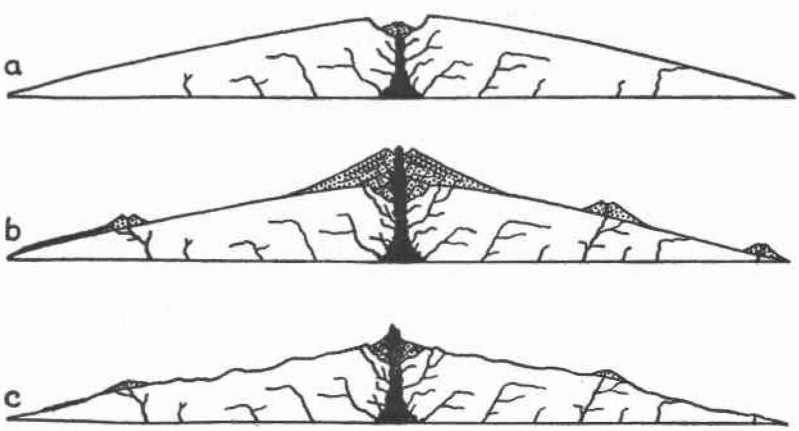
The ANCIENT VOLCANOES *of Oregon*

By HOWEL WILLIAMS



CONDON LECTURES
OREGON STATE SYSTEM OF HIGHER EDUCATION
EUGENE, OREGON . . . 1953

THE CONDON LECTURES

The Condon Lectureship was established in 1944 by the Oregon State Board of Higher Education upon the recommendation of the late Dr. John C. Merriam who was, at that time, a member of the faculty of the University of Oregon. The Lectureship was named in honor of Dr. Thomas Condon, the first professor of geology at the University.

The purpose of the lectures is to interpret the results of significant scientific research to the nonspecialist. The lectures, usually two annually, are delivered three times in the state, namely, at Eugene, Corvallis, and Portland. They are then published in appropriately adapted form.

CONDON LECTURE PUBLICATIONS

The Ancient Volcanoes of Oregon. By Howel Williams, Chairman, Department of Geological Sciences, University of California. Jan., 1948. (Out of print.)

Malaysia—Crossroads of the Orient. By Fay-Cooper Cole, Emeritus Chairman, Department of Anthropology, University of Chicago. Apr., 1948. 75 cents.

The Ancient Forests of Oregon. By Ralph W. Chaney, Professor of Paleontology, University of California. Dec., 1948. $1.00.

The China That Is To Be. By Kenneth Scott Latourette, and D. Willis James, Professor of Missions and Oriental History and Fellow of Berkeley College, Yale University. Mar., 1949. 75 cents.

The Pacific Island Peoples in the Postwar World. By Felix M. Keesing, Executive Head, Department of Sociology and Anthropology, Stanford University. Mar., 1950. 75 cents.

Pacific Coast Earthquakes. By Perry Byerly, Professor Seismology, University of California. May, 1952. 75 cents.

The Near East and the Foundations for Civilization. By Robert J. Braidwood, Associate Professor of Old World Prehistory, The Oriental Institute. Dec., 1952. $1.00.

Evolution and Geography, An Essay on Historical Biography with Special Reference to Mammals. By George Gaylord Simpson, Curator of Fossil Mammals and Birds. The American Museum of Natural History; Professor of Vertebrate Paleontology, Columbia University. Dec., 1953. $1.00.

The Ancient Volcanoes of Oregon (Second edition). By Howel Williams, Department of Biological Sciences, University of California. Nov., 1953.

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The ANCIENT VOLCANOES *of Oregon*

Second Edition

By HOWEL WILLIAMS

Department of Geological Sciences
University of California

CONDON LECTURES
OREGON STATE SYSTEM OF HIGHER EDUCATION
EUGENE, OREGON . . . 1953

Dedicated to the memory
of
Doctor John Campbell Merriam
Teacher, Scientist, Administrator

FOREWORD

THE late Doctor John C. Merriam, after his retirement from the presidency of the Carnegie Institution of Washington, D. C., in 1939, chose to spend most of his time in Oregon. He was appointed to the University of Oregon faculty as "Consultant and Lecturer on the Human Values of Science and Nature." This rather unusual title indicates the emphasis his work took in the latter years of his life.

Doctor Merriam believed that even the best scientific work falls short of the goal which may properly be expected of it unless it goes beyond the mere reporting of results. Beyond presenting such results in technical journals lies the obligation of interpreting them to the intelligent layman. Underlying this conviction was a profound belief in the capacity and desire of the average person to utilize the results of science in his own thinking and activities if those results are presented in terms of facts and their meanings. These ideals found positive expression in the organization and subsidy of the scientific work and the interpretative programs carried out by the Carnegie Institution under his direction. Doctor Merriam personally contributed to the interpretative aspect of the work, with numerous articles and addresses, and two books, "The Living Past," (1937) and "The Garment of God," (1943). During his final years at the University of Oregon, he was constantly exploring the vast store of his knowledge and experience as a paleontologist for values and meaning for human life.

In 1941 he was instrumental in having set up, under the sponsorship of the Oregon State Board of Higher Education, two organizations of scientists from various West Coast universities and colleges. These were the Advisory Board on Education Problems of Oregon Parks and the John Day Associates and were planned to stimulate research and develop interpretative information in their respective fields.

Doctor Merriam recommended to the Advisory Board the establishment of a lectureship in Oregon, under the State Board of Higher Education, to be known as the Condon Lectureship in honor of Doctor Thomas Condon, the first Professor of Geology at the University of Oregon and the first geologist to collect in, and call attention to, the now world-famous John Day fossil beds. The State Board approved the recommendation and established the lectureship on an annual basis.

While the plans originally contemplated that the lectures should deal with earth history and the life of the past, later developments and the planning of the committee have extended the range of subjects somewhat. We have felt that, in addition to earth history and the development of plant and animal life, different aspects of human adjustment to natural and cultural environments should be considered. Furthermore, we have felt that in view of Oregon's position on the Pacific Rim, attention should be directed to that vast and important area. Consequently, the program of lectures as contemplated will include a variety of subjects within this general frame of reference.

The lectures, usually two, are delivered three times in the state, namely, at the University of Oregon, at Oregon State College, and in Portland, but not necessarily in the order stated. With a view to reaching the widest possible audience, the lectures are published in appropriately adapted form. We take pleasure in presenting this first publication in the Condon Lectureship series, the adaptation of the lectures delivered by Doctor Howel Williams.

Condon Lectureship Committee
E. L. PACKARD
O. LARSELL
L. S. CRESSMAN, *Chairman*

FOREWORD TO THE SECOND EDITION

THE continuing demand for Dr. Williams' publication has made desirable the printing of a second edition. The generosity of the Oregon State Board of Higher Education has made the republication possible. Since the first edition the development of the radiocarbon (C14) method of dating has given more specific dates on certain events in the history of the Mt. Mazama and the Newberry eruptions. Paricutin died in March 1952. This second edition has been changed to the extent necessary to incorporate this new information.

L. S. CRESSMAN, Chairman
Condon Lectures Committee

PREFACE

IT WAS an honor and a pleasure to be asked by the Oregon State Board of Higher Education to give the first of the Condon Lectures. This was partly because it enabled me to share in the tribute paid to the memory of Oregon's distinguished geologist, Thomas Condon, whose pioneer work laid the firm foundation upon which all later geologists have built; partly, because the lectures gave me an opportunity of discussing the nature of volcanic action before a sympathetic audience interested in the origins of landscape and living in a region carved almost entirely from the products of ancient volcanoes. Under such conditions—why not confess it?—it was a joy to ride a hobby horse!

The volcanic scenery of Oregon is properly renowned. Not only the majestic snow- and ice-capped cones that rise along the crest, but also the whole Cascade Range is volcanic in origin. Crater Lake lies in the ruins of a beheaded volcano. Drive over the vast plateau of central Oregon or through the lake province of the south, follow the gorge of the Columbia River, wander among the "painted hills" of the John Day Valley, or travel the coast highway. Hardly a scene that meets the eye is not sculptured from the lavas and ashes of some ancient volcano.

Those who thrill to the beauty of landscapes should not rest with the experience unquestioned. Some find sufficient joy in noting the colors and forms of the scenes they view; others gain added pleasure from contemplation of how the scenes came to be, how older landscapes made the present vistas possible. The face of the earth is forever changing;

> "The hills are shadows and they flow
> From form to form, and nothing stands;
> They melt like mists, the solid lands,
> Like clouds they shape themselves and go."

The purpose of this book is first and foremost to portray in simple terms the volcanic history of Oregon during the last sixty million years, to tell of the succession of ancient landscapes that preceded those of today. My hope is to rouse in those who visit Oregon a deeper sense of beauty through an understanding of how its mountains and valleys have been shaped.

Since my own observations have been confined chiefly to the southern part of the Oregon Cascades, the Newberry Volcano, the Steens Mountains, and the John Day country, the major portion of the book is based upon the writings of others. The influences of these publications are too general and pervasive to permit of specification; yet the student of Oregon geology will not fail to perceive how much I owe to them. In a work of this kind, it did not seem wise to burden the pages with copious footnotes and references to original sources, since the reader anxious to pursue the subject further may begin easily by consulting the *Bibliography of North American Geology* published by the United States Geological Survey. I cannot refrain, however, from expressing my thanks to the following for their valued contributions: Professor R. W. Chaney, my principal source of information concerning the ancient climates and floras of Oregon, who also aided by a critical review of the manuscript; Professor C. E. Weaver, for most of the data bearing on marine conditions; Professors W. D. Smith, E. T. Hodge, and W. D. Wilkinson, and members of the Oregon State Department of Geology and Mineral Industries, for much material relating to the volcanic history. Without their work such a synthesis as I have attempted would not have been possible. The only originality that I can claim is that which may have resulted from combining their observations with mine to depict the changing panoramas of Oregon's volcanic past. While dispensing with professional phraseology as far as possible, I have tried to present the story as accurately as I could. The geological record itself is fragmentary, and much of it remains to be deciphered. Possibly the story as told may encourage others to join in decoding some more lines of the tattered script.

University of California,
Berkeley, 1947

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INTRODUCTION

Origin of Volcanoes

WHEN we deal with the ultimate causes of volcanic action, we move in a field only dimly lit, stumbling in shadows of doubt. But even though speculation is rife, some generalizations appear to be valid. Records from deep wells and mines show that the temperature of the earth's crust increases with depth. The rate of increase varies. In the outer shells of the earth it averages between 30°C. and 50°C. per mile; at greater depths the rate diminishes. Forty miles below the earth's surface the temperature is probably close to 1200°C. At that temperature in the laboratory almost all rocks melt. Yet earthquakes demonstrate beyond question that the material 40 miles beneath us is rigid enough to transmit shear waves. What keeps it from melting is the tremendous overburden, for with increase of pressure the temperature of fusion also rises.

Twenty to forty miles under the floors of the oceans and under the continents, according to most geologists, there is an earthshell made up of heavy basaltic material that grades downward into shells of still heavier rock increasingly charged with nickel and iron. Some maintain that this subcrustal shell of basalt is crystalline; others say it is so hot that it must be in the form of glass. Almost all agree that from time to time this basaltic shell is partly converted to a pasty liquid called *magma*, and that this is the primary source of all the lavas and ashes erupted by volcanoes.

How is the rigid basalt made liquid? The answer is—by reduction of pressure, by increase of temperature, or by a combination of these two processes. Now, as in the past, most volcanoes are concentrated in long, narrow belts across the face of the earth. Examples are the volcanoes of the Andes, the Cascades, the Aleutians, Japan, and the East Indies, parts of the "girdle of fire" encircling the Pacific Ocean.

These volcanic belts coincide closely with the major earthquake-belts of the earth, for volcanoes and earthquakes alike are symptoms of unrest in the crust of the globe. In addition, most volcanoes lie within or close to mountain ranges that, by geological standards, are youthful. The inference has therefore been drawn that bending and fracture of the earth's crust, by causing a local release of load at depth, convert some of the underlying rigid basalt into magma. Liquefaction may be brought about also by rise in temperature consequent to breakdown of radioactive substances in and beneath the crust.

The elements uranium and thorium are especially important in this regard; as they decay to lead by giving off helium they generate heat, and in the course of millions of years this may accumulate until large volumes of subcrustal basalt are changed to liquid.

Once magma is produced, it tends to rise. If ascent to the surface is rapid, the magma pours out of swarms of narrow fissures and spreads as floods of basaltic lava, like those which buried most of central Oregon in Miocene times (see Fig. 4). Alternatively, the lava flows pile up to build giant basaltic volcanoes like those now active on the Island of Hawaii. Usually, however, the rising magma is arrested temporarily at various levels in the earth's crust. Displacing the surrounding rocks, it comes to occupy reservoirs at depths of a few miles beneath the surface. These are the feeding chambers of most volcanoes.

Now it is well known that a single volcano may erupt quite different kinds of material at various times, and that neighboring volcanoes may discharge different lavas simultaneously. The explanation seems to be that the magma in the feeding chambers is always undergoing change, always tending to separate into fractions of different composition. As the liquid cools against its rocky walls, minerals begin to crystallize. Those forming first are usually poor in silica and rich in magnesia, like some olivines, or poor in silica and rich in lime, like some feldspars. As cooling proceeds, minerals richer in silica, iron, soda, and potash develop. Many of these crystals sink toward the bottom of the reservoir so that a light silica-rich residual liquid with few crystals comes to rest on a more basic, heavier liquid increasingly loaded with crystals toward the bottom. Since eruptions may take place at any stage in the process and eruptive fissures may tap any level in a feeding chamber, a wide variety of materials may be expelled.

If eruptions recur at brief intervals and the chamber is continually replenished from below, then the lavas and ashes are likely to be made up of olivine basalt, almost identical with the original magma. On the other hand, quiet intervals between eruptions may be long. Then, crystallization may continue until a light, siliceous liquid with sporadic crystals of quartz, feldspar, pyroxene, and hornblende collects at the top of the reservoir. Underneath is a layer of intermediate composition devoid of quartz and with more limy feldspars that rests in turn on heavy basaltic magma loaded with more and more olivine crystals toward the base. When layering of the reservoir progresses to this stage, the topmost quartz-bearing magma may be erupted either as rhyolite or dacite. If lower layers of quartz-free magma of intermediate composition are erupted, the material is referred to as andesite. This rock received its name because it forms the dominant product of the volcanoes crowning the Andes of South America. If still lower layers escape from the reservoir, they produce basaltic andesite and olivine basalt. Naturally, if crystallization does not continue long enough to yield rhyolite or dacite, only andesite and basalt can be discharged.

Probably the process of crystallization is the main cause of the diversity in composition of the products of volcanoes. Among many other causes is the contamination of magma by solution of the reservoir walls. Any kind of rock may enclose a reservoir; hence the effects of solution in modifying the magma are extremely varied.

A fundamental effect of the crystallization of magma, the concentration of gas in the liquid that remains, must be emphasized. The reason is simple enough: none of the early forming crystals abstracts gas from the magma. Consequently, the residual liquid becomes increasingly charged with volatile ingredients. Indeed, if crystallization goes on long enough, so much gas is concentrated in the remaining liquid that it can no longer be held in solution. Bubbles then begin to form; the magma starts to effervesce. Ultimately, the gas-pressure becomes too great for the reservoir roof to withstand, and the frothy magma blasts a passage to the surface, exploding violently into showers of ash and pumice. None can doubt that this accumulation of gas-pressure during crystallization is one of the prime causes of volcanic eruptions. Without gas, magma would be inert; in large measure, it is the expansion of gas that forces magma upward to the surface and propels ejecta from the crater of a volcano.

Products of Volcanoes

The products of volcanoes include gases, lavas, and fragmental ejecta. Consider first the gases. By far the principal gas given off by volcanoes is steam or water vapor. Seldom does it constitute less than 80 per cent of the total discharge, and generally it makes up more than 95 per cent. Next in importance is carbon dioxide; then various compounds of sulphur, such as hydrogen sulphide and sulphur dioxide. Along with these, there is usually some carbon monoxide, hydrochloric and hydrofluoric acid, hydrogen, hydrocarbons, ammonium chloride, ammonia, etc. Even during a single eruption, the proportions of these minor constituents vary considerably. Their importance should not be minimized. Were it not for the emanations of volcanoes in the past, there would not be enough carbon dioxide in the atmosphere to support plant life, and without plants, man and animals could not exist.

Consider next the fragmental products of volcanoes. These range in size from blocks weighing hundreds of tons to particles fine enough to be carried by winds around the world. The finest ejecta, particles smaller than peas, are referred to as volcanic dust and ashes. Compacted to rocks, they form volcanic tuffs. Pieces between the size of peas and walnuts are spoken of as lapilli. Still larger fragments are called blocks, if already solid when blown out, or bombs, if partly or wholly in a molten state when erupted. Rocks consisting mainly of blocks are classified as volcanic breccias, while those mainly composed of bombs are termed agglomerates. Highly inflated, frothy ejecta, light enough to float on water, are designated as pumice; they are usually composed of dacite or rhyolite. Darker, clinker-like lumps hurled out by basaltic volcanoes are commonly called cinders. Many of the small cones around Bend and in the High Cascades are built entirely of such materials.

The lavas erupted by volcanoes are no less diverse than the fragmental products. Their characters are controlled, likewise, by the chemical composition, gas-content, and temperature of the magma. Other things being equal, lavas poor in silica and rich in lime, iron, and magnesia, such as basalts, are more fluid than lavas like dacite and rhyolite in which the proportions of these constituents are reversed. Indeed, the most fluid basalts may pour along at the speed of a mountain stream, while rhyolitic and dacitic lavas crawl forward sluggishly. Hence it is not surprising that basaltic flows are usually much more extensive than siliceous ones. Besides, basaltic lavas are generally much hotter, their temperatures ranging mostly between 1000° and 1200°C., while rhyolitic and dacitic lavas vary normally between 600° and 850°C. Andesitic lavas tend to have intermediate temperatures. Cooler and more viscous rhyolitic and dacitic flows, therefore, form thick and stumpy tongues or steep-sided mounds, and they often solidify to the volcanic glass known as obsidian.

