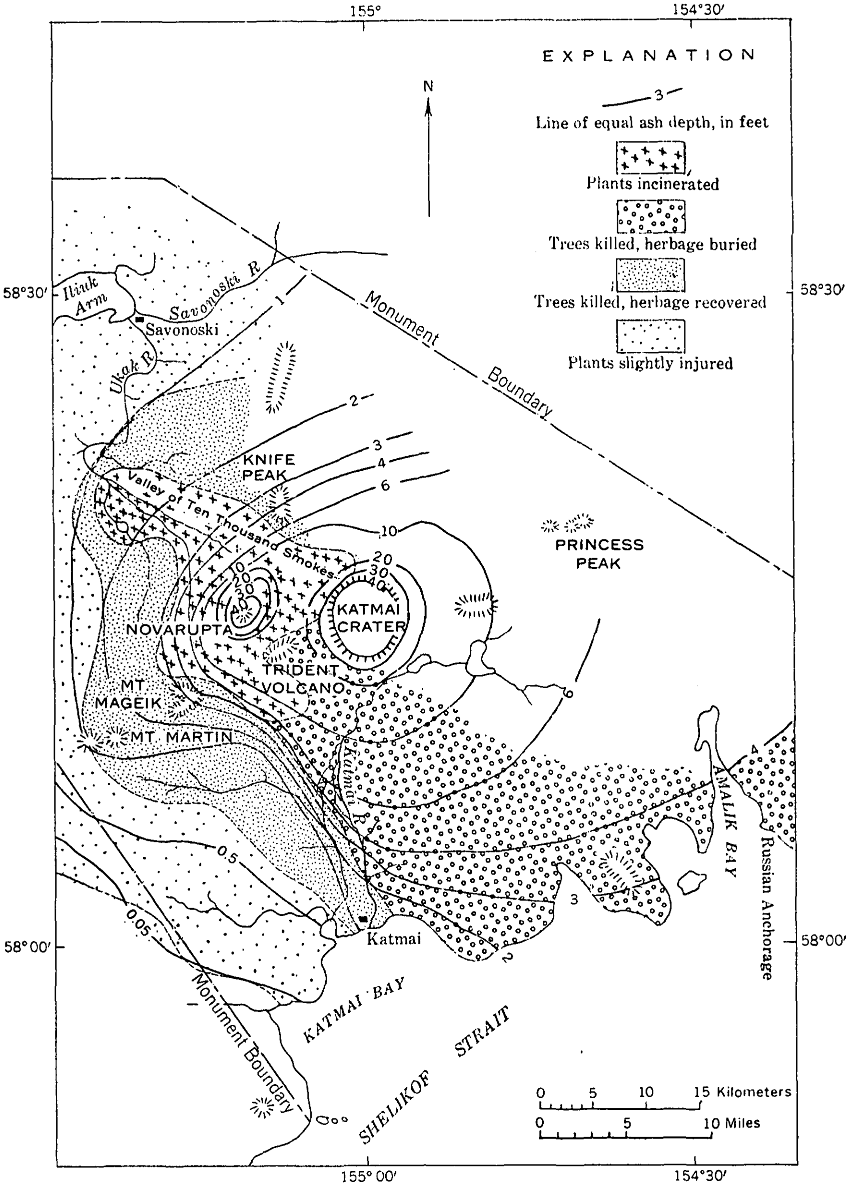

FIGURE 72.—Map of Mount Katmai, Alaska, showing destruction of vegetation in 1912 by the eruption and thickness of ash deposit (after Griggs, 1919b).

by the ash flow of the Valley of Ten Thousand Smokes. In this zone rank growths of low plants, mostly grasses such as horsetail and blue joint, had been able to come up through the ash layer from old roots.

To the east and south of the divide marked by Trident Volcano and extended to Amalik Bay lay a zone in which most trees were killed and herbage was buried too deeply by the ash fall to recover (map, fig. 72). The northern limit of this zone is indefinite because of lack of information. It lay within the zone of heavy ash fall, with thickness generally greater than 2 feet. Curiously, here some smaller balsam poplars survived, though adjacent larger ones were dead. Alders and most birches in valley of Katmai River had been killed, but willows seemed to have recovered better than the other trees. Low herbage had not reappeared except where ash had been partly removed and growth started again from old roots, as had been seen the first season after the eruption in the area around Russian Anchorage.

Griggs (1919*a*) concluded that all flowering plants had been damaged severely in these zones and that some species recovered more rapidly than others mainly because of special abilities that enabled them to cope better with the situation. He argued against toxic fumes at ordinary temperatures as the cause of widespread damage and proposed that a radially directed hot blast was responsible. These arguments are not altogether convincing, and it is felt that questions still remain. Although Griggs regarded the zones of damage as not concentric about the volcano, it seems fairly obvious from examination of his map, figure 72, that the different zones of damage can be correlated with the configurations of the two types of ash deposits: the ash fall strewn out downwind with its fumes, and the incandescent ash flow of the Valley of Ten Thousand Smokes.