No one can travel through the volcanic fields of Oregon without noting that the surface-forms of the lavas are extremely diverse. Some flows, especially basaltic ones, have smooth, satiny skins of glass that glisten in the sunlight. Others have crusts marked by ropy and cord-like corrugations of the kind known in Hawaii as *pahoehoe*. It is in such flows that tubes and tunnels, like the Malheur tube and many others in central Oregon, are best developed. Some of these tunnels are too small to crawl into; others measure 50 to 80 feet across and can be traced for a mile or more. Their origin is easy to understand. Lava solidifies first at the top, bottom, and sides, so that the interior continues to flow long after the marginal parts have come to rest. Hence, when the supply of fresh lava is checked or cut off at the source, the liquid interior may be drained by discharge at the snout of the flow, leaving the solid casing behind. The ceilings of many such tunnels are lined with slender stalactites caused by dripping of lava remelted by hot gases rising from the moving currents below. If the ceilings are thin, they may collapse to produce pits and elongate depressions on the surface of the flow.

Still other lavas, usually andesitic and basaltic ones, have indescribably rough, clinkery crusts that resemble seas of frozen foam. These the Hawaiians call *aa* flows. Then there are lavas having surfaces littered with chaotic piles of angular, smooth-faced blocks. *Block lavas* of this kind are typical of glassy, siliceous flows, especially of obsidians. They also may be found among basic flows provided they chill quickly to form a thick crust of glass that can be shattered by movement of the pasty liquid underneath. Finally, some flows, particularly basaltic ones erupted into water, break up into pillow- and sack-shaped bodies. Excellent examples of such *pillow lavas* may be seen among the oldest volcanic rocks of the Coast Ranges of Oregon.

Forms of Volcanoes

Perhaps the most familiar volcanic form is the graceful cone whose sides steepen toward the summit. Mounts Shasta, Hood, Rainier, and St. Helens are splendid illustrations. Volcanoes like these are built partly of lava flows and partly of fragmental layers. In other words, they grow by a combination of quiet, effusive eruptions and violent explosions. Hence, they are commonly classed as *composite volcanoes* (see Fig. 1). When they rise to great height, the lavas tend to escape more and more from cracks far down the sides instead of from the crater at the top, although explosive blasts may continue from the summit and plugs of viscous lava may be forced upward through the crater floor.

Contrasted with composite cones are the so-called *shield volcanoes,* built almost wholly by copious outwellings of fluid basalt. If the shields grow by overflows from a central vent on top and from more or less radial cracks on the flanks, they assume the forms of inverted saucers. If, on the other hand, overflows from the summit alternate with eruptions of lava from closely spaced, parallel fissures on the sides, the shields take on the shapes of inverted canoes. No better examples can be found of volcanic shields than Kilauea and Mauna Loa on the Island

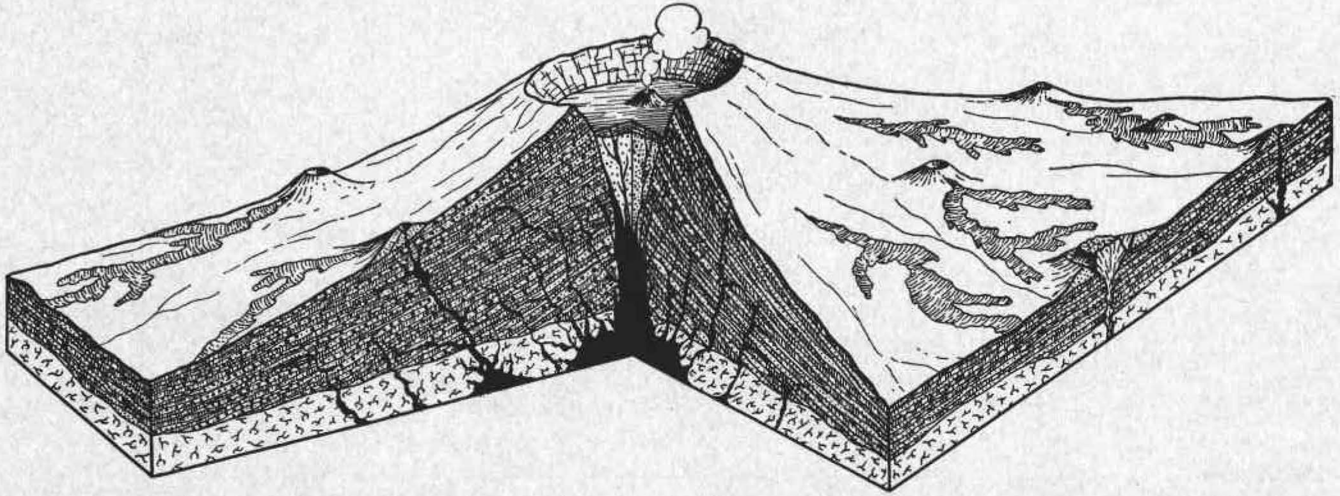


Fig. 1. Diagram of a composite volcano. Main cone built of lavas and fragmental ejecta. Five parasitic cinder cones on the flanks; also a plug dome within a parasitic cone, shown in section on the right. Many dikes cut the interior of the main cone, and one serves as a feeder to a parasitic cone.

of Hawaii. Later we shall see that many similar shields grew along the crest of the Cascade Range within the last ten million years.

Eruptions of clinkery ash, lapilli, and bombs produce the well-known *cinder cones,* such as Wizard Island in Crater Lake, Pilot Butte near Bend, and the scores of dark hillocks on the slopes of the Newberry Volcano in central Oregon. Few exceed 500 feet in height. The way in which they grow is exemplified by the activity of Paricutin in Mexico.

Not uncommonly, lava emerging from a vent is too viscous to spread far and therefore accumulates as steep-sided, bulbous mounds. Because such mounds are often of domical shape and serve to seal the underlying conduits, they are referred to as *plug domes.* Some grow by overflow of pasty lava from a crater on top; others, including Lassen Peak in California and some of the obsidian mounds in the Three Sisters region, are forced from the feeding pipes much in the same way as toothpaste is squeezed from a tube. The outside of the lava column solidifies at once to form a glassy crust; then, as the pasty liquid within continues to rise, the crust is shattered into blocks that accumulate on the summit of the growing mass or tumble down the flanks to form long banks of talus (see Plate III). Compared with the rate of growth of composite and shield volcanoes, the rise of plug domes is phenomenally rapid. Volcanoes such as Mounts Hood, Rainier, and Shasta were a million years in the making; Lassen Peak and similar huge domes may have grown in less than a decade.

Types of Eruption

The activity of most volcanoes changes from time to time. Periods of violent explosions may alternate with periods of quiet effusion. Many vents may be active simultaneously within a single crater, each behaving in a different fashion. Despite these variations, certain well-known volcanoes erupt in a characteristic way for long periods; their names have thus come to be used in classifying types of eruption.

The *Hawaiian type* is exemplified by basaltic shield volcanoes like Mauna Loa and Kilauea. Extremely hot and fluid lavas pour from vents on the summits of the shields and from long fissures on the flanks. Sometimes fountains of lava may spout during the first phases of an eruption, but the fragmental material blown out is trivial in volume compared with the lava flows.

The *Strombolian type* takes its name from the Italian volcano, Stromboli, which has been almost continuously active since the days of Homer. Normally, the mode of eruption is a more or less rhythmic discharge, every few seconds or minutes, of pasty, glowing clots of magma that cool to ropy, spindle- and almond-shaped bombs and clinkery lapilli. Quiet intervals are rarely long enough to allow lava to congeal in the feeding pipe; hence, few solid fragments are expelled. Outpouring of lava is on a much smaller scale than on Hawaiian volcanoes, and the flows are usually much more viscous. The characteristic form produced by Strombolian activity is a cinder cone.

Not far from Stromboli is Vulcano, from which the word *volcano* is derived and the *Vulcanian type* of eruption takes its name. Activity here is marked by discharge of still more viscous magma. Explosions, instead of being rhythmic and fairly continuous, take place between irregular intervals of repose. Solid, angular fragments are blown out along with lumps of pasty magma that fall to earth as bombs with glassy crusts and as frothy pieces of pumice. Few fragments are hot enough to glow or liquid enough to be rounded as they spin through the air. Huge cauliflower clouds of steam, heavily charged with fine ash and riddled with flashes of lightning, rise from the crater. Flows are rare and those that do escape cool to thick, stumpy tongues of obsidian. Eruptions of this kind are exceptional on basaltic volcanoes; they are characteristic of volcanoes fed by more siliceous magmas.

When no lava is discharged during an eruption and the fragmental ejecta are made up entirely of old rock fragments, the activity is said to be of *Ultra-Vulcanian type*. Eruptions of this character are simply low-temperature steam blasts. The first outbreak of a new volcano and the initial explosions of volcanoes that have lain dormant for a long time are frequently of this type.

In 1902, viscous lava was forced upward into the summit crater of the West Indian volcano, Mont Pelé. Unable to spread laterally, it piled over the vent as a bulbous dome. Similar domical protrusions are said to be of *Pelean type*. Often their rise is accompanied by explosions of frightful intensity. While the dome of Mont Pelé grew, repeated blasts of superheated steam shot from its sides, carrying with them vast quantities of glowing ash and blocks. So voluminous were these ejecta that they fell at once on the adjacent slopes, then raced down the mountainsides at hurricane speeds. Some of these glowing avalanches were observed to move at rates of more than 100 miles an hour. One overwhelmed the town of Sainte Pierre in an instant, killing all but one of its 28,000 inhabitants.

Escape of lava from fissures on the sides of volcanoes rather than from central vents is a common phenomenon. But the most copious fissure eruptions are not those related to cones and shield volcanoes. On the contrary, they produce plains and plateaux of enormous extent. Many times during the earth's history, colossal floods of fluid basalt have risen through narrow, vertical fissures to spread over the surface in far-reaching floods, converting mountainous regions into level wastes. No less than a quarter of a million square miles of Oregon and Washington were formerly inundated in this fashion.

Although basaltic lava is the principal product of such large scale fissure eruptions, the most siliceous magma, rhyolite, also may be poured out in immense volumes from narrow cracks in the ground. Usually, however, the rhyolite is not erupted as flows, but as fragmental pumice and ash. Instead of being hurled high into the air, as in most explosive eruptions, the effervescing magma wells from the fissures as a mixture of hot gases, spray, and pasty clots. Having unusual mobility, the material spreads swiftly as incandescent sheets and travels far even over surfaces that are practically horizontal. Eruptions of this kind once devastated much of the John Day Valley.

From what has been said, it may be judged that the nature of volcanic eruptions is determined mainly by the gas-pressure and viscosity of the magma involved. Other things being equal, the lower the viscosity the greater the tendency to quiet outflow of lava; the higher the gas-pressure the greater the tendency to explosive activity. A magma with strong gas-pressure may cause violent explosions; the same magma impoverished in gas may be forced out slowly to form a plug dome. The hotter a lava is and the more gas it contains, the more fluid it becomes. Composition is also important, for siliceous lavas are generally more viscous than basaltic ones. It is the complex interplay of all these and other factors which accounts for the multitude of ways in which volcanoes behave.

The Growth of Paricutin Volcano, Mexico

To those familiar with the volcanic landscapes of Oregon, the history of Paricutin, the volcano born in Mexico in 1943, is of special interest; its activity shows how scores of the cinder cones in the Cascades and on the plateau to the east were formed.

The birth of a new volcano and the revival of activity on volcanoes after periods of repose are usually heralded by earthquakes. The birth of Paricutin was not an exception. For three weeks before the first eruptions, the ground in the vicinity shook almost continuously, and as the fatal day approached the quakes increased in strength. On the morning of February 20, when Dionisio Pulido, a Tarascan Indian, went to till his cornpatch he was amazed to see a wisp of vapor spiralling upward from a hole in the ground, a few inches wide. Within a few hours the wisp changed to a dark ash-laden column and the hole widened to 30 feet across. Late that night, glowing bombs, and cindery clots began to issue, falling round the vent to build a cone. Next morning, the cone was already 120 feet high. Every few seconds, deafening blasts vomited showers of incandescent fragments, adding to its size. On the second day, a small tongue of basaltic lava emerged. It was amazing how rapidly the cone gained in height; on the third day, it was 200 feet high; on the twelfth, it was 450 feet high and lava had covered 120 acres. Enormous clouds towered over the summit of the volcano; sometimes they were shaped like a column that mushroomed at the top and sometimes like quickly expanding cauliflowers. They rose for three miles or more before being drifted away by the winds. Bombs up to several feet across rained down on the cone and around its base; farther away a steady shower of fine ash fell, laying waste to the countryside. At night, the view was indescribably grand. Volleys of glowing projectiles, like fiery bouquets, shot from the crater. The cone sparkled with a myriad moving lights as bright red and golden bombs rolled and bounced down the sides while the overhanging clouds reflected a fitful, lurid glare. Above the deep roar of the cannonade could be heard the patter and thudding of falling fragments. The streams of lava flowing from the foot of the cone looked like incandescent ribbons. Without cease the ground trembled (see Plate II).

The noises of the explosions varied. For long spells, loud detonations recurred at intervals of a few seconds; then the sound changed to a dull, continuous roar like that of surf beating on a distant shore. The appearance of the eruption cloud also changed, passing from fleecy white to almost black as the amount of ash increased.

In the middle of March, following a period of exceptional violence, a new flow escaped from the base of the volcano. Early in April, activity became so intense that fine dust fell on Mexico City, 200 miles away. At Uruapan, 20 miles distant, the streets and housetops were heavily blanketed with cindery fragments. In mid-April a third flow issued from the foot of the cone. In June a fourth broke out from a point about halfway up the side. It undermined and carried away a large part of the cone. By mid-July the volcano was 1,000 feet high and more than 3,000 feet wide at the bottom. During September still another flow emerged from the foot of the cone. Throughout these months, explosions continued with unabated fury.

On October 19, 1943, a strange thing happened. Coincident with a sharp decrease in the explosive activity of Paricutin, a new cone, Zapicho, was born at its base. Spectacular reddish and golden yellow fountains of lava gushed from its mouth, and a long flow poured through a breach in its wall. For 79 days, until January 6, 1944, while Paricutin itself lay almost dormant, Zapicho erupted with vigor, building to a height of more than 200 feet. No sooner did it stop than Paricutin took up the refrain. Two flows burst from vents low on the flanks, and explosions from the summit-crater became so strong that heavy falls of ash were noted 100 miles away.

All through the early months of 1944, lava continued to pour from the base of the volcano. In May the principal flow, having travelled five miles, began to bury the town of San Juan (see Plate I); by late July, all but a small part of the town had been overwhelmed. Other flows burst from the base of the cone during the next few months. The village of Paricutin had long been rendered uninhabitable by heavy falls of ash. In October lava descended from the cone in a series of magnificent cascades and buried most of the buildings that remained. Early in November still another vent opened at the foot of the cone, and for more than three months lava issued from it in a steady stream, no matter whether the summit-crater lay quiet or erupted with violence for days on end.

When the volcano was two years old, in February, 1945, the principal cone had a deep, funnel-shaped crater, approximately one-fourth mile wide at the rim. On the crater floor were two vertical pipes that were astonishingly small considering the great volume of ash and bombs they discharged. Lavas had covered more than four and one-half square miles, and close to the cone they had accumulated to a depth of about 600 feet.

After the second anniversary, there was little change in the type of activity. Quiet spells, when scarcely a wisp of vapor rose from the top of the cone, alternated with periods of strong explosions, sometimes as intense as those of the first few months. Flow after flow emerged from the foot of the cone; some lasted only for a few days, and others for a few weeks or months. Shortly after one ceased, another broke out from a nearby vent. The lava changed gradually from olivine-rich basalt or basaltic andesite to olivine-poor andesite, considerably richer in silica. At the same time, both the volume and rate of lava discharge diminished, though irregularly, and the successive flows tended to be shorter and more viscous. Close to the points of emission, their temperature was usually between 1150° and 1200°C., and even two or three miles from the vents, the central portions of some flows showed temperatures as high as 1100°C. Near the vents, most of the flows moved at rates varying from a meter to about 15 meters a minute, depending largely on the slope of the ground; at their snouts they crept forward only 20 to 200 or 300 meters a day.

The outstanding features of Paricutin's life were: the phenomenal rate at which the cone grew and the great volume of lava expelled. Among the scores of flows erupted, all but a few broke out from vents at the base of the cone. Noteworthy also was the fact that while some flows were preceded by periods of strong explosions most of them behaved without apparent regard to the activity of the summit-crater.

In March 1952, when little more than nine years old, Paricutin died. The cone had reached a height of more than 1200 feet above the original cornfield at its base. Altogether, some 2,230 million metric tons of ash and about 1,330 million metric tons of lava had been erupted during this brief span of time. And if we may judge from these figures, it seems likely that none of the countless basaltic cinder cones that dot the ancient volcanic fields of Oregon can have been active for more than a few years or at most a few decades. Here, indeed, is vivid testimony to the rapidity with which a volcanic landscape may be changed.

The time has come to turn to our principal theme, the volcanic history of Oregon since it rose from the sea at the end of Cretaceous time, 60 million years ago. Of the earlier volcanic history, going back a billion years or more, nothing will be said, for it is too little known and too difficult to decipher.

CORRELATION OF FORMATIONS

Period	Western Washington	Western Oregon	Oregon Cascades	Eastern Washington	Eastern Oregon
RECENT	Last eruptions of Cascade volcanoes	Elevation of Coast Ranges and formation of marine terraces	Destruction of Mount Mazama. Last eruptions of Cascade cones; last intracanyon basaltic flows	Alluviation and erosion	Last eruptions of Newberry Volcano and adjacent cones Diamond, Jordan, and Bowden Craters
ICE AGE	Growth of Mounts Rainier, Baker Adams, and St. Helens	Elevation of Coast Ranges and formation of marine terraces	Growth of large andesite cones (Hood, Jefferson, South Sister, Mazama, etc.) in High Cascades	Glaciation	Growth of Newberry Volcano; eruptions near Harney Basin, Harper district, etc.
PLIOCENE	Montesano	Empire	Growth of basaltic and basic andesite shield volcanoes in High Cascades. Deposition on flanks of range of Troutdale, Dalles, Rhododendron, Madras, and Deschutes formations	Volcanic eruptions Ellensburg	Ochoco lavas; Harney tuffs. Rattlesnake tuff and Danforth formation Steens Basalts Steens andesites, dacites, and rhyolites Alvord Creek beds
MIOCENE	Astoria	Astoria	Stayton and Sardine volcanics (Western Cascade Volcanic Series)	Columbia River basalts	Mascall and Payette volcanics and lake-beds Columbia River basalts
OLIGOCENE	Sooke Blakeley	Nye shales and Scappoose beds	Un-named volcanics Eugene, Illahe and Mehama volcanics (Breitenbush) (Western Cascade Volcanic Series)	Main Keechelus Volcanic Series	John Day beds
	Lincoln Keasey	Tunnel Point, Yaquina, and Pittsburg Bluff Bassendorf, Keasey and Toledo	Fisher Comstock (Breitenbush) (Western Cascade Volcanic Series)		
EOCENE	Cowlitz (Puget) Crescent (Puget) Metchosin Submarine lavas	Arago Tyee Umpqua Tillamook and Metchosin lavas	Spencer Calapooya and Umpqua ?Pre-Umpqua basalts (Western Cascade Volcanic Series)	Roslyn and Manastash Teanaway basalts Kachess lavas Swauk	Clarno beds

THE VOLCANIC HISTORY OF OREGON

Late Cretaceous Time
(75 to 60 million years ago)

There have been times in the history of North America when volcanoes were especially numerous and vigorous, and other times when they were rare and seldom erupted. Few periods were less volcanic than the Cretaceous. At scattered points in California there were sporadic eruptions of rhyolitic ash, but for the most part there was relative quiet along the Pacific border. This was a time when the oceans spread far over the lands. Almost the whole of California and Oregon was submerged beneath a shallow sea whose waves lapped against the Blue Mountains and Sierra Nevada. Where the Klamath Mountains now stand, a large island rose from the sea. Over the present site of the Coast and Cascade ranges, warm waters teemed with crabs, shellfish, squidlike belemnites and coiled ammonites. Huge marine lizards swam in the sea while winged reptiles glided above in search of prey. On the neighboring lands, grotesque dinosaurs roamed among lush tropical forests or waded in swamps and rivers, browsing along the banks.

Early and Middle Eocene Time
(60 to 50 million years ago)

Toward the close of the Cretaceous period and at the beginning of the Eocene, the entire western part of the continent was slowly deformed. Throughout millions of years, the earth's crust was differentially upheaved, folded, and fractured, just as the Coastal Ranges of California are being disturbed today. Gradually, the floor of the Cretaceous ocean rose above water, forcing the Oregon coastline westward beyond its present position. Then followed a long interval of erosion during which the newborn land was reduced to a plain only slightly above the level of the sea, stretching east beyond the Blue and Wallowa mountains into Idaho. Subsequently, but still within the first half of Eocene time, some coastal portions of the plain were warped downward, permitting the ocean to readvance over Oregon through shallow bays. Nowhere did the inundation spread farther than the present western foothills of the Cascade Range; indeed never again in the history of Oregon did the ocean extend beyond this line.

It was in response to these disturbances that volcanic activity began in the Pacific Northwest about 60 million years ago. Just when the first eruptions occured is still a little doubtful, but already in early Eocene time a few thick flows of pasty lava (Kachess rhyolite) were discharged from volcanoes in eastern Washington. Certainly, before half of the Eocene period had passed, volcanism was widespread and intense. Copious sheets of fluid lava (Teannaway basalts) were expelled from swarms of vertical cracks in the region now forming the eastern flank of the Cascade Range in Washington. Flow piled on flow until in places their aggregate thickness was more than 5,000 feet.

About the same time, submarine eruptions took place on a truly stupendous scale in western Washington and western Oregon. From Vancouver Island south to the edge of the Klamath Mountains, and east to the present foothills of the Cascades, flows of basalt poured from fractures on the floor of the sea. Many large cones were built and some of them rose until they formed temporary islands in the sea. Periodically, they burst into strong explosive activity, strewing the sea floor and adjacent lands with ash. But for the most part, the eruptions were of the quiet, effusive kind. Indeed, most of the flows, instead of forming cones around a series of central vents, issued now from one submarine fissure and then from another to spread over the sea floor in expansive sheets. And there were times when lavas, unable to escape at the surface, after rising from the depths, were injected into the muds on the bottom of the sea.

These submarine eruptions continued for millions of years. In fact there were places where the flows accumulated on top of each other to thicknesses of thousands of feet, making the sea floor sag under their weight. Some lavas were discharged in such quick succession that before one solidified completely it was buried by another. No doubt the sea itself was agitated and warmed, and perhaps the layers of limy sediment found between some of the flows were produced by precipitation from heated waters. The lavas themselves developed the pillow structures characteristic of submarine basalts. No sooner did a flow emerge onto the sea floor than its surface was chilled to a glassy crust. Immediately, the crust was ruptured by the onward urge of the pasty lava within. From cracks in the snout of every advancing flow, red-hot lava oozed in viscous blobs. Quickly the blobs became encased in glass, then expanded into pillow- and sack-like bodies a few feet or yards across, and broke loose to tumble ahead and be buried by other pillows. Thick flows, and those rapidly covered by others, remained hot and partly fluid for a long time. Water present in wet muds on the sea floor and between pillows was converted to steam, so that the slowly cooling cores of the flows were thoroughly stewed, and

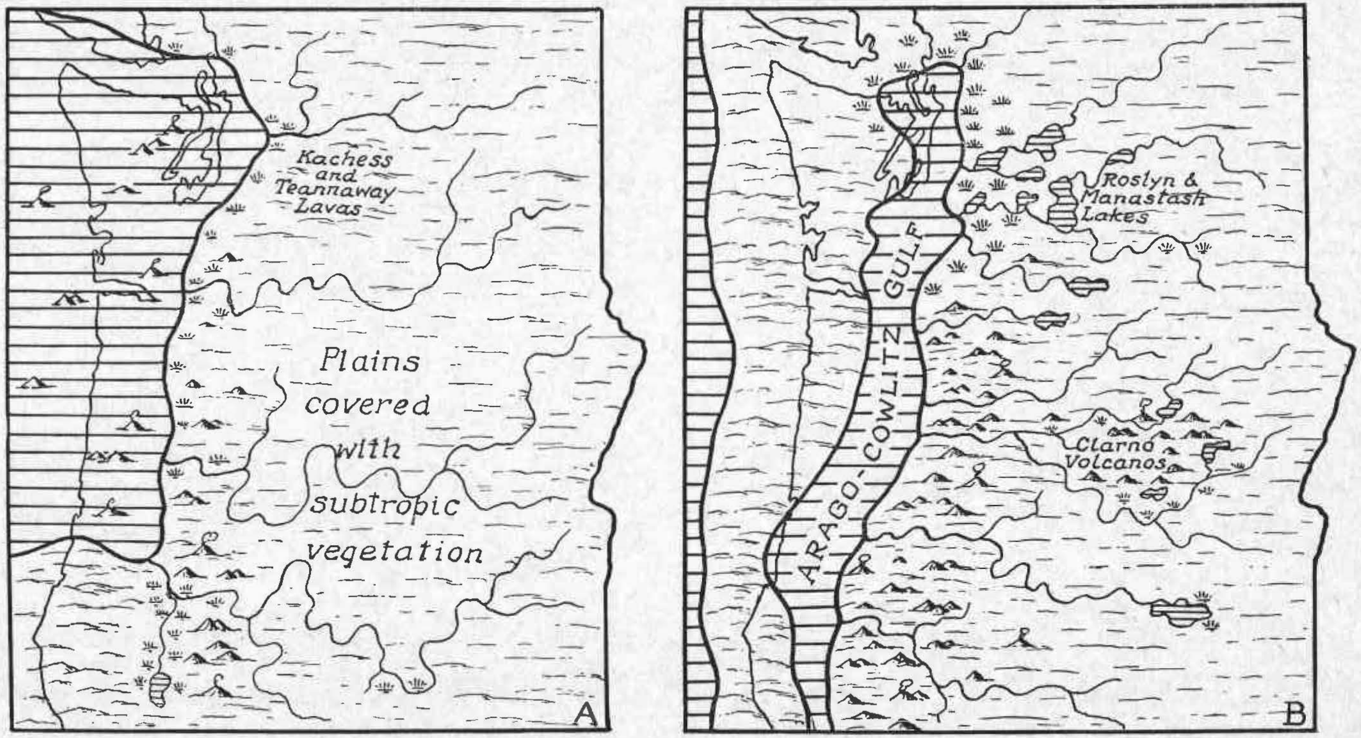


Fig. 2. A—Early and middle Eocene. Submarine basaltic eruptions, and beginnings of Cascade Range. Marshes along coast and in Ashland-Medford region, on flanks of Klamath Mts. B—Late Eocene. Time of the great inland gulf and the long peninsula to the west. Abundant lakes and marshes in eastern Washington; numerous volcanoes active in the ancestral Cascades and in the John Day country.

locally the rising solutions leached iron and manganese from the lavas to deposit them at the tops of the flows and among the overlying sediments.

By the close of middle Eocene time, no less than 50,000 cubic miles of basalt had been discharged onto the ocean floor! Today, these dark, much altered lavas (Metchosin, Tillamook, and Umpqua basalts) form the core of the coastal ranges of Oregon and Washington, and hardly a road that crosses the mountains fails to reveal them to the traveller.

As to what was happening on land while these submarine eruptions were going on there is little information. During the middle Eocene period, the Oregon coast ran along the present Cascade foothills, near Portland, Salem, and Eugene to Roseburg where it swung westward to the present shore. Farther south, in what is now the Ashland-Medford valley rivers were spreading sand and gravel over their flood-plains, and in large swamps fringed by subtropical forests peat was accumulating, later to be converted into coal. Somewhere near at hand, probably to the east, the earliest land volcanoes of Oregon were beginning to erupt showers of ash. Today, their products form layers of tuff interbedded with the river-deposits of the Umpqua formation near Medford. Over the rest of Oregon there are no signs to indicate what was taking place; presumably the area was a low-lying land thickly clothed with subtropical vegetation and traversed by broad, slow-moving streams draining westward to the sea.

Late Eocene Time
(50 to 40 million years ago)

Late Eocene time was marked by waning and extinction of the submarine volcanoes and by a great increase in the number and activity of land volcanoes. Now cones began to erupt on a grand scale, not only in the Cascades but also in the eastern part of Oregon.

Much careful study by Weaver and others has provided a reasonably clear picture of the coastline during this period. Warping of the earlier Eocene lavas had produced a long north-south peninsula, somewhat like the present peninsula of Lower California, extending from Vancouver Island through the present Olympic Mountains into northwest Oregon and thence west of today's coast to beyond Coos Bay. Between this long, low-lying peninsula and the mainland lay a shallow, warm-water gulf, locally more than 100 miles across (see Fig. 2 B). The floor of the gulf subsided intermittently and its shores moved in accordance with movements of the land. Around its head, in the Puget Sound area, sagging of the floor permitted deposition of a thick series of fresh and brackish-water sandstones, shales, and carbonaceous beds. Here and there, along the fluctuating borders of the gulf, were tropical swamps in which peat was laid down, to be changed subsequently to the coals of the Puget and Coaledo formations. From both sides, streams carried sediment into the sea. Along the shore of the mainland, sluggish rivers built enormous deltas. While vast quantities of sand, silt, and pebbles were dumped into the gulf (Arago and Cowlitz formations), showers of ash, blown from nearby cones, settled in the waters. Some flows of basaltic lava entered the gulf from adjacent cones and others were erupted from vents on its floor, but no longer in the copious amounts of earlier days. Gradually, the rate of deposition overtook the rate of subsidence, and save for a few shallow basins the inland gulf was almost filled. Just before it finally disappeared at the close of the Eocene period, slight downwarping of the land permitted the sea to readvance over northwest Oregon, so that pebbly, ashy sands and silts (lower and middle Keasey beds) were laid down upon the tilted sediments of Arago-Cowlitz age. About the same time, muds were being deposited in quiet waters near Coos Bay (lower Bassendorf shales).

Such, in brief, was how the Oregon coast appeared. What were the conditions on the mainland to the east? Already in middle Eocene (Umpqua) time, as has been noted, a few volcanoes had begun to develop in the Cascade belt. Now, their number was greatly increased. East of Ashland and Medford, the landscape was diversified by scores of cones. Predominant among the varied lavas they discharged were thin flows of andesite. Mild outbursts of fine ash alternated with violent blasts that blew out bombs and blocks in profusion. As the cones gained height, the invigorated streams on their flanks eroded ever more rapidly, carrying pebbles, cobbles, and boulders to the plains below. Sometimes the drainage was deranged by heavy falls of ash and lakes were formed in this way, and on the bottoms of some of them thin layers of white diatom-ooze and dark, peaty ash accumulated.

Not far to the north, around Evans Valley, the rise of andesitic cones was preceded by eruptions like those that took place in 1912 in the Valley of Ten Thousand Smokes, Alaska. Vast quantities of rhyolitic ash and pumice foamed to the surface through narrow, vertical fissures and spread for miles as glowing avalanches. In places the layer they left behind was no less than 300 feet in thickness.

Still farther north, in the country now crossed by the North

Umpqua River and Calapooya Creek, many imposing volcanoes rose among the subtropical forests bordering the inland gulf. These were steep-sided cones composed of andesitic lavas and coarse, fragmental debris. Much of the fine ash that they erupted was drifted westward by winds and fell into the sea. Much was wafted in the opposite direction and settled in showers over central and eastern Oregon. When heavy rains fell, the swollen rivers flooded the lowlands with bouldery detritus and carried sand and gravel far out into the neighboring gulf. Today, near Blackbutte and Elkhead, the feeding pipes of some of these ancient volcanoes stand revealed by erosion as more or less cylindrical plugs a mile or so across.

Near Eugene, on the coastal flats, rivers desposited loads of ashy mud, silt, and sand derived from volcanoes in the uplands to the east. Few lavas descended to the coast, but time and again the adjacent plains were blanketed by fall of ash. Fossil leaves and petrified wood entombed in these deposits (Comstock formation) provide information concerning the forests of those times. Subsequently, but before the close of the Eocene period, the region around Eugene was slightly warped by earth-movements. The growing volcanoes became more explosive, erupting coarse ejecta and fine ash in abundance, while the rivers, becoming more powerful as the uplands increased in elevation, deposited heavier loads of volcanic waste on the coastal plains (Fisher formation).

Still farther north, in the region now drained by the Willamette, Santiam, and Breitenbush rivers, volcanoes erupted flows of rhyolite and green, pumiceous ash, now to be seen on the canyon walls near Oakridge, Cascadia, and Detroit.

Such, briefly, were the beginnings of the Cascade Range. Many more millions of years were to elapse before a continuous and high volcanic chain was formed; by the end of the Eocene period, only a broad, north-south belt of scattered volcanoes existed here, and many streams, rising in eastern Oregon, followed easy passageways between them to empty into the gulf beyond.

East of the incipient Cascades in Washington were broad valleys and plains dotted with swamps and peat bogs and a few large lakes to which rivers carried mud, sand, and gravel (Roslyn and Manastash formations). Apparently there were few, if any, volcanoes in the vicinity. In central and eastern Oregon, on the contrary, volcanoes were plentiful. They grew from a low plain above which rose scattered hills and occasional ridges one or two thousand feet high at the most. Today, their products, the Clarno formation, are best displayed in the valley of the John Day River, although they spread westward to the foot of the Cascades and southward into Lake and Harney counties.

The materials discharged by the Clarno volcanoes were extremely diverse. At first most of the lavas were dark flows of andesite and basalt; subsequently, many flows of rhyolite were erupted. In the Horse Heaven area, the lower series is almost 6,000 feet thick; in the Mutton Mountains, the upper series exceeds 2,000 feet in thickness. Clearly, the volcanoes were closely spaced, and in general their activity was more explosive than effusive. Coarse breccias and bomb-rich agglomerates piled on the sides of the cones and on the neighboring flats, while fine ash was dispersed afar by winds. Much ash remained where it fell, but more was washed from the hills after every rain and carried into the valleys by the streams. In this way, depressions were filled to depths of several hundreds of feet with air- and water-borne ejecta. Subsequently, the materials were slowly and deeply decomposed, so that now they form gently molded, clayey hills tinted in pastel shades of green, maroon, yellow, cream, and purplish gray. Here and there among these varicolored beds are layers of papery, carbonaceous shale and lignitic coal, and bands of white diatomite rich in fossil leaves—ample proof that many swamps and lakes were scattered in the forested lowlands between the old volcanoes.

Close to the Deschutes River, 9 miles south of Maupin, eruptions took place within a lake of considerable depth. First, a steep cone of andesite was built; then explosions of rhyolite laid down glassy tuffs and breccias on the floor of the lake. Subsequently, the lake was filled with viscous flows of rhyolite that were drastically chilled by the water so as to form sheets of glassy perlite.