The zone of plant incineration includes the Valley of Ten Thousand Smokes and the Katmai Pass areas, in which all plant life was buried by the sudden outflow of ash, initially called a "hot mud flow" by Griggs (1918*b*) but later shown by Fenner 1923) to have been an incandescent ash flow. The thickness of this ash flow deposit is still not known but must be several hundred feet in the medial part of the valley, thinning to as little as 10 feet on the lateral edges and lower extremity. Former tundra vegetation, within but near the edges of the flow, was found to have been reduced to a thin layer of charcoal, and all parts of trees immersed in the ash flow were thoroughly charred. In areas of undisturbed bare ash on the surface of the ash flow, no vegetation had appeared by the end of 7 years, and when Griggs returned in 1930 at the end of 18 years only one type of plant, the leafy liverworts, had obtained a significant foothold (Griggs, 1933). Locally they formed a felted carpet half an inch thick that extended its cover as far as the stability of the ash soil permitted, that is, up to the edge of areas of erosion and deposition. The gradual reduction of the extent of bare ash surfaces, with the encroachment of liverworts over undisturbed ash and other plant types on reworked ash, was leading to a decreasing rate of wind erosion and sand blasting and, with this, to an increased momentum in the progress toward stabilization.

The presence of the liverworts as thriving pioneers on the raw ash surface and their absence or very subordinate role on reworked ash and old soil surfaces at Mount Katmai in 1930 led Griggs to investigate these plants in some detail, especially as regards their requirements for nitrogen, which he had found to be notably lacking in the raw ash. Griggs concluded (1933, 1936) that these particular liverworts, especially *Cephaloziella byssacea,* could thrive on lower concentrations of nitrogen compounds in the soil than other competing types, such as mosses, algae, and seed plants. Smith and Griggs (1932) ran laboratory tests on bacteria (chiefly *B. radiobacters*) associated with the liverworts and found none of them able to fix atmospheric nitrogen. Additional laboratory investigations by Griggs and Ready (1934) confirmed that the liverworts could subsist and reproduce, apparently on amounts of nitrogen too low to be detected by the available chemical tests, and that when the nitrogen content of the media was high, the competing plants, such as mosses and algae, smothered the very slow growing liverworts. They suggest that the amount of ammonia in the rainfall at Mount Katmai, even though very low as compared with industrialized areas, might have been sufficient to support the liverwort growth.

Additional studies of revegetation near Mount Katmai were started in the 1953 and 1954 seasons by V. H. Cahalane as part of a cooperative project of the National Park Service and other governmental agencies and organizations. Although Cahalane was unable to adequately resurvey the same ground in Valley of Katmai River in which so much of Griggs' work had been concentrated, he made collections at three stations there for comparison with Griggs' collections of 1915–17. In the Valley of Ten Thousand Smokes, much of which was still barren, six plots of about one-eighth acre size of differing degrees of vegetative cover were laid out in differing ecological situations as a start toward a long-term systematic investigation of the vegetation recovery. Results of this initial survey are to be published at an early date by the National Park Service (Cahalane, written communication). The extensive mats of liverworts described by Griggs on the ash-flow surface no longer existed in 1953–54. Algae and mosses, too, had practically vanished except for a few survivors in the throats of the declining fumaroles. The disappearance of the liverworts, algae, and mosses from the ash flow surface is related by Cahalane to the cessation of permeation of the ash by steam. On the hill slopes away from the ash flow in 1953 and 1954, there was a considerable representation of horsetail, fireweed, small willows, grasses, and sedges, and in the bottoms of shallow depressions there was abundant alpine wood rush. Wind erosion, sand blasting, and rapid desiccation of the ash "soil" continued to be important deterrants to vegetative recovery on the hill slopes as well as on the valley ash flow.

At Parícutin volcano in Mexico the prolongation of ash eruptions for several years after the initial strong activity of 1943 acted as a handicap to the recovery of natural vegetation. The problem was studied by Eggler (1948) 2½ years after the start of the eruption. He found that oaks had apparently survived in ash depths up to 70 inches, alder, in depths up to 59 inches; some pines (5 to 12 inches in diameter), in depths up to 49 inches; *Crataegus*, in depths to 40 inches; and trailing-arbutus, up to 35 inches. The most hardy shrubs were *Cestrum* and *Smilax*, which survived in ash depths as great as 50 inches, while the common *Baccharis* survived after burial to as much as 22 inches and showed ability to put out adventitious roots from the buried parts of the stems. Among the herbaceous plants, the prickly poppy and mimosa survived in ash depths up to 29 inches. A most important survivor in ash depths of less than 10 inches was Bermuda grass, which was spreading vegetatively in some areas and, with somewhat less persistent crabgrass, was acting to check erosion. Reproduction from seeds in the undisturbed ash had not yet become significant for any of the plants by 1946.