Life and Climate of Late Eocene Time

No region is better suited for preservation of fossil plants than one periodically covered by volcanic ash. Much vegetation is destroyed by the eruptions; wood and leaves are quickly buried and preserved from decay; and most ash is readily compacted and decomposed, so that percolating ground waters, enriched in silica, petrify the vegetation. No wonder many of the finest forests of the world and many of the richest collections of fossil leaves are found among deposits of volcanic ash and ashy sediment. It is enough to recall the "petrified forests" of Yellowstone and Arizona. Extensive fossil floras in the Comstock formation near Eugene and in the Clarno formation of the John Day country provide a clear picture of the climate and vegetation of Oregon during late Eocene time.

Essentially, the climate was uniform from the coast inland to Idaho, for the volcanoes of the Cascade belt were too low and far between to check moisture-bearing ocean winds from carrying rains far into the interior. Mild and humid, semitropical conditions prevailed over the entire state. Avocados, cinnamons, figs, and persimmons flourished in the lowlands. On the higher hills and cones more temperate forests grew. They were rich in redwood, alder, tan oak, and elm. In general, as Chaney has shown, the vegetation resembled that now growing on the lower slopes of the Andes in Venezuela, on the savannahs of Panama and in the mountains of Costa Rica and Guatemala. It must not be thought that these lush forests were ever laid waste completely by the volcanic activity, for the intervals between eruptions were long and most of the volcanoes were far apart, so that only small areas were devastated at a time, and even these were quickly reforested. Indeed, where ash fell thinly, to a depth of a foot or less, the vegetation was not only unimpaired but much invigorated, for the light, loose mantle served as a mulch to hold moisture in the ground. And where forests were killed, new ones sprang up after a few decades or a few centuries at most. Some 25 square miles of vegetation were demolished by the outbursts of Jorullo Volcano in Mexico in 1759-60, yet the lost ground was practically reclaimed a century later. Not a living thing survived the cataclysmic eruptions on the East Indian islands of Krakatoa in 1883, yet within 50 years, the islands were thickly clothed in a jungle of ferns, shrubs and trees.

Strangely enough, no fossil bones other than the tooth of a rhinoceros have been found among the Eocene volcanic rocks of Oregon. Doubtless many animals, alarmed by the falling ash and by the earthquakes that preceded and accompanied every eruption, fled at the first onset of volcanic activity, just as many animals fled when Paricutin broke out in Mexico. Nevertheless, after especially violent explosions, the toll of life from famine and disease must have been high. Damage to pastures during the outbursts of Laki Volcano in Iceland in 1783 destroyed most of the herds of sheep, cattle, and horses. Ponds and streams were polluted and the vegetation was coated with dust, sulphur, and corrosive acids. Close to the centers of eruption, animals died of suffocation. Beasts killed in the same way by the Eocene eruptions of Oregon were either devoured by scavengers or rotted on the ground before they were entombed. But the survivors probably returned after each eruption. Only a few years after the great eruption of Katmai

Volcano in Alaska in 1912, many animals returned; approximately 60 years have passed since the explosions of Krakatoa wiped out the island-population, yet today it is almost wholly restored.

Because of the lack of abundant fossil bones from the Eocene rocks of Oregon, knowledge of the fauna must be based on finds elsewhere. These inform us that the country was inhabited by 3- and 4-toed horses no larger than foxes and by rhinoceroses, some swift-running and others stump-legged, aquatic types. Slender camels, hardly bigger than rabbits, squirrel-like rodents, and carnivorous creodonts roamed through the forests and glades. Insect-eaters and opposum-like marsupials were common, and the streams abounded with alligators. To a modern observer, nothing would have been more striking than the small size of most of these animals in comparison with their living relations.

To summarize: most of Oregon in late Eocene time was a low, undulating land across which broad rivers ran westward to a great inland gulf. Above the plains and rolling hills rose a belt of scattered volcanic cones in the vicinity of the present Cascades while other volcanoes diversified the landscape to the east. In the lowlands, between lakes and glades, were dense subtropical forests that merged into redwood forests on the higher slopes. Throughout this varied land lived diminutive beasts, ancestors of the larger, familiar forms of today.

Early and Middle Oligocene Time
(40 to 30 million years ago)

The long peninsula west of the inland gulf began to break down during early Oligocene time into a chain of islands. Subsequently, these were submerged and the open sea again swept over western Oregon. It was a warm, shallow sea bordered by shifting deltas, brackish water bays, and peaty swamps. The coastline, although changing position as the adjacent land was warped, ran close to the present foothills of the Cascade Range, near Eugene, Salem, and Portland. Sediments deposited in the sea came mainly from rivers draining the volcanic country to the east. Far from land and where feeble streams entered the sea, muds and sands were laid down; closer to shore and at the mouths of powerful rivers, sand, gravel, and boulders accumulated. Much ash was washed from the neighboring lands, and during violent eruptions much fell directly into the sea from the air. As time passed, volcanism became more intense, and heavier showers of ejecta formed layers of white tuff on the sea-floor. Close to shore, massive beds of water-borne ash and conglomerates rich in volcanic pebbles were laid down (Illahe formation). To the north, in Washington, the amount of volcanic debris contributed to the sea was considerably less.

On land, the ancestral Cascade volcanoes continued to erupt with increasing vigor. Indeed, by middle Oligocene time, their products had piled up locally to a thickness of almost 10,000 feet. Had the land not subsided almost as rapidly as the lavas and ashes accumulated, an imposing mountain range would have been produced. True, some of the highest volcanoes did tower several thousands of feet above sea-level, but most of the Cascade belt was probably no more than a few hundreds of feet above the sea.

Volcanoes of great variety were now scattered throughout the coastal land. Near Eugene, they erupted lavas and fragmental ejecta ranging in composition from basalt to rhyolite (Fisher formation); near Mill City and Stayton, white and greenish ash, rich in petrified wood, accumulated between lavas and beds of coarse breccia (Mehama formation), while to the east, near Detroit, thick sheets of wind-blown and water-borne ash were laid down with coarser volcanic debris and occasional tongues of lava (Lower Breitenbush formation). In the southern part of the ancestral Cascades, the volcanic products were no less varied.

Many lakes and stagnant ponds lay between the volcanic cones, and vigorous streams flowing from the uplands deposited sand and gravel on broad floodplains below. Erosion was unusually rapid. After each violent eruption, the country was mantled by loose ash, and with every rain the debris was swept into the streams, converting them into torrents of mud and boulders that scored the valley sides.

East of the growing Cascades the volcanoes of Clarno time had become extinct during the dawn of the Oligocene. Subsequently, the region was differentially warped, and locally mountains were elevated. The remainder of early and middle Oligocene time in this region was one of relative quiet. Slowly erosion wore down the mountains until the country was once again reduced to rolling hills and plains, relieved by sporadic peaks between 2,000 and 3,000 feet in height.

Late Oligocene and Early Miocene Time
(30 to 20 million years ago)

By the close of the middle Oligocene epoch, gentle uplifts coupled with the growth of deltas had forced the coastline far to the west. But in late Oligocene time, subsidence again took place, permitting the sea to spread over the land through shallow bays. It flooded most of what is now the Upper Nehalem River Valley and much of the coastal strip of Washington. Vast quantities of sediment were washed into these new embayments along with volcanic detritus, and periodically showers of ash from the Cascade cones settled into them (Blakeley, Nye, and Scappoose formations). Finally, during early Miocene time, the whole of western Oregon, including the Cascade belt, was upheaved and the seas once more retreated westward beyond the present shores.

Throughout this long interval, the Cascade volcanoes grew larger and more numerous. Among them were some of enormous size, like that near Bonneville. The relics of this volcano form a thick pile of ashes, agglomerates, and basaltic and andesitic lavas known as the Eagle Creek formation. Voluminous eruptions of andesitic lava and fragmental material also took place in the Washington Cascades (Keechelus formation).

In central Oregon many streams were checked in their course to the sea by the rising Cascade barrier; some were impounded to form large lakes, while others were so reduced in gradient that they were forced to deposit most of their sediment on broad alluvial plains. It

Fig. 3. Early Miocene (late John Day). Volcanoes active throughout the length of the ancestral Cascades and in the John Day region.

was under these conditions that the most colorful of all the volcanic rocks of central Oregon were laid down—the John Day beds, famous the world over for their wealth of fossil bones. All who travel to see the Picture Gorge marvel at the "painted hills" and castellated crags carved in this remarkable formation.

At first, most of the ash and pumice that fell in this region was carried there by winds from distant volcanoes in the Cascades, but soon heavy showers of ejecta were discharged by local volcanoes. Some ash and pumice fell into peat bogs and quiet bodies of water, entombing fish and aquatic insects and leaves drifted in by winds and streams; some dropped on hillsides and was washed into the valleys along with sediment derived by erosion of older volcanic rocks. Accumulating slowly in a warm, humid climate, the deposits were thoroughly decomposed to clays and rusty iron oxides. Hence the prevailing colors of the lower John Day beds are reddish, brown, and yellow.

Subsequently, explosive eruptions became more violent and the number of local volcanoes greatly increased. Devastating showers of ash began to fall more frequently. The valleys became choked with debris, the overloaded streams built ever wider flood plains and the hills were rapidly lowered by erosion. Now the water-table was so close to the surface and the layers of ash piled on each other so quickly that oxidation and decomposition were checked. The prevailing colors of the middle John Day beds are therefore pale green, cream, and white.

During early Miocene time when the topmost John Day beds were laid down, most of central Oregon was an extensive plain relieved only by a few hills and ridges. Some volcanoes poured out short flows of andesite and rhyolite, but explosive eruptions were far more common than quiet effusions. Time and again the country was deluged by white ash that gave the landscape an odd wintry aspect as if the forests had been covered by powdery snow.

Life and Climate of Late Oligocene and Early Miocene Time

The ancestral Cascades were still too low to act as a climatic barrier. Over the whole of Oregon the climate was mild and humid, marked by an annual rainfall of approximately 40 inches. From the coastal flats inland to the confines of Idaho, there was little variation in the vegetation except for that dictated by topography. The redwood was still dominant in most of the forests, thriving side by side with alder, hazel, dogwood, pepperwood, and tan oak. Bordering the redwoods, just as they are today in California, were ash, cherry, hackberry, live oak, madrone, pine, plane tree, rose, and willow. On some of the coastal hills, overlooking sheltered bays, the upper slopes were thick with redwoods while below grew warm-temperate and even subtropical forms like avocado, lancewood, and palmetto, an association that today is without a counterpart anywhere.

Toward the close of early Miocene time, when erosion of the hills and filling of the valleys with ash had made most of central Oregon an undulating plain, the forests became less dense and more parklike. Open glades were numerous, and in places the forests gave way to wide, grass-covered savannahs.

Fossil bones in the upper John Day beds clearly indicate this kind of landscape. Killed by disease and famine, poisoned by acid waters and ash-coated vegetation, drowned by floods when streams were blocked by ash, and trapped by torrents of mud, mammals typical of the forests and plains were entombed together. It was a varied fauna, and to a modern observer it would have seemed strange indeed. Giant pigs and primitive peccaries rooted under the trees for nuts. Long-tailed oreodonts, three-toed browsing horses six hands high at the withers, camels the size of sheep, squirrels, and weasels were plentiful. Wolves, bear-dogs, saber-toothed cats, and flesh-eating creodonts roamed in herds, searching for prey. Large, horned beasts resembling rhinoceroses lived on the banks of rivers while beavers and turtles swam in the waters.

Middle Miocene Time
(20 to 15 million years ago)

During most, if not all of early Miocene time, the Pacific shore lay west of its present position. When the coastal belt once more subsided, the sea flooded much of western Washington and northwest Oregon (see figure 4). The deposits washed by streams into this middle Miocene sea consisted in the main of sandstones, shales, and conglomerates (Astoria formation). Traced from Washington into Oregon, and from west to east, they become richer in volcanic materials, especially in their upper part. The implication is that eruptions became more common and stronger as time passed. Ultimately, many flows of basaltic lava poured into the Astoria sea from the adjacent land. Today, they may be seen between layers of sandstone in the country bordering the Columbia River below Portland. Other basaltic lavas rose through fissures on the floor of the Astoria sea; still others were discharged

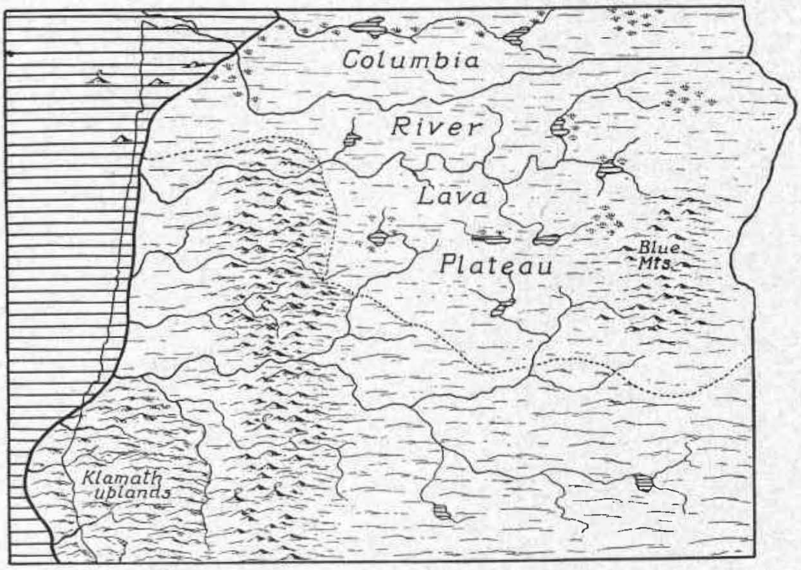


Fig. 4. Middle Miocene. Submarine volcanoes in the Astoria Sea. Vigorous volcanism in the ancestral Cascades, and in the Blue Mts. Much of Oregon and Washington converted into a vast lava plateau by floods of Columbia River basalt. Lakes, marshes, and meandering rivers on the plateau.

along with much fragmental material from submarine cones. The products of these underwater eruptions are now clearly revealed at many points along the Oregon coast including Yachats, Yaquina Bay, and Otter Rock.

On land, middle Miocene time was one unequalled in the magnitude of volcanic activity. All over the Pacific Northwest and much of California, volcanism was intense. In the Cascades of Oregon, lavas of many kinds were erupted on a grand scale, chiefly from fissures rather than from volcanic cones. For instance, no less than 6,000 feet of lavas accumulated in the region between Stayton and Detroit. Andesitic flows predominate, but rhyolites and basalts are also present (Sardine series). Equally varied lavas (Stayton series) inundated the region around Salem, and elsewhere in the Cascades the range grew higher as flows and heterogeneous fragmental ejecta piled on each other. Streams and mudflows sweeping down the western slopes deposited sandy and bouldery fans at the foot of the rising mountains.

The conical forms and the craters of these ancient Cascade volcanoes have long since vanished, and it is now a matter of no small difficulty to tell where the original vents were located. The approximate position of some is indicated by the distribution of coarse fragmental ejecta that cannot have been blown far from their sources; the position of a few is marked by cylindrical plugs of lava and by bodies of coarsely crystalline plutonic rock that represent the consolidated fillings of volcanic pipes and feeding reservoirs. Among such plugs and plutonic bodies are those in the Bohemia, North Santiam, Quartzville, and Blue River mining districts; those near Blackbutte, Elkhead and the Rogue-Elk junction, and the cluster of porphyry hills in Shasta Valley. Many more await discovery, and doubtless many are buried beneath the products of later volcanoes in the higher part of the Cascade Range. All that can be said with certainty is that the ancestral Cascade cones were concentrated in a broad, north-south belt roughly coincident with the present mountains.

Meanwhile, in the country to the east of the Cascades, eruptions were taking place on an even vaster scale. Indeed, the whole of north-central Oregon, most of eastern Washington, and part of Idaho were being overwhelmed by floods of basaltic lava. These are the dark flows, spoken of as the Columbia River or Yakima basalts, that now form the wide plateau bordering the Columbia and Snake rivers.

By conservative estimate, these lavas cover 250,000 square miles. Being discharged on to an uneven surface, their thickness is variable. In the canyon of the Snake River above Lewiston, they are exposed to a depth of more than a mile; along the walls of the Columbia gorge they reach a maximum thickness of 4,000 feet; southward, they become thinner, attaining a maximum of about 2,500 feet in the John Day Valley. How far they extended beyond the John Day country, is uncertain. Their total volume cannot be less than 100,000 cubic miles!

Needless to say, discharge of this colossal amount of lava involved a span of time measurable in millions of years, and, no doubt, eruptions continued longer in some regions than in others. In the John Day Valley the eruptions were restricted to middle Miocene time; however, the upper flows along the Columbia gorge and in Washington may not have been extruded until early Pliocene time.

No strong earth-movements heralded these gigantic outpourings of lava. On the contrary, they were preceded by a long interval of relative quiet during which the John Day and older formations were eroded to a hilly and mountainous terrane. As flow succeeded flow, the depressions on this surface were gradually filled; then the hills were submerged, and finally even the mountains, including most of the peaks of the Blue and Wallowa mountains, were buried. By the close of activity, most of Oregon and Washington had been changed to a vast and almost level plateau.

How were the lavas erupted? Certainly not from high volcanic cones; instead they rose to the surface through swarms of vertical fissures, usually only a few feet or at the most a few tens of feet wide. Hundreds of lava-filled fissures (dikes) have been observed, and some merge upward into horizontal sheets of lava. These mark the feeding channels of the surface flows. Some fissures were sealed after discharging a single flow; others were reopened to erupt a succession of flows. Where the fissures were closely spaced and the discharge was especially copious, broad, low mounds of lava were built, simulating in miniature the shield volcanoes of Hawaii save for the absence of summit sinks. Where the fissures were more widely spaced, the lava floods spread as almost horizontal sheets of great extent. Eruptions on this scale have never been witnessed during historic times, although there have been many fissure-flows of basalt in Iceland of somewhat similar type (see Plate IV).

With rare exceptions, the eruptions were of the quiet, effusive kind. The lavas were so hot and fluid that many spread 10 miles or more even over the gentlest gradients. They ranged in thickness from 20 to 100 feet. A few exceeded 200 feet. Their tops were usually red and clinkery, and most flows developed a columnar structure as they solidified. They varied little in composition and were mostly dark and somewhat glassy basalts with little or no olivine.

Where flows poured into lakes and ponds or emptied into the ocean, their fronts were sometimes shattered and granulated into fine glassy fragments that tumbled into the water, building deltas across the tops of which the main parts of the flows advanced as if on dry land. More viscous lavas, reaching the water's edge, broke into pillow-like masses that plunged ahead and accumulated to the depth of the water, after which the pillows were covered by the principal portions of the flows.

There were times when eruptions followed each other in such quick succession that before one flow was completely cool it was buried by a second or even a third flow. Usually, however, long intervals elapsed between successive eruptions. Indeed, the periods of repose often lasted for decades or centuries during which the lavas were decomposed to fertile soils and mantled with forests before being overwhelmed by new sheets of basalt. In the Oneonta gorge, closely spaced trees up to a yard in diameter were buried in this way. Elsewhere, layers of sand and gravel were laid down between successive flows, for as the lavas filled the main depressions, the tributary streams were much reduced in gradient and were forced to dump their loads of sediment.

Periodically, the quiet outflows of lava were interrupted by explosions of basaltic ash and scoria. Near Owyhee Dam and in the Picture

Gorge, for example, many layers of fragmental ejecta were deposited between the lava flows. Where the eruptive fissures cut across water-soaked ground, the explosions were particularly strong. For instance, close to the Snake River, south of Lewiston, a chain of deep, elongate craters was produced by steam blasts when lava rising through a vertical fissure encountered water-bearing gravels near the surface.

While central and northern Oregon were being flooded by the Columbia River basalts, more varied eruptions were taking place in the eastern part of the state, on the flanks of the Blue Mountains near Sumpter and Baker. Even while flows of Columbia River lava were spreading into this region, local volcanoes were discharging andesites and rhyolitic obsidians and periodically drenching the countryside with showers of rhyolitic ash.

By the close of middle Miocene time, most of Oregon was a dreary plateau of dark basalt. It was not far above sea-level for the land had sagged repeatedly under the heavy load of lava. It was by no means a barren waste, for in the mild and humid climate that then prevailed, trees and grasses soon spread over the lands devastated by eruptions. Slow-moving streams meandered over the plateau in wide, sandy beds quite unlike the formidable gorges through which the present rivers flow. Shallow lakes and ponds were plentiful. Around the mouth of the Columbia River, the plateau sloped uninterruptedly to the sea; to the south, it ended against the ancestral Cascades, which by this time had become a broad belt of coalescing cones with an average elevation of perhaps 3,000 to 5,000 feet above the sea. In eastern Oregon, there were no Blue and Wallowa mountains as they are today, only clusters of volcanic cones rising above the basaltic flats.

Late Miocene Time
(15 to 10 million years ago)

Earth-movements affected the whole of Oregon at the end of middle Miocene time, and the ocean was once more driven westward beyond the present coast. A long period of erosion followed. Late in the Miocene and early in the succeeding Pliocene period downsinking of the coastal belt allowed the sea to encroach on the land, but, compared with previous inundations, this one was slight.

In the Cascades, there was no break in the volcanic activity. Just as in middle Miocene time, heterogeneous lavas and fragmental materials continued to accumulate. Fossil leaves found in beds of tuff near Ashland show that a temperate upland flora flourished on the flanks of the Cascade cones.

One important effect of the growth of the Cascades was to prevent many of the streams of central Oregon from making their way to the sea. Thus impeded, they emptied into large lakes. Other streams began to meander sluggishly over wide alluvial flats. The drainage was further deranged by gentle warping of the Columbia River lava-plateau and by falls of ash from new volcanoes in the interior region. In brief, the country east of the Cascades was marked in late Miocene time by lakes, swamps, and flood plains. Above the gently undulating surface rose occasional ridges of "bedrock" and scores of volcanic cones.

This was the environment in which the Mascall formation was laid down in the John Day basin. Typically, it consists of andesitic and rhyolitic ash and ashy sediment, delicately tinted in yellows, reds, browns, and greens, with partings of fine, white pumice. In part, these ejecta were carried into the region by winds from the ancestral Cascades, but most of them were erupted by local volcanoes. While some of these Mascall cones, especially in the upper reaches of the John Day Valley, discharged flows of andesite and basalt, the activity of most was strongly explosive rather than effusive. Interbedded with their products are lenses of sandstone and conglomerate formed by rivers winding over broad flood plains. Beds of papery, white, diatomaceous shales, some of them rich in fossil leaves, show that there were tree-fringed

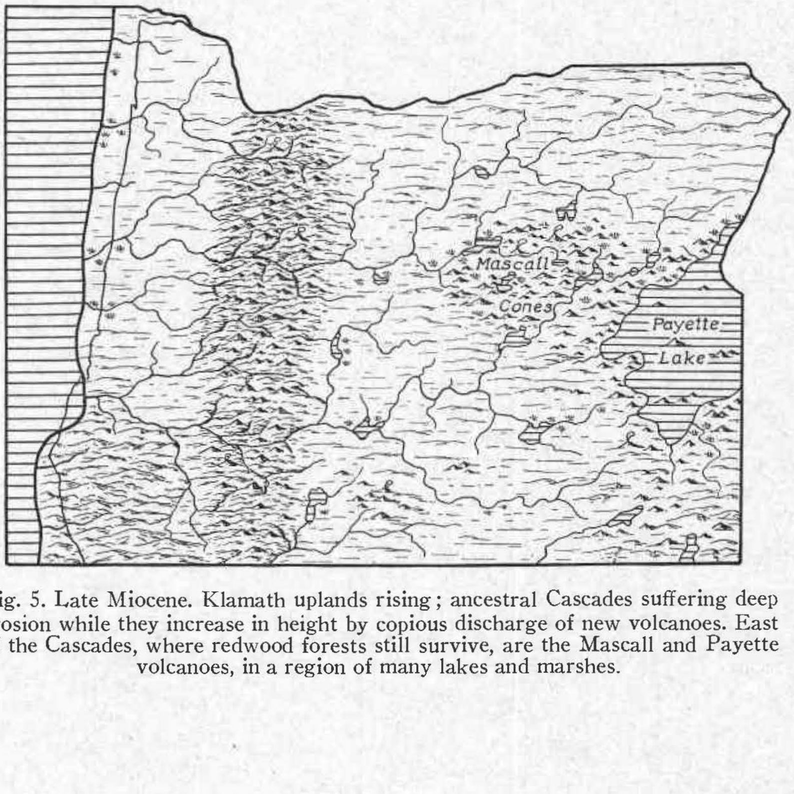


Fig. 5. Late Miocene. Klamath uplands rising; ancestral Cascades suffering deep erosion while they increase in height by copious discharge of new volcanoes. East of the Cascades, where redwood forests still survive, are the Mascall and Payette volcanoes, in a region of many lakes and marshes.

ponds and lakes in the lowlands, and seams of lignitic coal denote the existence of peaty swamps.

Large as many of them were, the Mascall lakes were dwarfed by comparison with the shallow lake that covered much of eastern Oregon and the adjacent parts of Idaho. The center of this lake was near Payette; the shores spread west as far as Drewsey in northeast Harney County and south as far as Rome in central Malheur County. Within this Payette Lake and around its banks were many imposing volcanic cones of rhyolite and dacite. Occasionally they erupted thick, stumpy flows of obsidian; more often they were violently explosive. Time and again they belched ash and pumice in staggering amounts. Indeed, some of the outbursts were truly catastrophic, for among the ejecta laid down on the floor of the Payette Lake are beds of pure, white ash no less than 40 feet in thickness.

The Payette Lake lasted a long time, although it dwindled and expanded as uplift and subsidence of the land caused the shores to migrate to and fro. Near the middle of the lake, deposition of sediment and volcanic ejecta was continuous, but close to the edges it was interrupted repeatedly by periods of erosion. It must suffice to refer to evidence in the Harper district. Hereabouts, the first ashes and agglomerates to accumulate on the floor of the lake were soon upheaved above water, then considerably eroded and resubmerged. During the ensuing interval of quiet, they were covered by thick layers of diatom-ooze. Subsequently, showers of white ash fell into the lake and a second uplift took place, exposing the deposits to erosion once more. They were then covered by new layers of ash and by the debris of volcanic mudflows. Erosion of these had already begun when sinking of the land caused the lake to expand; again the beds were submerged and slowly more diatom-ooze accumulated on top of them. Once more the lake-floor rose, baring the deposits to erosion. Then they were covered by a flow of rhyolitic lava. Finally, the land sank again, and the whole series of beds was drowned and then buried by a culminating shower of yellow ash.

Elsewhere along the borders of the Payette Lake the sequence of events was equally varied. There were times when the lake divided into many separate bodies of water with peaty marshes along the banks; and other times, after uplifts of the land, when rejuvenated streams almost filled the lake with sheets of sand and gravel.

Volcanic regions are notably unstable, but late Miocene time in Oregon was one of particular unrest. Even as the Mascall and Payette lakes were being disturbed by crustal movements, the Ochoco Mountains were beginning to rise toward their present height, and in the ancestral Cascades, as we shall see, these movements were to come to a climax at the close of the Miocene in a general uplift of first-class magnitude.

Little is known of what was happening in south and southeast Oregon during the life of the Mascall and Payette lakes, for rocks of this age are only sparingly revealed there. Bordering the Sprague River, about 40 miles northeast of Klamath Falls, plugs of andesitic lava associated with agglomerates denote the existence of coeval volcanoes. And along Trout Creek, east of Alvord Valley, layers of diatomite accompanying flows of basalt and beds of coarse ejecta indicate the presence of volcanoes along the borders of a lake. Fossil leaves found in the diatomite suggest a highland habitat of varied but not strong relief, probably like that of the country around the Klamath lakes today.

Life and Climate of Late Miocene Time

The forests of the Miocene, writes Chaney, were "like those of today in the valleys of Michigan and Ohio, and in the Redwood Belt of California; they were essentially like those which had lived in the uplands during the Eocene." Over most of the state the climate was warm and humid. The Cascade Range, although exerting a greater influence than before, was still not a sufficient barrier to reduce the annual rainfall over central and eastern Oregon by more than a few inches. Redwoods still grew in the John Day country, mingling with warm-temperate trees such as bald cypress, mahogany, persimmon, and sweet gum. Madrones and oaks occupied the drier slopes, while willows and maples fringed the lakes and streams. Interspersed with the forests were wide grasslands. In the higher parts of southeast Oregon, where the annual rainfall approximated 40 inches, a cool-temperate flora prevailed, somewhat like the tan oak, madrone, Douglas fir, and Port Orford cedar association that now occupies the Klamath Mountains.

The fauna more nearly resembled that of today than it had during the preceding epochs, and most of the animals were larger than their predecessors. There were long-necked giraffe-camels, three-toed browsing and grazing horses, horned and hornless rhinoceroses, giant pigs and peccaries, deerlike antelopes, tapirs and oreodons. Huge, bearlike dogs, wolves, foxes, and cats were numerous, and with them were weasels and the first raccoons, tree- and ground-squirrels, and a genus related to the mountain beaver. True bears had still to make their appearance.

Earth Movements at the Close of the Miocene

At intervals throughout Eocene, Oligocene, and Miocene time, as we have seen, the surface of Oregon was differentially raised and lowered. We have noted how the coast advanced and retreated in response to these disturbances, how the size and depth of the Payette and Mascall lakes varied with oscillations of the land, how hills and mountains were formed by bending and tilting of the rocks, only to be wiped out by erosion, and how, periodically, parts of Oregon sagged as heavy loads of lava were piled on the surface. Certain it is that if there had not been repeated sinking as the volcanic materials accumulated, the Cascades would have become a towering mass of mountains before the close of the Miocene period, and the country to the east would have stood far higher than it does today. But in late Miocene time, the Cascades were still not high enough to check ocean winds from providing ample rains to the redwood forests of eastern Oregon.

It was at the end of the Miocene that the entire Cascade belt was greatly upheaved by folding and tilting; it was then for the first time that eastern Oregon was cut-off from moisture-laden winds. Redwoods continued to grow on the wet western slopes, but to the east of the range they disappeared. There was also a major uplift of the Klamath Mountain region, and the coastal belt to the north was elevated to a less extent. However, many more millions of years were to pass before the uplifts that were responsible for the present Coast Ranges of Oregon.

Elevation of the Cascades was not a sudden movement. As the mountains rose, the rivers gained power to erode them, so that the range was already deeply dissected by canyons before the Pliocene period was well advanced. In part, the uplift was caused by folding and arching of the rocks; in part, by the mountains' rising as a tilted block. Near Mount Jefferson, uplift formed an east-facing scarp some 2,000 feet in height. In the Crater Lake region also the range was hoisted *en masse* along steeply inclined planes of fracture. Particularly important in its effect on later volcanic activity was the fact that uplift was accompanied by opening of many north-south fissures along the crest of the rising range, for it was through these fissures that the Pliocene lavas were extruded to build the crowning volcanic peaks of Oregon, the snow- and ice-capped cones strung like gems on the green belt of the Cascade forests.

Pliocene Time

(10 to 1 million years ago)

The principal events of the Pliocene volcanic history were the growth of a chain of large shield volcanoes along the crest of the

Cascades, and the voluminous outflow of fluid lavas from fissures in south-central and southeast Oregon.

The coastal plain developed by erosion after the uplifts of late Miocene time was locally downwarped and flooded by shallow seas so that the shore was indented by several bays. In one of these, near the present Coos Bay, the sandstones and conglomerates of the Empire formation were laid down; in another, on the Washington coast, the sediments of the Montesano formation were deposited. But these marine invasions were small compared with previous ones, and before the end of Pliocene time the bays had disappeared.

The Cascade Range is divisible lengthwise into two belts, the Western and the High Cascades. The former consists of the tremendous volcanic accumulations of Eocene, Oligocene, and Miocene times. In this belt profound canyons are separated by narrow ridges, and no trace remains of the original volcanic landscapes. The land-forms here are entirely a result of erosion. The High Cascades, on the other hand, are made up of Pliocene and younger volcanic cones whose original forms, even though modified by erosion, are easy to recognize.

Great diversity of behavior and products had characterized the earlier Cascade volcanoes. They had erupted lavas as different as rhyolite and basalt, and their activity had varied from quiet outpouring

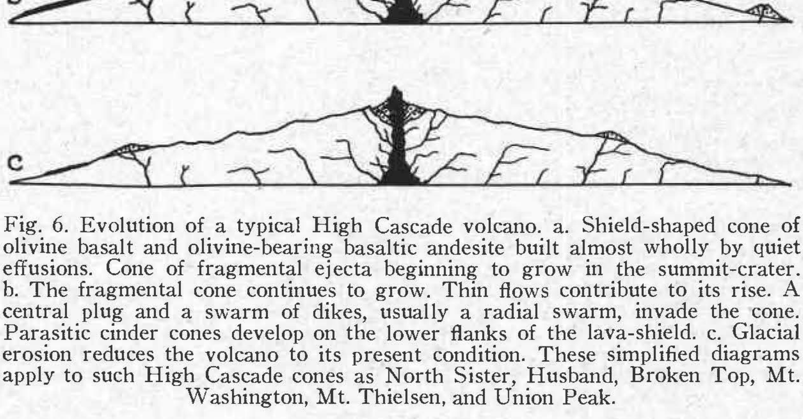


Fig. 6. Evolution of a typical High Cascade volcano. a. Shield-shaped cone of olivine basalt and olivine-bearing basaltic andesite built almost wholly by quiet effusions. Cone of fragmental ejecta beginning to grow in the summit-crater. b. The fragmental cone continues to grow. Thin flows contribute to its rise. A central plug and a swarm of dikes, usually a radial swarm, invade the cone. Parasitic cinder cones develop on the lower flanks of the lava-shield. c. Glacial erosion reduces the volcano to its present condition. These simplified diagrams apply to such High Cascade cones as North Sister, Husband, Broken Top, Mt. Washington, Mt. Thielsen, and Union Peak.

of flows to vigorous explosions of fragmental debris. On the contrary, nothing was more typical of the Pliocene volcanoes than the sameness of their modes of growth and the singular resemblance of almost all their products. Except for a few composite, steep-sided cones of andesite, such as the Battle Ax Mountain volcano, near Detroit, they were low and broad shield volcanoes built almost wholly by quiet effusion of flows of olivine basalt and olivine-bearing basaltic andesite. In their final stages of growth, they became explosive; parasitic cinder cones developed on their flanks and the summits of the shields were buried by cones of fragmental ejecta, as illustrated in Figure 6.

Each of these Pliocene shield volcanoes has been reduced by erosion to a series of radiating ridges separated by amphitheater-headed valleys; the parasitic cinder cones have all but vanished, and the summit-cones have been so far denuded that the more resistant lava-fillings of the central pipes stand out as monoliths, like miniature Matterhorns, forming the topmost pinnacles. Vivid examples of these dissected volcanoes are Three Fingered Jack, Mounts Washington and Thielsen, the North Sister, and Union Peak. Less conspicuous are Minto Mountain; the Husband, Wife, and Broken Top; Howlock Mountain; Devil's Peak, and scores of others.

While these shield volcanoes were active on the Cascade crest, flows of fluid basalt issued from fissures at their feet and poured long distances down canyons on both sides of the range. These were the first of the so-called "Intracanyon flows" that were to become increasingly numerous during and after the Ice Age.

Uplifts had already increased the height of the Cascade Range; now the growth of shield volcanoes made the range still higher. As a consequence, erosion was much accelerated. Powerful rivers swept sand, gravel, and boulders onto the plains below, and from time to time hot mudflows, charged with coarse volcanic debris, rushed down from the summit-region. Occasionally, tongues of basaltic lava debouched from the canyons, and showers of ash fell on the piedmont belts. In brief, heterogeneous deposits, some wind-borne and some water-borne, began to pile along the margins of the range.