Bare lava flows appear to require enormously greater time for plant colonization than ash deposits in a similar environment; in some cases at least, the recovery lags until windblown or waterborne clastic material filters into cracks or is added to the surface. The smooth lava surface alone in a dry or cold climate would not ordinarily support vegetation until its mechanical and chemical breakdown is well underway. In some tropical regions of very high year-round rainfall, however, such as in parts of Hawaii and the Belgian Congo, the vegetation does not observe this restriction, and certain types of trees and other plants spring up within a matter of months after the lava surface (but not necessarily the interior of the flow) has cooled. It may be simply that a hydroponic situation is involved that makes unnecessary a granular substrate to protect seeds and rootlets from intermittent desiccation.

Lichens are commonly the pioneers on bare lava surfaces (Forbes, 1912; Robyns and Lamb, 1939; Eggler, 1941), and they, perhaps with other elementary forms of plant life able to endure long periods of desiccation, may appear on the rock surfaces soon after the flow has been emplaced. Although they provide significant aid to the inorganic chemical and mechanical agents of rock weathering in the long process of reducing the surface to a condition suitable for growth of higher orders of plants, doubt has been expressed that they are commonly able themselves to provide an adequate mat on which larger plants may subsist. It is obvious that without the intervention of other factors it would take many hundreds or thousands of years to produce a true soil in this manner.

Usually there is at least a small amount of airborne dust deposited on the lava surface, and this eventually comes to rest in the cracks and small depressions that abound on the lava. Cracks appear to be significant sites for the beginning of revegetation, and, according to Eggler (1941), the most favorable situations in the lavas of the Snake River Plains of Idaho are crevices just deep and narrow enough to provide a soil in their bottoms and protection from the wind and sun for the aerial parts of the plants that get a start. Thin pockets of soil (in part wind transported) on the young Carrizozo basalt flow of south-central New Mexico are found by Shields, Mitchell and Drouet (1957) to support algal and lichen growths, which in turn may be important nitrogen sources for higher order seed plants. It has been found, both in Idaho and Hawaii, that plant colonization on smooth (pahoehoe) surfaces proceeds to completion somewhat faster than that on craggy or rubbly (aa) surfaces, and this has been attributed to the availability on the smooth lava of more suitable sites for plant growth in the abundant cracks that catch the small amount of airborne dust. A similar amount of airborne dust deposited on the craggy or rubbly surface filters down to depths too great to permit germination of the seed or growth of the plants.

Plant foliage protruding out of the cracks induces additional deposition of windblown soil, as well as providing bulk to the deposit in the form of fallen leaves and other plant debris from season to season. As the cracks fill up the deposit begins to extend laterally over the lava surface and provides a larger area for plant growth but a new environmental situation. The plant types adaptable to this situation may be different from those that grew in the crevices, and in the Snake River Plain, the new assemblage, which also becomes the climax type, is dominated by grasses and sagebrush (Eggler, 1941).

Eruption of abundant pyroclastic material simultaneously with the lavas from some volcanoes leads to mantling of earlier lava flows by airborne volcanic ash and immediately gives a great advantage in revegetation to these flows over flows that lack the mantle. In this manner a granular "protosoil" is provided ready-made, and on a thick cover of this kind colonization may proceed much in the manner discussed above for revegetation of ash deposits on old soil. Many lava flows in areas of topographic relief are favorably situated also to receive ash brought in from surrounding ash-mantled slopes by gravity, water or wind. Where there has been appreciable admixture of old soil and organic debris, these secondary deposits may even furnish a medium for agricultural rehabilitation.

Long-range beneficial effects of submarine volcanic activity on marine life, analogous in some ways to the beneficial effects of subaerial volcanism on subaerial plant life discussed above, are suggested by Buljan (1955), based chiefly on his studies of the Adriatic Sea and adjacent waters. He outlines evidence indicating that significant amounts of nutrient materials, notably compounds of phosphorus, nitrogen, silicon, iron, and others, are introduced into waters in areas of recurrent submarine volcanic activity, chiefly in the form of vapor exhalations. These may play an important part in increasing the productivity of these areas, and in this respect Buljan cites the abundance of marine organisms in such volcanically active areas as the Japanese, Indonesian, and Aleutian arcs.

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INDEX

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