Much difficulty has been experienced in dating and correlating these piedmont deposits owing to their varied character and the fact that they accumulated in local basins. On the east flank of the range, they have been called the Madras, Deschutes, and Dalles formations; on the opposite side, they have been referred to as the Troutdale and Rhododendron beds.

During early Pliocene time, streams pouring down the steep, upper slopes of the Cascade Range emptied from narrow gorges on to broad flood-plains that stretched uninterruptedly from the area east of Portland to the sea, for there were then no Coast Ranges as today. Great quantities of volcanic sand and gravel were deposited by the streams along their lower courses, and occasionally bouldery mudflows sweeping down from the Cascade peaks inundated the plains with debris. Some ash also fell on the lowlands, but not much because the prevailing winds were from the west. Together, these deposits comprise the Troutdale formation. Similar beds of approximately the same age accumulated in the valleys of the McKenzie, Calapooya, Santiam, and Clackamas rivers, where they are known as the Rhododendron formation.

On the opposite flank of the Cascades, the foothills and adjacent depressions were likewise covered by the deposits of streams and mudflows, by showers of pumice and ash, and by occasional flows of basaltic lava. The occurrence of layers of white diatomite among these volcanic materials shows that many temporary lakes and ponds were scattered over this piedmont country.

Little is known concerning the history of south-central and southeast Oregon prior to the Pliocene period. If volcanoes were active there while the Clarno, John Day, and Mascall ones were erupting to the

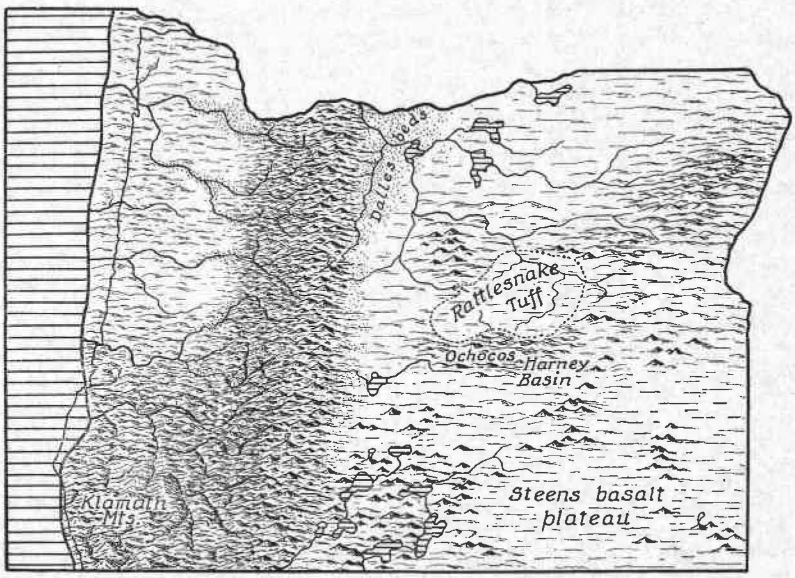


Fig. 7. Pliocene. Klamath Mts. stand high, but Coast Ranges still only low hills. Western Cascades deeply eroded; shield volcanoes active in High Cascades. Piedmont alluvial fans (dotted areas) on both sides of the range. Blue, Wallowa, and Ochoco Mts. rising. Great basaltic eruptions in south-central and southeast Oregon, and of rhyolite tuff in the John Day Valley.

north, their products are almost completely buried by the colossal outpourings of Pliocene time. Virtually the entire "lake province" of southern Oregon was inundated by sheets of fluid lava during the Pliocene period so that it became a vast, hummocky plateau. It was at the close of the Pliocene and later that this plateau was buckled by earth-movements and broken into the mosaic of fault-block mountains and valleys characteristic of the present scenery.

Among the first of the Pliocene volcanoes in this part of Oregon were those whose products are now revealed along the foot of the great scarp of Steens Mountain. These were rhyolitic and andesitic volcanoes, and their activity was more often explosive than effusive. They erupted abundant ash and pumice, some of which fell into adjacent lakes, forming beds of tuff between thin flows of lava and layers of white diatomite.

Shortly after these cones became extinct, a line of rhyolitic and dacitic volcanoes broke into eruption in the same region and along the southern edge of the Harney Basin, discharging much white ash and many thick, bulbous masses and stumpy flows of glassy lava. A little later, copious flows of andesite issued from vents along the front of Steens Mountain, including one no less than 900 feet in thickness. Probably other volcanoes were active elsewhere in southern Oregon at this time, but the evidence is not quite conclusive.

It was during middle Pliocene time that the most voluminous eruptions took place. These were fissure-eruptions like those that had produced the Columbia River lavas during Miocene time, and they were on a scale almost equally grand. Floods of exceptionally fluid and gas-rich olivine basalt poured from swarms of narrow, vertical cracks. Because they are now revealed in spectacular display to a thickness of 3,000 feet along the upper part of the Steens Mountain scarp, they are referred to as the Steens basalts. Some idea of their extreme fluidity may be gained from observing that flows only a foot or two thick are traceable for long distances. Indeed the average flow is not more than 10 feet thick, and few exceed 70 feet although they may be followed for miles. In especially fluid flows, crystals of olivine sank toward the bottoms while the lavas were still in motion. A large part of southeast Oregon was buried by these Steens basalts, from the Harney Basin in the north to Hart Mountain, Abert Rim, and Warner Valley in the south, and west to the Glass Buttes in northern Lake County. On Steens Mountain, the feeding fissures are concentrated on the east-facing scarp close to the vents of the older volcanoes. This suggests that the scarp itself originated by fracture and uplift along an ancient belt of tension. Other mountain scarps in southern Oregon may also coincide with old zones of fissuring.

As the outpouring of Steens basalts drew to a close, the centers of eruption became more localized and their products more diverse, so that locally the basalts were buried by thick flows of andesite, dacite, and rhyolite. About the same time, downsinking produced the initial Harney Basin. Lake- and river-deposits accumulated in the new depression while showers of ash fell into it and viscous flows of glassy rhyolite were discharged by volcanoes along its margins (Danforth formation).

During middle and late Pliocene time, the country north and east of Klamath Falls contained many large lakes, like the Upper Klamath Lake of today. Within them and around their borders were numerous volcanoes that erupted flows of andesite and basalt and showers of fragmental ejecta. Some flows emptied into the lakes, while abundant ash fell directly into them and was washed in from the neighboring hills. The floors of the lakes were covered with the delicate shells of minute aquatic plants (diatoms) that flourished in the waters. The evidence of these conditions is plainly seen in roadcuts and quarries that reveal beds of white diatomite between red and brown layers of cindery ash and sheets of dark lava.

In central Oregon, in the region stretching from Mount Vernon and Dayville to the southern flank of the Ochoco Mountains, the mid-Pliocene eruptions were of a different kind. The mountains elevated here at the close of the Miocene period had already been reduced to a gently undulating surface before the eruptions began. Meandering over the surface, between low banks of sand and gravel, were the ancestral John Day River and its tributaries. About the time when the Steens basalts were welling from fissures in southern Oregon, this ancient John Day Valley was also riven by swarms of cracks. But here it was not basaltic lava that rose to the surface; instead it was an effervescing emulsion of rhyolite in the form of glowing clots and spray. The ejecta were not hurled high into the air, but foamed quietly from the fissures and then spread across the plains as incandescent avalanches, like those that swept down the Valley of Ten Thousand Smokes, Alaska, in 1912. So mobile were these avalanches of ash and pumice that they moved swiftly for long distances over the gentlest gradients. Long after coming to rest, they remained intensely hot and gave off clouds of acid gas. While the fragments of frothy glass were still plastic, they were firmly annealed to each other, and the larger lumps were flattened into thin discs by the weight of the material on top. In this way the debris was converted into compact and streaky tuff closely resembling banded lava. More than 1,000 square miles were inundated by these glowing torrents of ejecta. The drainage of the John Day basin was completely changed, and the tuff-sheet was quickly and thickly covered by the sands and gravels of overloaded streams. Erosion has since dismembered the once continuous sheet of Rattlesnake tuff; the relics rest on the upturned edges of the older volcanic rocks as flat caps, like those on the hills bordering the John Day River near Picture Gorge.

Perhaps it was while these eruptions were taking place that volcanoes in the Horse Heaven region to the north were discharging steep-sided, domical piles of viscous, siliceous lava and exploding vast quantities of pumice and coarse ejecta.

Late in Pliocene time, fluid flows of andesite and olivine basalt (Ochoco lavas) built broad and low shield volcanoes east of Prineville. Copious flows of basalt were also erupted, both from fissures and from cones, in the Harper district of Malheur County, in the Otis Basin of Harney County, and in the Owyhee country. Meanwhile, the Harney Basin was further depressed. Fissure-eruptions of basaltic tuff, not unlike those that produced the Rattlesnake tuff, occurred along its margins, while cindery ash and pumice, blown from volcanoes not far away, fell into the depression.

Life and Climate of Pliocene Time

Save for slight fluctuations, the Oregon climate had been growing cooler from Eocene time to the end of the Miocene period, though even then it was still mild and humid. Throughout that interval of 40 million years, there had been little difference between conditions in the eastern and western parts of the state, for the Cascade Range was not high enough to serve as a climatic barrier. But upheaval of the Cascades at the end of Miocene time was reflected at once in differences between the Pliocene vegetation on opposite sides of the range. On the west side, during early Pliocene (Troutdale) time, the climate was marked by summer rains. The annual rainfall, although less than during the Miocene, approximated 35 inches. Redwoods thrived in sheltered valleys close to oaks on the more exposed slopes. With the redwoods grew persimmon, sweet gum, and liu-shu. Clearly, the temperature was not unlike that on the adjacent coast of Oregon today.

On the opposite side of the Cascades, the rainfall was approximately 10 inches less, although now it is 30 inches less than to the west. The vegetation on this lee side of the mountains was similar to that now living along the western edge of the Sacramento Valley of California. Box elders grew along the banks of streams, together with willows, sycamores, red-buds, and grapes, while oaks occupied the neighboring hills. In the John Day country the forests were much thinner than they had been in earlier times, and between them were wide grasslands over which ranged herds of antelopes, camels, and grazing horses.

In southeast Oregon the annual rainfall was about 20 inches, twice what it is today, and the seasonal temperatures were more moderate than now, the average yearly temperature being 10° F. higher. In the lowlands, mountain mahogany, toyon, and juniper grew; on cooler, higher slopes, a pine and Douglas fir community passed upward into forests of spruce, poplar, and mountain ash.

As the Cascade barrier rose, less rain fell on the eastern slopes. In the Deschutes formation, of late Pliocene age, the meager fossil flora of aspens, willows, cherries, box elders, and cottonwoods indicates a cool, semiarid climate. By this time, the annual rainfall had diminished to approximately fifteen inches, little more than half of what it had been at the dawn of the Pliocene period, although five inches more than at present.

At the close of Pliocene time the climate became much cooler. Snows falling on the high peaks no longer melted completely in the summer sun. Year after year the patches of permanent snow grew larger and thicker. Ultimately, they gave birth to glaciers, and gradually these pushed farther down the mountainsides. The world was about to undergo another of its great ice ages.

As for the Pliocene animals, they were far more modern in aspect than their ancestors. Hardly bigger than ponies, the horses were larger than in Miocene times. Among them was the first single-toed form, *Pliohippus*. The streams and marshes were frequented by the last of the rhinoceroses, by hippopotami, and by giant beavers. There were mastodons and elephants, horned antelopes, long-limbed giraffe-camels, and bear-dogs as large as the largest Alaskan brown bears. Bison, buffalo, and musk ox wandered in herds through the open spaces, while hyena-dogs, primitive coyotes, and many kinds of wolves and cats prowled in search of prey.

The Ice Age
(1 million to 25,000 years ago)

The Pliocene volcanoes of the High Cascades were mostly broad shields built by quiet effusion of olivine-bearing andesites and basalts. Their flanks are now scored by profound canyons and the fillings of their central conduits have been laid bare by erosion. On the other hand, the volcanoes that grew during the Ice Age, although sculptured by glaciers, retain much of their original conical forms. Among them are most of the crowning peaks of the Cascade skyline—Mounts Shasta, Pitt, and Mazama; the South Sister and the Bachelor; Mounts Jefferson, Hood, St. Helens, Adams, and Rainier. These are composite cones, built partly by eruption of lava and partly by explosive discharge of fragmental ejecta, and in the main they consist of andesite.

Effusion of basalt from shield volcanoes did not come to an end when these Ice Age cones of andesite began to rise; on the contrary, shield and composite volcanoes erupted side by side, and long flows of basalt escaped from fissures at the feet of the composite cones to pour down canyons on either side of the Cascade Range. Typical of the younger shield volcanoes are the Goose Nest near Shasta, Brown Mountain near Mount Pitt, Tumalo Mountain near the Three Sisters, and many low, domical mounds close to the south rim of the Columbia Gorge not far from Portland. Volcanism during the Ice Age was thus as varied as it was uniform during the Pliocene period. The new volcanoes grew on the eroded remnants of their predecessors, and, like them, they were mostly alined in a north-south belt, although in the region adjoining the Columbia River many were arranged at right angles to this dominant trend.

In their manner of growth, the huge composite cones resembled Vesuvius, Fujiyama, Orizaba, and Mayon. Their activity changed repeatedly from quiet emission of lava to outbursts of pumice, ash, and cinders. Often decades, and sometimes centuries, of repose intervened between eruptions, and usually the longer the interval of rest the stronger the activity that followed. At first the cones developed chiefly by overflows of andesitic lava from the summit-craters, but as they approached full height, lavas issued more and more frequently from fissures on their lower slopes. When the central pipes were firmly plugged, upward pressure of the underlying magma was often enough to open radial splits through the flanks. Then, tongues of lava broke from lateral vents, or parasitic cones of cinders were formed around them. Commonly, these lateral eruptions drained much lava from the central pipes, causing such a reduction of pressure on the reservoir below that powerful explosions issued from the summit-craters. Showers of glowing projectiles rose from the tops of the cones while streams of lava oozed from openings on the flanks.

Many Cascade volcanoes, particularly the northern ones, such as Mounts Hood, Rainier, and Baker, continued to erupt andesite to the last; others, having produced andesite during most of their growth, began to discharge a great variety of lavas and fragmental ejecta during old age. On the one hand, they erupted basaltic flows and cinders from parasitic vents; on the other, they erupted viscous flows and bulbous domes of rhyolite and dacite, or hurled out frothy, siliceous pumice in vast amount. Probable reasons have already been suggested (pages 2 and 3). As the volcanoes became older, the intervals of quiet between eruptions tended to lengthen so that the magma in the underlying reservoirs separated into fractions of different composition. There was much variation in the content and pressure of the gases, and variation also in the degree of crystallization of the magma in the reservoirs prior to discharge. Besides, fissures began to tap different levels in the feeding chambers, draining layers of different material. Here, as on volcanoes elsewhere, the increased diversity of the eruptive products was a mark of decadence and approaching extinction.

During most of their growth, the Ice Age volcanoes of the Cascades were covered by glaciers that advanced and retreated in response to fluctuations in the climate. Many glaciers still survive on the higher peaks, but these are trivial compared with those that mantled the cones when they were in full vigor. There were periods when ice spread down the mountainsides for distances of 20 miles or more, when the glaciers in the canyons were more than 1,000 feet thick and even the ridge-tops were concealed. At such times, showers of hot ash falling on the ice caused devastating torrents of mud and boulders to sweep down and lay waste to the plains below. At other times, during warm interglacial spells, the glaciers all but disappeared, and forests crept up the slopes in their wake.

The marks of these vanished glaciers are nowhere more dramatically revealed than on the walls of Crater Lake, in the interior of the beheaded volcano of Mount Mazama. Here, layers of glacial debris and river-borne sands separate sheets of lava, and from lake-level to the crater rim the crusts of the flows show scratches made by passing ice, eloquent evidence of the advance and retreat of glaciers on the sides of the rising volcano.

Toward the close of the Ice Age, as volcanic activity waned, glacial erosion gained the upper hand. It was then that the deep cirques and great U-shaped canyons were gouged in the flanks of the Cascade cones.

Periodically, while the composite cones and shield volcanoes were erupting along the crest of the Cascades, streams of fluid olivine basalt burst from cracks around their feet and poured for miles down the canyons. In places, flows piled on flows to a depth of 1,500 feet. Today their remnants form flat-topped benches on the canyon walls of the North Santiam, McKenzie, Willamette, Salt Creek, North Umpqua, Rogue River, and Butte Creek, and many roads that cross the Cascades follow the gentle gradients of their upper surfaces. The oldest of these intracanyon flows have been reduced by erosion to detached mesas, like the Table Rocks near Medford; the youngest still preserve the ropy forms, blisters, and pressure-ridges of their original crusts.

East of the Cascades, as we have seen, volcanic activity was intense and widespread during the Pliocene period. During the Ice Age, the centers of eruption were greatly reduced in number. Although the interior plateau was profoundly disturbed by earth-movements that elevated some blocks to form mountains and dropped others to form valleys, few new volcanoes were born. Among these were vents close to the southern edge of the Harney Basin, near Hines and Voltage. Flows of basalt from the latter covered 125 square miles, and by damming Malheur Gap they cut off the Harney Basin from the drainage of the Malheur River, an important consequence of which was the filling of the basin with the alluvium that now forms the rich farmlands adjacent to the town of Burns. Other basaltic flows issued from fissures near Bend, and in the Harper district of Malheur County several flows of glassy, siliceous lava were extruded.

Of all the Ice Age volcanoes east of the Cascades, the largest by far was the Newberry Volcano, some 25 miles south of Bend. Its summit, Paulina Peak, rises almost 4,000 feet above the encircling plateau. The volcano is of the shield type, and has the shape of an inverted saucer, deeply dented on top and ornamented on the sides with many small knobs. Across the base, it measures 20 miles; on its flanks are more than 150 cinder cones; and on its summit there is a cauldron, four by five miles wide, hemmed in on all but one side by precipitous walls up to 1,500 feet in height. Within this huge depression lie Paulina and East lakes.

Although the final eruptions of this volcano took place only two thousand years ago, its principal activity was contemporaneous with that of Hood, Jefferson, Mazama, and the other composite cones of the High Cascades. But whereas the products of these were mainly andesitic, the lavas of the Newberry Volcano were almost exclusively basalt and rhyolite. Until the volcano was 2,000 feet high, only basaltic flows were erupted. Thick sheets of rhyolite were then discharged, and these were succeeded by explosions of basaltic ash. During the later stages of growth, flows of basalt, andesite, and rhyolite poured from the summit-crater. When the volcano had reached its maximum size, its top stood at least 1,000 feet higher than the present peak, and the crater was very much smaller than the present cauldron. How then was the great summit-depression formed? Surely not by a catastrophic explosion, for there are no thick piles of ejecta around the rim. On the contrary, it was the quiet but rapid outflow of basaltic lava from fissures low on the flanks of the volcano that drained the central feeding pipes, and so withdrew support from beneath the summit. The result was inevitable; the top of the mountain collapsed along concentric fractures. As far as can be judged, this event occurred about the end of the Ice

Age, perhaps 20,000 or 25,000 years ago. How long an interval of rest ensued, there is no means of telling, but after a pause new eruptions began on the floor of the cauldron and on the outer slopes of the beheaded volcano.

The Last 25,000 Years

That volcanic activity in Oregon was on a smaller scale during the Ice Age than during the preceding Pliocene period, can hardly be doubted; that it has diminished further since the last glaciation seems equally certain. Nevertheless, many High Cascade volcanoes have continued to erupt at intervals down to historic times. Mount Shasta blew out ash as recently as 1786; Mount St. Helens was active several times between 1831 and 1854; Cinder Cone, near Lassen Peak, discharged a flow of basaltic lava in 1851; and Lassen Peak itself erupted both ash and lava from 1914 to 1917. It seems likely that Mounts Rainier and Hood were also active during the last century. The Indians who occupied Oregon for thousands of years before the arrival of the white man must have witnessed countless eruptions.

In the pages that follow, a brief account is given of some of the outstanding events of postglacial time, beginning with eruptions in the High Cascades and concluding with others on the plateau to the east.

The Destruction of Mount Mazama and Formation of Crater Lake

No event in the long volcanic history of Oregon was more dramatic than the decapitation of Mount Mazama. It was a cataclysm seen from afar by the early Indians. They had long been familiar with the majestic ice-capped cone, for it rose to a height of 12,000 feet, a mile above its present ruins. At the culmination of the last glacial advance, the mountain was completely enveloped by ice. Glaciers choked the canyons to their brims, and one of them extended for 17 miles down the Rogue River Valley. With amelioration of the climate, the ice sheets dwindled. Meanwhile showers of ash and pumice were erupted from the summit-crater, and parasitic cinder cones and mounds of glassy dacite were built over vents on the flanks of the volcano.

Approximately 6,500 years ago, the glaciers had shrunk so far that none stretched from the mountaintop beyond the present rim of Crater Lake, except for three thin tongues on the south slope, in Munson, Sun, and Kerr valleys, and even these were only four miles long. The lower slopes of the mountain were clothed in heavy forests similar to those of today.

A few decades, perhaps a few centuries of quiet preceded the climactic explosions. During that interval, the volcano gathered strength. The liquid magma in the feeding chamber slowly crystallized until the gas-pressure became too great for the roof to withstand. Cracks opened and the magma urged upward, shouldering aside the rocky walls. For miles around, the ground shook violently. Alarmed by the quakes, most of the animals fled, and the Indians, aware of the menace, withdrew to a safer distance.

Finally, a plume of white vapor rose from the summit. Within a few hours, it changed to a towering column, becoming darker and more ominous as the content of ash increased. At first, the eruptions were mild, and the fragments falling from the cloud were no larger than particles of sand. But day after day, the intensity of the explosions mounted. Huge cauliflower clouds rose higher into the sky, to be drifted eastward by the wind. Night after night, the clouds were more brightly lit by incandescent ejecta describing fiery arcs in their flight. The roars from the crater grew louder, and frenzied streaks of lightning multiplied in number. Many of the falling fragments were now as large as a clenched fist, and showers of fine ash began to fall hundreds of miles away, on the plateau east and northeast of the volcano. In lands thousands of miles distant, men marvelled at the brilliant colors in the sky as the rays of the setting and rising sun shone through the dustladen air. (See Plate VIII).

After several weeks these preliminary eruptions came to an end. The scene was one of utter desolation. Over thousands of square miles, a gray-white mantle of ash covered everything, like newly fallen snow. On the mountain itself, the banks of pumice were more than 50 feet thick; 70 miles away, on the present site of Bend, the sheet of ejecta was six inches deep. All that remained of the green forests on the montainside were gaunt, charred stumps.*

During the few days of calm that followed, it seemed as if the fury of the volcano had been spent. But, fearsome as the first eruptions had been, they were only a prelude to the devastating blasts to come. The end came with alarming suddenness. A puff of vapor from the summit-crater gave warning. Quickly it expanded, like a cluster of giant balloons, boiling and seething with incredible energy. Then came an ear-splitting roar; part of the eruption-cloud spread sideways and settled over the top of the mountain in billowing folds. Almost immediately, the cloud divided into many branches that surged down the canyons, racing along with ever greater speed. At the mountain base, the clouds hurtled forward at hurricane rate. Some travelled 50 to 100 miles an hour. At the bottom of each, almost hidden from view, there

* From the amount of radioactive carbon (C 14) still remaining in these charcoal stumps, Dr. W. F. Libby determined that they were burned about 6,500 years ago. This, accordingly, is the age of the climactic eruptions of Mount Mazama and the age of Crater Lake itself.

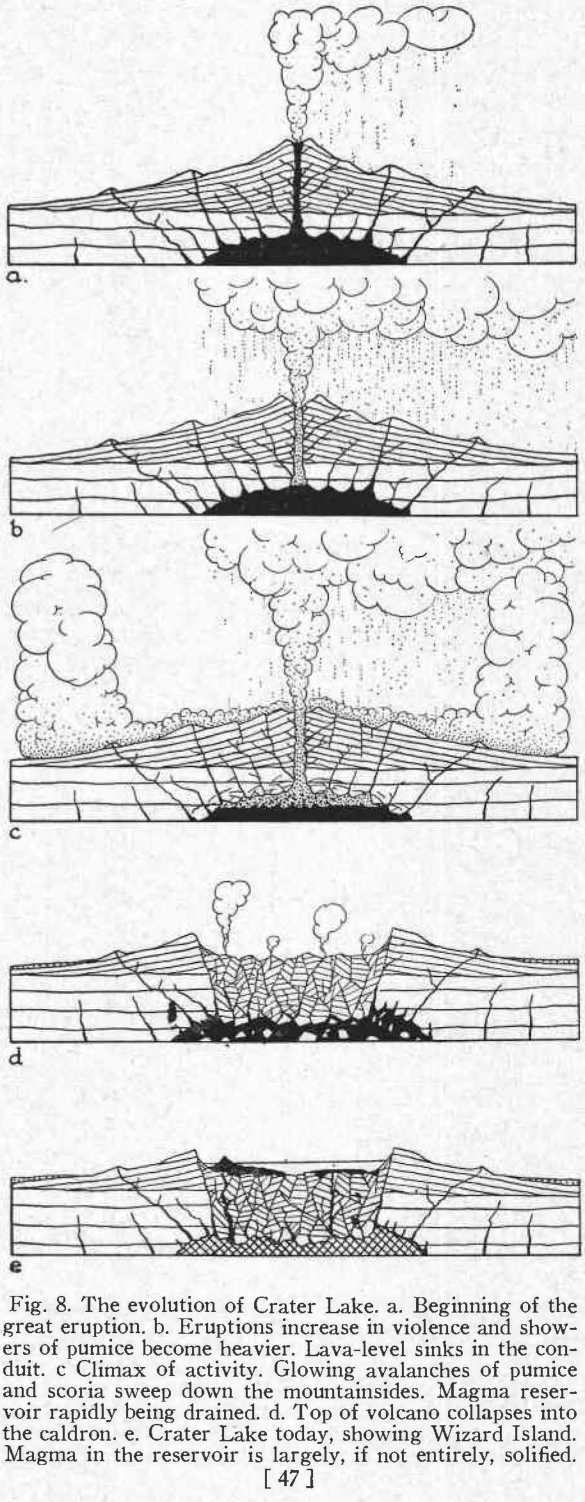


Fig. 8. The evolution of Crater Lake. a. Beginning of the great eruption. b. Eruptions increase in violence and showers of pumice become heavier. Lava-level sinks in the conduit. c Climax of activity. Glowing avalanches of pumice and scoria sweep down the mountainsides. Magma reservoir rapidly being drained. d. Top of volcano collapses into the caldron. e. Crater Lake today, showing Wizard Island. Magma in the reservoir is largely, if not entirely, solified.

was an avalanche of glowing ash and pumice. It was atonishing how far the material rushed, raging through the forests like turbulent torrents. Some avalanches swept down the valley of the Rogue River for 35 miles; others poured over the plateau, now crossed by the Dalles-California Highway, as far as Chemult, carrying lumps of pumice up to 14 feet across. Still others raced across Diamond Lake into the canyon of the North Umpqua. What was it that gave them their amazing strength and velocity? Chiefly, it was the great momentum of the heavy loads as they plunged down from the steep, upper slopes of the volcano; in part, it was the mobility imparted to them by the abundance of hot, compressed gases they contained. Their internal energy was tremendous, for the glowing bombs were continually bursting.

By the time these first avalanches had come to rest, the glacial canyons on the mountainsides were filled to depths of 200 or 300 feet with debris. At night, it seemed as if the canyons were occupied by streams of glowing embers. Next day, more avalanches rushed down from the summit. These were different from the preceding ones; they consisted not of white pumice fragments but of dark, cinder-like scoria heavily laden with crystals. It was clear that lower levels of the reservoir were being expelled and the end was approaching. Even as these dark avalanches were racing down, noises of terrifying strength came from the mountaintop. It sounded as if the whole volcano were breaking asunder. For miles around, the ground shook frightfully. The noises were quite different from the peals of thunder continually rumbling; they resembled the tumultuous roars, magnified a thousandfold, that great rock slides make when they crash after a quarry blast.

The activity ended almost as quickly as it had begun. Several days later, when winds had cleared the air, the mountain was again revealed. The change in its shape was one to stagger the imagination. The ice-clad peak that had formerly risen in grandeur above all its neighbors had vanished. In its place was a stupendous caldron, between five and six miles wide and 4,000 feet deep, enclosed by precipitous walls. Pungent smells and smarting fumes of acid rose from the pit, and clouds of dust-charged vapor tossed like curtains in the gusty wind. The floor of the colossal basin was a chaotic jumble of enormous blocks, between which were many pools, some milky white, others dark green, and others of ochreous mud, all boiling and spattering. (See Plate IX).

Outside the caldron, the slopes of the mountain were dreary wastes of ashen gray. Each of the pumice- and scoria-filled canyons was a "Valley of Ten Thousand Smokes" from which rose dense clouds of acid gas. Even decades later, some of the ejecta were still so hot that when rains fell the surface was shrouded in vapor.

Seventeen cubic miles of the mountaintop had disappeared. It was not that the volcano had blown off its head, for not more than 1½ cubic miles of the ejecta consisted of old rock fragments from the mountain itself. The rest of the material, approximately 10 cubic miles, was composed of fresh, frothy magma discharged from the reservoir underground. So rapidly was the feeding chamber drained of its contents by these eruptions and injection of magma into subterranean fissures that support was withdrawn from beneath the mountain top. Within a few hours, or at most a few days, the summit collapsed into the void below.

How long a period of quiet followed, there is no accurate way of telling. The volcano had spent prodigious energy, and it may have lain exhausted for centuries. Forests returned to the outer slopes; year by year they crept upward. But the volcano was not yet extinct; some magma still remained in the reservoir, and slowly it regathered strength. Finally, it forced a passage through the floor of the caldron, forming a lake of lava. Subsequently, it broke out again, this time close to the southwestern edge of the pit. Flow piled on flow until they reached the present level of the lake. Then the quiet effusions gave way to explosions of ash and pasty clots that accumulated around the orifice to form the cone of Wizard Island. Finally, lava oozed from cracks at the foot of the cone and spread sluggishly until they almost reached the adjacent wall of the caldron. From the age of the oldest trees on Wizard Island, it seems that these last eruptions took place no more than 1,000 years ago. Nowadays, there are no gas vents or hot springs in the vicinity to indicate the presence of magma underground. It would be rash, however, to say that Mount Mazama will never erupt again.

The Three Sisters Region and McKenzie Pass

During the past few thousand years, there has been more volcanic activity in the Three Sisters region than in any other part of the Cascade Range. Indeed, many cinder cones have probably been built and numerous flows of basalt and obsidian have been erupted during the present millennium. To find a comparable wealth and variety of recent lavas, one must go to the eastern base of the Cascades, either to the Newberry Volcano or to the Medicine Lake Highlands and Modoc Lava Beds of California.

Of the Three Sisters themselves, the last to erupt was the South Sister, although its beginnings go back well over a million years, to the late Pliocene period. First, a broad shield volcano of basalt was formed; then, during the Ice Age, a steep cone of andesite and dacite was built on top of the shield. Finally, after the glaciers began their last retreat, two cones of basaltic lava and cinders developed around the summit. The younger of these cones has a beautifully-preserved crater rimmed by cinders and bombs and by slaggy layers of lava. It seems so fresh that the final outburst may well have taken place less than 1,000 years ago.

Close to the southwest base of the South Sister another youthful cinder cone discharged a long stream of basalt that poured almost as far as Elk Lake; a second cone on the southwest flank of Broken Top erupted a shorter flow that almost reached the edge of Sparks Lake. About the same time, long streams of basalt issued from parasitic cinder cones on the sides of the Bachelor. (see Plate VI).

Young and remarkably fresh as they are, these basaltic flows are not the latest products of activity in the region. Subsequent to their formation, vents opened on the south slopes of the South Sister. From one, at Rock Mesa, explosions of gas-rich magma deluged the countryside with fragments of frothy pumice; then gas-poor magma rose sluggishly to spread as a thick sheet of blocky obsidian. At about the same time, a long north-south fissure opened a mile or so to the east, and from many points along it viscous lava was extruded as flows and steepsided mounds, the tops of which are littered with angular blocks and bristle with minarets of obsidian. The Century Drive from Bend provides a splendid view of some of the almost treeless, chaotic piles of glistening volcanic glass, and those who see them can hardly doubt that they were formed only a few centuries ago (see Plate III).

Equally arresting in the landscape are the black and red cinder cones clustered on the north flank of the North Sister, and the barren streams of basalt that descend from them to the McKenzie Pass. From one cone, close to the snout of the Collier Glacier, a long flow spilled into White Branch Creek, followed it for several miles, then overflowed into Linton Creek, damming it to form Linton Lake.

Still more spectacular is the black wilderness of basalt that surrounds the Belknap Cones on the north side of McKenzie Pass. Surely it is one of the largest and most impressive sheets of recent lava anywhere in the United States. Properly to appreciate the panorama, the traveler should pause in his journey over the pass to climb the Lookout Tower on the summit. From there, he sees in one direction 70 square miles of Belknap lava, and in another the tongues of basalt which came from cinder cones on the slopes of the North Sister. And he should stop at other points along the highway to examine the Belknap lavas where they froze to a standstill in the act of creeping over ice-scratched pavements of much older flows. It almost seems as if some of the lavas had just congealed (see Plate XIII).

Other eruptions took place recently in the country to the north, close to the Santiam Highway. Several small cones were built there, and a flow of basalt from one of them obstructed the local drainage to produce Clear Lake. That these eruptions occurred within the present millennium seems quite likely, for standing on the floor of the lake are the upright trees of a drowned forest.

Today, there are neither hot springs nor fumaroles in the Three Sisters region; nevertheless, it would be unwise to deduce that all the volcanoes are extinct; some of them may be merely dormant.

Other Recent Eruptions in the High Cascades

Too much space would be occupied by listing the signs of postglacial volcanic activity elsewhere along the crest of the Cascades, for there are youthful flows and cinder cones by the score. Suffice to mention these: the line of basaltic cones that runs south from the Bachelor; the flow that serves as dam for Davis Lake, and the blocky, dark lavas adjacent to Fish Lake and Lake of the Woods, products of the last eruptions of Mount Pitt (McLoughlin) and the Brown Mountain Volcano. Much work remains to be done before an adequate account can be written of these closing Cascade eruptions. For Oregon geologists, the field is a most inviting one.

Last Eruptions of the Newberry Volcano

About the close of the Ice Age, as noted already, the top of the Newberry Volcano collapsed to form a caldron many miles across. After a quiet spell, rhyolitic lava issued from fissures high on the north wall of the caldron and cascaded down to the floor. Mounds of glassy lava then rose on the shores of Paulina Lake, and cones of basaltic ash were built on the banks of East Lake. Subsequently, a north-south crack opened across the middle of the caldron, and many cones were built along it, some by explosions of basaltic ash and some by explosions of pumice. This explosive activity lasted a long time. Indians were living in caves near Fort Rock when showers of hot pumice drove them away and scorched the sandals they left behind in their flight to safety. Dr. Libby's radiocarbon analysis of the sandals shows that this eruption took place approximately 9,000 years ago. Yet final eruptions of pumice from the Newberry vents occurred no more than 2,054 $\pm$ 230 years ago, as indicated by fragments of charcoal discovered in the topmost pumice layer in roadcuts between Paulina and East Lakes.

While activity was going on inside the summit caldron of the Newberry Volcano, domes of rhyolitic lava and more than 150 cinder cones were built on the outer slopes. From some of them long flows of basalt descended toward the Dalles-California Highway, destroying forests in their path. Other cones, such as the well-known Pilot Butte, near Bend, were active about the same time on the surrounding plateau. The final eruptions in this region were those that formed the striking cone, known as Lava Butte, adjacent to the highway a short distance south of Bend. Copious floods of basalt escaped from fissures at the base of the cone and poured northward into the Deschutes River at Benham Falls. It may be that less than a thousand years ago Indians living nearby witnessed eruptions identical with those recently ended at Paricutin in Mexico.

Many postglacial flows of basalt were also erupted from fissures closer to Bend, spreading northward to tumble into the gorge of the Metolius River. Other flows emptied into the gorges of the Deschutes and Crooked rivers, following them to their confluence west of Madras. Most of these are younger than the lavas of Hood and Jefferson, although older than the postcaldron eruptions of the Newberry Volcano.

Eruptions in Central and Eastern Oregon

Certainly, by far the majority of the Oregon volcanoes active during postglacial time lie in or close to the foot of the Cascade Range. Some, however, are to be found far to the east. Of these, three groups are especially interesting; namely, the Diamond, Jordan, and Bowden Craters. These three volcanic fields, although not as widely known as the comparable Modoc Lava Beds of California and the Craters of the Moon in Idaho, are scarcely less spectacular or instructive. Their cones are so fresh and the lava-crusts so little affected by decomposition, that activity may only have ended a few centuries ago. The visitor needs little imagination to picture columns of vapor still rising from the craters and see the flows still creeping forward.

The Diamond Craters are situated near the southern edge of the Harney Basin, in an almost barren waste of black basaltic lava that covers 25 square miles, and culminates in a domical mound approximately 400 feet high. For anyone anxious to examine a variety of lava forms, this is an attractive region. Here one may see smooth-crusted, ropy (pahoehoe), and clinkery (aa) flows, lava tubes, pressure ridges, and depressions formed by the collapse of lava crusts when the liquid

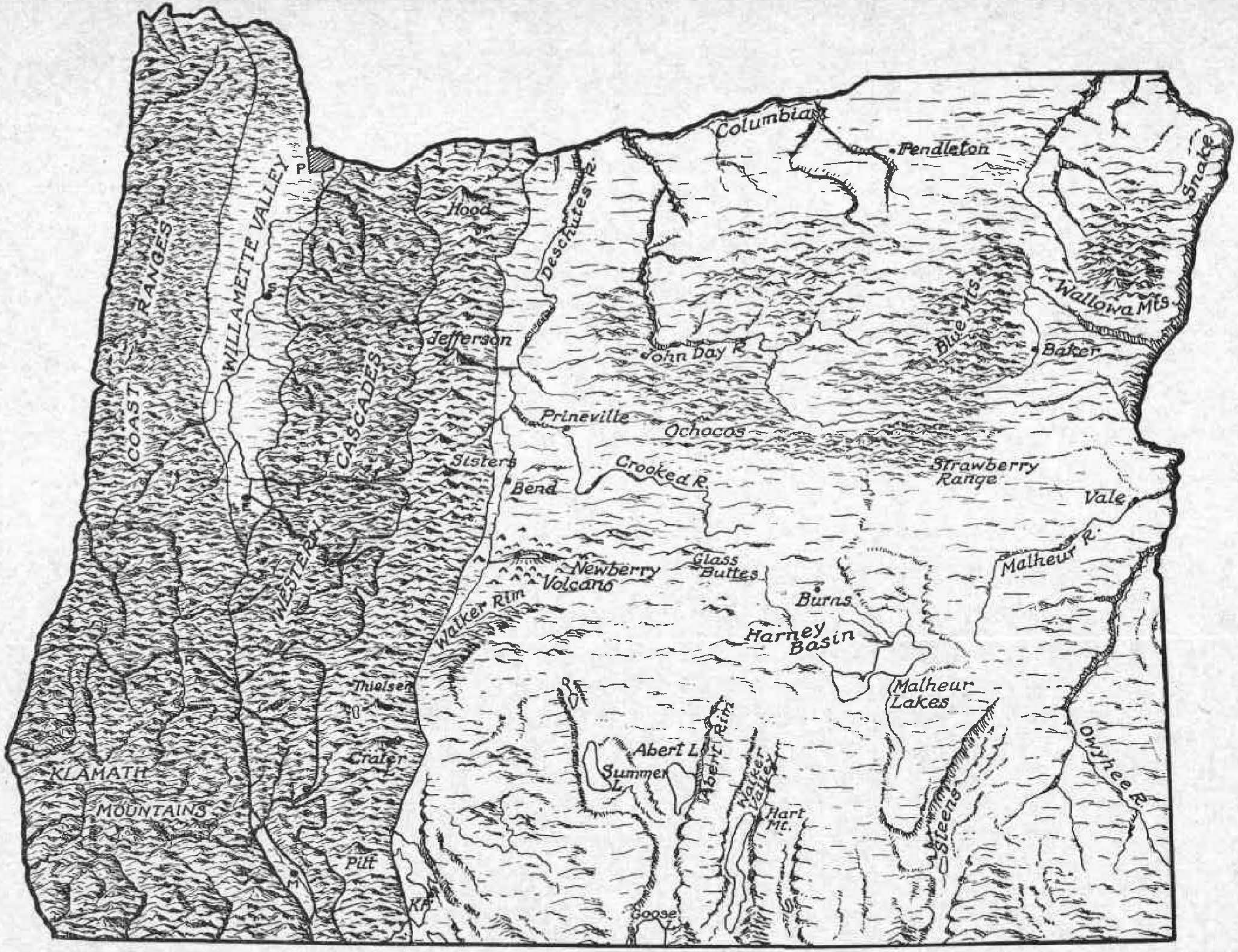


Fig. 9. Physiographic diagram of Oregon. E—Eugene; KF—Klamath Falls; M—Medford; P—Portland; S—Salem.

beneath was withdrawn by drainage. So recently did the eruptions take place that small cinder cones and even the tenuous lips of spatter cones have scarcely been modified by disintegration.

In east-central Malheur County, close to the Oregon-Idaho boundary, are the seldom-visited Jordan Craters, a line of four cinder cones standing three to five miles apart and surrounded by wide sheets of basaltic lava. One flow alone covers between 50 and 60 square miles. The ropy crusts of the lavas are wonderfully fresh, and tubes, gutters, and pressure ridges are plentifully displayed. Where liquid lava bubbled through cracks in the crusts of the flows, there are small driblet cones on the inner walls of some of which hang delicate stalactites formed of lava re-fused by burning gases.

About 30 miles south of the Jordan Craters, lies Bowden Crater. Here, the eruptions appear to have been entirely effusive. Surmounting a field of basaltic lava that covers 100 square miles is a small mound in the summit of which is a depression 600 feet wide and 40 feet deep. Clearly, the summit-mound was formed by the last over-flows from the principal vent, and its central pit resulted from collapse when lava was drained through lateral tubes. Although the crusts of the flows are considerably weathered and largely covered with sagebrush and bunch grass, it may be that the eruptions date back no more than a millennium or two.

THE FUTURE

The eruptions of the last 25,000 years appear to mark the dying phases of a long volcanic episode. Even the catastrophic outburst that beheaded Mount Mazama was a sign of old age and decadence. And all the parasitic cinder cones and domes of obsidian scattered on the flanks and around the feet of the great composite volcanoes of the Cascades are but products of declining activity. Yet it would be foolish to say that new eruptions will not take place, considering how many have occurred during the past few thousand years. Who can say that some of the Cascade cones, such as Shasta, Hood and Rainier, on which hot springs and fumaroles still survive, are not just dormant, preparing again to burst into violent activity? If they should revive, they will blow out ash and pumice from their summits, or domes of viscous lava will be forced upward through their craters, or flows and fragmental ejecta will be discharged from parasitic vents far down their sides. Perhaps obsidian mounds and cinder cones will be formed and new flows of basaltic lava will issue in the High Cascades or on the plateau to the east. If activity is resumed, earthquakes will serve as heralds and the warning should be ample.

But of this there can be no doubt—the long volcanic cycle is drawing to a close. It was from the struggle between volcanism and glaciation, "out of the ancient rage of fire and frost," that the lofty Cascade cones were shaped, but now the agents of erosion are supreme over the forces of construction. Relentlessly, they are eating into the sides of the old volcanoes, and streams are carrying the waste downward through the valleys to the sea, to the grave of mountains everywhere. First the giant cones on the crest will disappear; then the whole Cascade Range will be wiped away and all the mountains of eastern Oregon will be erased. The landscape is changing endlessly, and the face of the earth is always in motion, pulsating like a living thing.

PLATES

THE ANCIENT VOLCANOES OF OREGON

Typical explosive eruption of Paricutin.

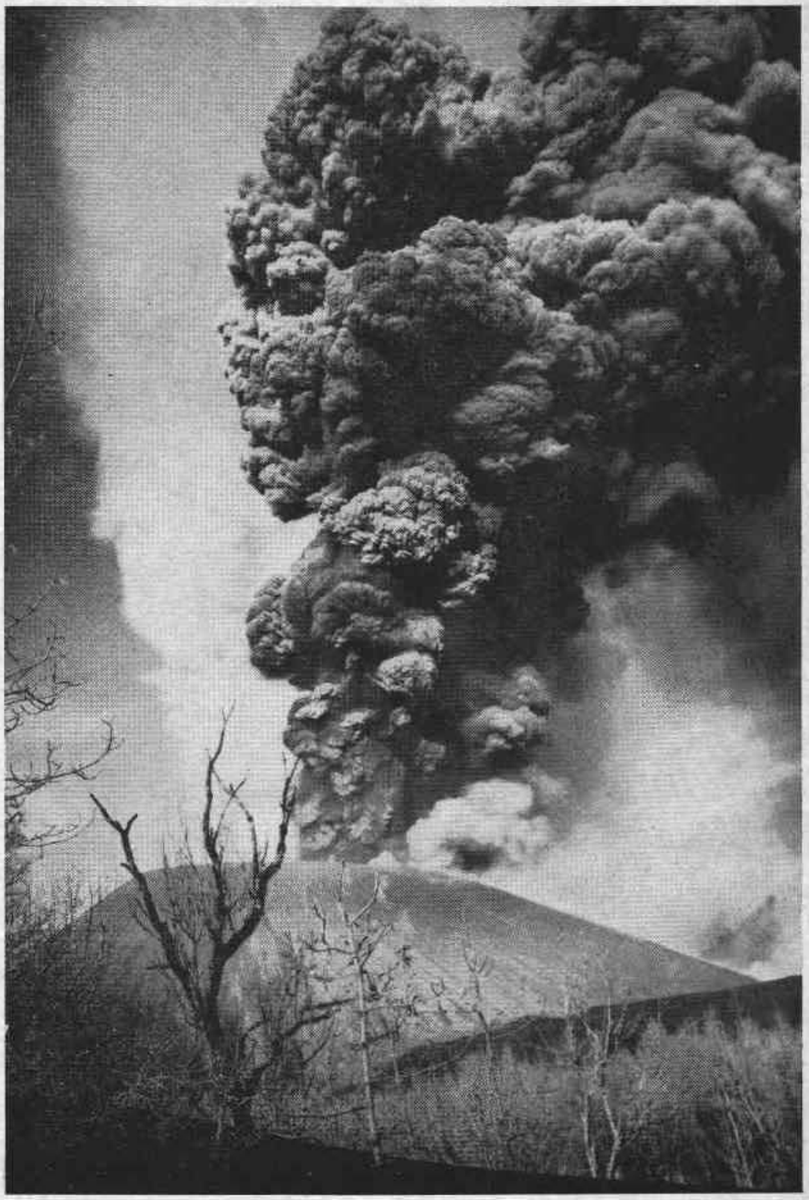
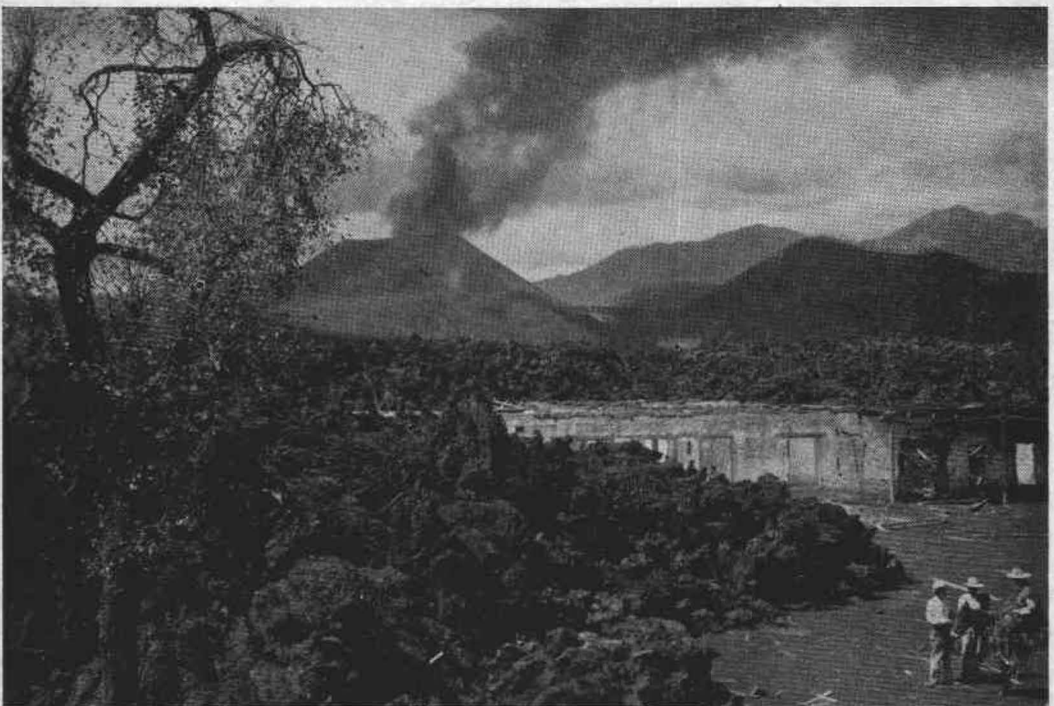


Plate I. Lava from Paricutin entering San Juan. June 1944. Photo. A. Brehme.



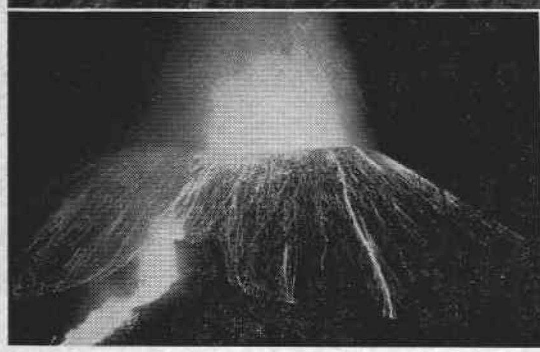


Plate II. Paricutin, Mexico, in eruption. Lava issuing from fissure while showers of bombs erupted from the summit-crater fall on the flanks of the cone. Photo taken early in 1943 by Navarro.

Plate III. Three domes of obsidian on the south flank of South Sister. These are among the latest products of volcanic activity in the Oregon Cascades.

Plate IV. Typical section in the Columbia Lava plateau. View of the Yakima basalts at Crescent Bar, Washington. Photo. Simmer.

Plate V. The Three Sisters from the north. From left to right, the North, Middle, and South Sisters. Beyond lies the denuded cone of Broken Top; behind it, the younger volcanoes of Tumalo Mountain and Bachelor Butte. Photo. U. S. Army Air Corps.

Plate VI. Bachelor Butte. A composite volcano in the Cascades. Its activity began during the Ice Age and has continued to the present millennium. Photo. Howard Coombs.

Plate VII. Part of the Cascade skyline. From left to right, Broken Top, South Sister, North Sister, Black Crater, Belknap cone, and Mt. Washington. The recent lavas from Belknap, bordering McKenzie Pass, are covered with snow. In the wooded, middle distance are several small cinder cones. Photo. U. S. Forest Service.

Plate VIII. Mount Mazama shortly before the disappearance of its summit. Beginning of the climactic eruptions. From a painting by Paul Rockwood.

Plate IX. Mount Mazama immediately after the collapse of its summit. Note three beheaded glaciers on the south rim of the caldron. The glacial canyons are almost filled with the deposits of glowing avalanches from which rise clouds of acid vapors. From a painting by Paul Rockwood.

Plate X. The Pinnacles, Crater Lake National Park. Deposits of glowing avalanches erupted by Mount Mazama prior to the collapse of the summit. White lump-pumice underlies dark scoria capped by crystal-rich ash. The pinnacles are produced by erosion along vertical cracks; many are hollow inside and represent "fossil fumaroles." The overlying ash has been reddened by fumarolic action. Photo. National Park Service.

Plate XI. Recent flow of basalt entering Davis Lake, Oregon Cascades. Photo. Brubaker Aerial Surveys.

Plate XII. Crater Lake from the west. Mount Scott rises beyond the eastern rim; beyond, stretches a basaltic plateau thickly covered by pumice blown from Mount Mazama during its climactic eruptions. Photo. 116th. Photo. Section, Washington National Guard.

Plate XIII. The Belknap cones. McKenzie Pass. After the main Belknap cone (left-center) became extinct, floods of fluid basalt issued from Little Belknap (right-center), probably within the last thousand years. Two old cinder cones (to left) were surrounded by the lava. In the distance, on the right, is the summit-pinnacle of Mount Washington. Photo. Dotson.